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26. MEDNARODNO POSVETOVANJE

26TH INTERNATIONAL EXPERT MEETING

KOMUNALNA ENERGETIKA

POWER ENGINEERING

9. do 11. maj 2017 Maribor, Slovenija

May 9TH to 11TH 2017 Maribor, Slovenia

(konferenčni zbornik)

Urednik:
dr. Jože Pihler

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(9. do 11. maj 2017, Maribor, Slovenija)

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JOŽE PIHLER

Na Fakulteti za elektrotehniko, računalništvo in informatiko, Univerze v Mariboru že šestindvajseto leto organiziramo mednarodno posvetovanje Komunalna energetika – oskrba z energijo. V teh letih smo v nekaj sto referatih obravnavali različno tematiko povezano z oskrbo z energijo na nivoju lokalnih skupnosti, republike Slovenije in širše. Referati so obravnavali tudi najnovejše raziskovalne dosežke s tega področja. Ker je oskrba z energijo temeljna potreba sodobnega človeka, se bomo z organizacijo posvetovanja trudili tudi v bodoče.

Poseben poudarek letošnjega posvetovanja je na "UPRAVLJANJU Z ENERGIJO". Na področju regulative je sprejet slovenski standard SIST EN ISO 50001 "Sistem upravljanja z energijo", katerega namen je omogočiti organizacijam, da vzpostavijo sisteme in postopke, ki so potrebni za izboljšanje energetske učinkovitosti, vključno z energijsko učinkovitostjo, rabo in porabo. Vabljena predavanja so v celoti posvečena tej tematiki. S strani direktorata za energijo, ministrstva za infrastrukturo bo predstavljena regulativa, dosedanje prakse in smernice za prihodnost na področju upravljanja z energijo. Agencija za energijo ima pomembno vlogo pri oskrbi z vsemi vrstami energije in sicer z električno energijo, zemeljskim plinom in toploto. Največ izkušenj je trenutno pri upravljanju z električno energijo, upravljanje z zemeljskim plinom že nekaj časa poteka, upravljanje s toploto pa je v začetni fazi. Strokovnjaki s posameznih področij bodo predstavili razmere v Sloveniji.

Referati posvetovanja so predstavljeni v šestih tematskih sklopih in sicer: Energetski vplivi na podnebje in okolje; Energetske naprave aparati in omrežja; Energetska učinkovitost in upravljanje z energijo; IKT v energetiki; Financiranje energetskih projektov in Študentski sklop.

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Izvajanje politike energetske učinkovitosti v Sloveniji

MOJCA KOKOT KRAJNC & ALENKA DOMJAN

Povzetek Energetska učinkovitost predstavlja enega izmed ključnih stebrov podnebno-energetske politike Evropske unije, saj uresničuje spoznanje, da je energija, ki je ne porabimo, najcenejša, najbolj čista in najbolj zanesljiva. To je bila podlaga za spremembe v veljavni direktivi o energetski učinkovitosti, ki obveznost doseganja prihrankov podaljšuje do leta 2030. V prispevku podrobneje predstavljamo novosti, ki jih bo morala Slovenija na področju politike učinkovite rabe energije upoštevati. Prav tako pa prikazujemo rezultate poročanja o doseženih prihrankih v letu 2015 ter napovedujemo novosti, ki bodo prispevale k izpolnjevanju zastavljenih ciljev dopolnjene direktive.

Ključne besede: • energetska učinkovitost • Direktiva 2012/27/EU • varčevanje z energijo • prihranki energije • poročanje o doseženih prihrankih energije •

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Performing Energy Efficiency Policy in Slovenia

MOJCA KOKOT KRAJNC & ALENKA DOMJAN

Abstract Energy efficiency is one of the key pillars of the EU's climate and energy policy, as it pursues the awareness that only the energy that we don't use is the cheapest, cleanest and the most reliable. This awareness was the basis for amendments of existing Directive on energy efficiency, which extends the energy savings targets by 2030. In this article, we present novelties that Slovenia will have to take into account regarding energy efficiency. We also introduce the results of energy savings that were reported for 2015, as well as new measures, which will contribute to achieving the objectives set out in the amended Directive.

Keywords: • energy efficiency • Directive 2012/27/EU • saving energy • energy savings • reporting achieved energy savings •

CORRESPONDENCE ADDRESS: Mojca Kokot Krajnc, Ph.D., Energy Agency, Strossmayerjeva ulica 30, p. p. 1579, 2000 Maribor, Slovenia, mag. Alenka Domjan, Energy Agency, Strossmayerjeva ulica 30, p. p. 1579, 2000 Maribor, Slovenia.

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Uvod

Energetska učinkovitost ni samo orodje za varčevanje z energijo, temveč je uspešno orodje za doseganje trajnostnega razvoja, ker so ukrepi usmerjeni k izboljševanju zanesljivosti oskrbe z energijo, zagotavljanju čistejšega okolja, izboljševanju življenjskega standarda in ustvarjanju novih delovnih mest [7].

Bistvo energetske učinkovitosti je v tem, da je ob hkratni manjši izrabi energije končni rezultat energetsko izboljšane dejavnosti enake (ali celo boljše) kakovosti, kot je bil pred izvedbo ukrepa energetske učinkovitosti. Zato energetske učinkovitosti nikoli ne smemo razumeti zgolj kot varčevanje z energijo, saj je varčevanje pogosto povezano z zmanjševanjem udobja.
Zaradi številnih prednosti energetska učinkovitost ostaja eden ključnih ciljev podnebno-energetske politike Evropske unije, ki to politiko povezuje s stališčem, da lahko zgolj z energetsko učinkovitostjo dosežemo spoznanje, da je samo tista energija, ki je ne porabimo, najcenejša, najbolj čista in najbolj zanesljiva. Uresničevanje tega cilja predstavlja enega od stroškovno najbolj učinkovitih načinov spodbujanja prehoda na nizkoogljično gospodarstvo ter ustvarja priložnosti za gospodarsko rast, razvoj in za zaposlovanje ter daje naložbene priložnosti [2, 3].

Te ugotovitve so v energetskih krogih Evropske unije pripeljale do potrebe po dopolnitvah in spremembah Direktive 2012/27/EU o energetski učinkovitosti v okviru »zimskega svežnja«. Bistvo sprememb je vezano na dodatne prihranke energije kot rezultat nadaljnjega intenzivnega izvajanja ukrepov učinkovite rabe energije ter odpravo ovir in pomanjkljivosti energetskega trga, ki ovirajo učinkovitost pri oskrbi in rabi energije.

Novosti v direktivi 2012/27/eu o energetski učinkovitosti

V okviru »zimskega svežnja« predlagane spremembe direktive o energetski učinkovitosti države članice tudi v obdobju 2021 – 2030 obvezujejo k doseganju enakih ciljnih deležev prihranka končne energije na letni ravni kot v prvem obdobju, torej 1,5 % končne rabe energije. Opredelitev količin ciljnih prihrankov v obsegu 1,5 % končne energije v obdobju 2020 – 2030 bo prav tako temeljila na povprečni letni prodaji energije končnim porabnikom zadnjih treh let pred začetkom izvajanja te obveznosti, torej zadnja tri leta pred letom 21, na enak način, kot so bile ciljne količine prihrankov določene za obdobje 2014 – 2020 [2, 3, 4].

Prav tako direktiva ohranja različne možnosti doseganja prihrankov energije, in sicer bodo imele države članice še zmeraj na voljo dva sistema: sistem obveznosti energetske učinkovitosti in alternativne ukrepe, ki so v predlagani spremembi direktive v členu 7b. natančneje opredeljeni; tako kot do sedaj, bodo lahko ta dva sistema tudi kombinirale. V predlogu prenovljene direktive so v Aneksu V. natančneje definirani tudi predlogi za izračun prihrankov, realiziranih v okviru ukrepov učinkovite rabe [2, 3].

Predlagana sprememba države članice tudi zavezuje, da morajo v shemo obveznosti energetske učinkovitosti vključiti ukrepe in dejanja v okviru vključitve socialno šibkih gospodinjstev. Priporoča se, da se pri zasnovi alternativnih oblik doseganja ciljev energetske učinkovitosti upošteva tudi vpliv na gospodinjstva, ki jih je prizadela energetska revščina [2, 3]. Za Slovenijo to konkretno pomeni, da se bodo prihranki, doseženi v okviru šibkih gospodinjstev, upoštevali pri alternativnih ukrepih, torej bo zanje skrbel Eko sklad.

Države članice bodo tudi v prihodnje imele možnost same opredeliti sistem obveznosti in določiti akterje, ki bodo vključeni v sistem. Poudarek je dan predvsem prihrankom, doseženim v zvezi s prenovo stavb. Pričakuje se, da bi z obnovo stavb države članice lahko dosegle okoli 40-odstotno znižanje porabe končne energije [2].

V predlogu sprememb direktive je velik poudarek tudi na spremljanju in nadzoru izvajanja ukrepov. Države članice bodo morale zagotoviti sistem, v katerem bo neodvisen organ preveril statistično pomemben del in reprezentativen vzorec izvedenih ukrepov [2]. Prenovljena direktiva zahteva, da se spremljajo tako prihranki, doseženi s strani zavezancev, kakor tudi alternativni ukrepi, s čimer se lahko v celoti in uspešno izključi dvojno štetje istih prihrankov energije.

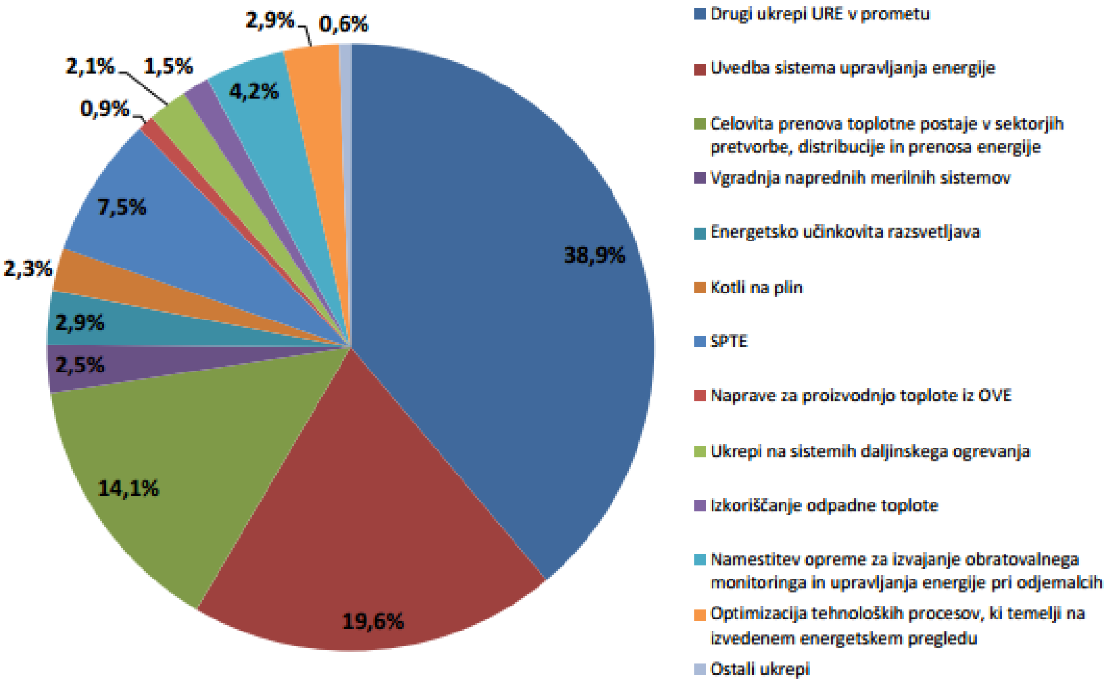
Z vidika trajnostnega razvoja prenovljena direktiva poudarja, da morajo države članice spremljati ne samo prihranke energije z izvedenimi ukrepi, temveč tudi, koliko so s posameznim ukrepom uspele zmanjšati izpuste CO_2 in povečati rabo obnovljivih virov energije [2].

Uspešnost izvajanja politike energetske učinkovitosti v Sloveniji

Skladno s 3. členom Direktive 2012/27/EU o energetski učinkovitosti EED si je Slovenija v okviru Akcijskega načrta učinkovite rabe energije zastavila cilj izboljšanja energetske učinkovitosti do leta 2020 tako, da raba primarne energije leta 2020 ne bo presegla 7,125 mio toe (82,86 TWh) [1].

V skladu z Akcijskim načrtom učinkovite rabe energije naj bi Slovenija leta 2015 skladno s 7. členom direktive dosegla zmanjšanje rabe končne energije za 349 GWh, od tega 87 GWh v okviru sheme obveznega doseganja prihrankov končne energije za podjetja, ki prodajajo energijo, 262 GWh pa z alternativnim ukrepom, to je s spodbudami, ki jih za ukrepe URE namenja Eko sklad iz sredstev, zbranih s prispevkom na rabo energije za povečanje energetske učinkovitosti [1].

Leta 2015 je Slovenija uveljavila novo shema zagotavljanja prihrankov energije, ki je obveznost zagotavljanja ciljnih prihrankov energije naložila dobaviteljem energentov (zavezanci) in Eko skladu, ki prihranke dosega z alternativnimi ukrepi. Obveza za zavezance je v letu 2015 znašala 125,7 GWh energije, z izvedenimi ukrepi pa so jih dosegli 502,3 GWh ter s tem ustvarili presežke prihrankov, ki jih bodo v okviru svojih obveznosti lahko uveljavljali v naslednjih treh letih. Skoraj tri četrtine teh prihrankov je bilo doseženih samo s tremi ukrepi (dodajanje aditiva pogonskemu gorivu, uvedba sistema upravljanja energije, celovita prenova toplotnih postaj v sektorjih pretvorbe, distribucije in prenosa energije). Presežek doseženih prihrankov energije bo mogoče prenesti v leti 2016 in 2017 [1, 6].

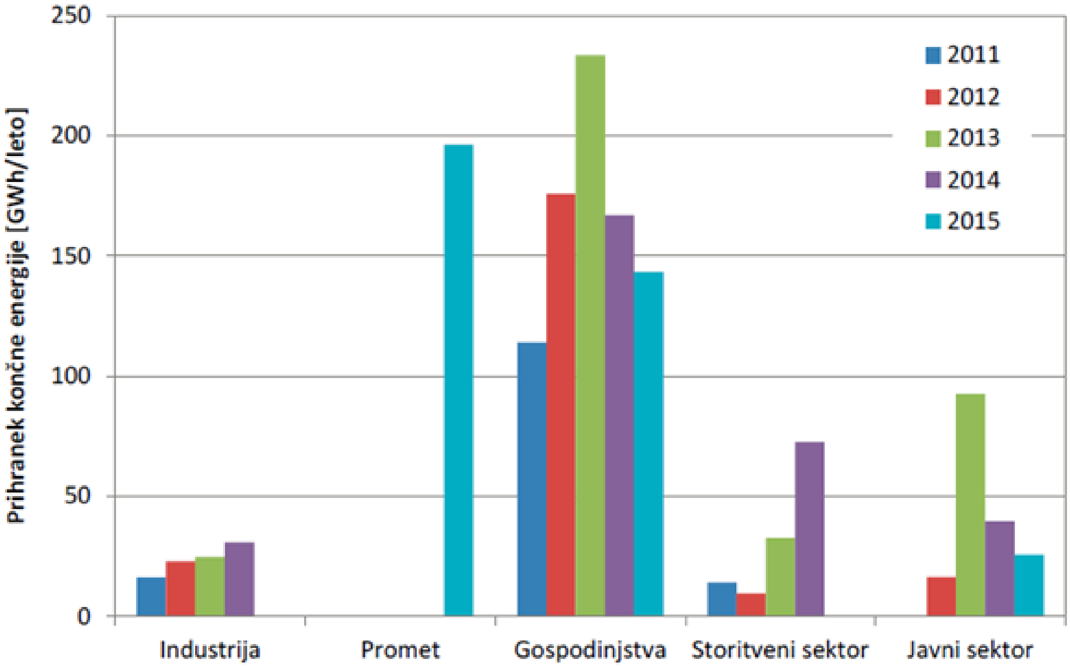


Slika 1.1: Porazdelitev doseženih prihrankov končne energije po posameznih ukrepih, izvedenih v okviru sheme obveznega doseganja prihrankov končne energije za zavezance leta 2015; Vir: Poročanje o izvajanju AN URE 2020 za leto 2015

Prihranki, doseženi z alternativnimi ukrepi, so bili v letu 2015 nižji kot v letu 2014, in sicer so znašali 102,3 GWh. Leta 2015 je bilo z nepovratnimi sredstvi Eko sklada doseženega 27,9 % manj prihranka končne energije kot leto prej.

Ker so prihranki, doseženi z alternativnimi ukrepi, leta 2015 zaostajali za ciljem, zavezanci pa bodo presežne prihranke predvidoma prenesli na naslednja leta, je bilo leta 2015 skupaj doseženo 228 GWh prihranka končne energije, kar pa pomeni, da skupni cilj iz AN URE 2020 za to leto, ki znaša 349 GWh, ponovno ni bil dosežen [1].

Leta 2015 so prihranki končne energije, doseženi znotraj sheme zavezancev, znašali 502,3 GWh, kar je bistveno več od z AN URE 2020 predvidenega indikativnega cilja 87 GWh oz. tudi bistveno več od dejanskega cilja doseganja prihranka v višini 0,25 % prodane energije v letu prej, ki znaša 125,7 GWh. Skoraj tri četrtine tega prihranka je bilo doseženega samo s tremi ukrepi (dodajanje aditiva pogonskemu gorivu, uvedba sistema upravljanja energije, celovita prenova toplotnih postaj v sektorjih pretvorbe, distribucije in prenosa energije). Presežek doseženih prihrankov energije lahko zavezanci prenesejo v leti 2016 in 2017 [1, 6].



Slika 1.2: Prihranki končne energije po sektorjih med letoma 2011 in 2015; Vir: Poročanje o izvajanju AN URE 2020 za leto 2015

Kot kaže Slika 1.2, je možno opaziti, da je bilo največ prihrankov v tem obdobju doseženih pri gospodinjstvih. V letu 2015 je bil največji delež prihrankov, 56,6 %, dosežen z izvajanjem ukrepov v gospodarstvu, z 39,1 % je sledilo izvajanje ukrepov v prometu. Posamičen ukrep, ki izstopa z največ doseženimi prihranki, so drugi ukrepi za povečanje energetske učinkovitosti v prometu, kamor sodi tudi dodajanje aditiva pogonskemu gorivu. S temi ukrepi, ki jih je izvajalo 30 zavezancev, je bilo doseženih skoraj 39 % vseh prihrankov, sledila pa sta ukrepa uvedbe sistema upravljanja energije z 19,6 % in celovite prenove toplotnih postaj v sektorjih pretvorbe, distribucije in prenosa energije s 14,1 % [1].

Slovenija na ravni rabe primarne energije zadovoljivo ostaja v okvirih cilja za leto 2020, na ravni rabe končne energije pa je prišlo do povečanja rabe v industriji, kjer bo treba naraščajočemu trendu v prihodnje slediti z realizacijo prihrankov energije. Ob zaznani rasti 2,8 % bi bila namreč raba končne energije v industriji leta 2020 za skoraj 8 % večja od načrtovane. V gospodinjstvih, kjer je raba v letu 2014 sicer padla pod vrednost cilja za leto 2020, pa bo treba izvajanje ukrepov URE v prihodnje pospešiti. Leta 2015 se je zaradi uveljavitve izvajanja ukrepa dodajanja aditivov pogonskemu gorivu v primerjavi z leti prej nesorazmerno povečal prihranek končne energije v sektorju prometa [1].V PRIHODNJE

Slovenija bo morala, tako kot tudi druge članice, ob uveljavitvi predlaganih dopolnitev direktive vse do leta 2030 dosegati enake ciljne deleže letnih prihrankov energije, kot jim je zavezana sedaj (vendar brez olajšav). V skladu z akcijskim načrtom mora Slovenija v letu 2016 doseči 697 GWh prihrankov energije, in sicer 0,75 % prihrankov z alternativnimi ukrepi in 0,50 % s shemo obvezne energetske učinkovitosti.; pri čemer pa je treba opomniti, da zavezanci lahko v letu 2016 vključijo v to obvezo doseženi presežek v višini 376,6 GWh.

Novost pri poročanju zavezancev o doseženih prihrankih v letu 2016 je tudi dopolnjen obrazec, ki od zavezancev poleg podatkov o doseženih prihrankih energije in ukrepih, s katerimi so bili prihranki realizirani, zahteva tudi podatke o zmanjšanju izpustov CO_2 po posameznem ukrepu

in o morebitnem povečanju rabo obnovljivih virov energije. S to obvezo se tudi izpolnjujejo cilji prenovljene direktive, ki od članic zahteva bolj podrobne podatke o povezavi med doseženimi prihranki energije in izpustih CO_2 ter večji rabi obnovljivih virov energije.
Poleg navedenega velja tudi izpostaviti, da je bila marca 2017 uveljavljena sprememba Pravilnika o metodah za določanje prihrankov energije , v katerem so prenovljene nekatere metode za prihranke po posameznih ukrepih ter tudi dodane nove metode. Tudi na ravni Evropske unije je ugotovljeno, da je kar 86 % vseh doseženih prihrankov energije rizičnih glede na zastavljene metodologije izračunov, zato so države članice pozvane k spremembam nacionalnih metodologij [5].

Zaključek

Prvo poročanje o uspešnosti doseganja ciljev učinkovite rabe energije na podlagi prenovljenega sistema doseganja ciljev kaže, da Slovenija delno dosega zastavljene cilje. V okviru sheme so uspešni predvsem zavezanci, ki niso samo dosegli svojih obveznih ciljev, temveč so jih celo presegli. Na drugi strani pa niso doseženi cilji prihranka energije z izvedenimi alternativnimi ukrepi, saj se količina prihranjene energije z izvedenimi alternativnimi ukrepi iz leta v leto celo manjša. Spremembe v prenovljeni direktivi kakor tudi spremembe v okviru poročanja o doseženih prihrankih v Sloveniji želijo spodbuditi zanimanje za alternativne ukrepe ter tudi omogočiti možnosti doseganja ciljev, zastavljenih tako v okviru politike energetske učinkovitosti kot tudi politike v boju proti podnebnim spremembam.

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Koncept prostorske analize rabe in proizvodnje toplote v Mestni občini Maribor

JURE ČIŽMAN, DAMIR STANIČIĆ, MATJAŽ ČESEN, MIRAN ROŽMAN, LJUBO GERMIČ & FILIP KOKALJ

Povzetek Trajnostne rešitve za ogrevanje in hlajenje temeljijo na sodobnih tehnologijah in vedno večjem povezovanju različnih sektorjev rabe in proizvodnje energije – stavb, industrije, proizvodnje električne energije ter prometa. Sistemi daljinskega ogrevanja in hlajenja omogočajo povezovanje različnih sektorjev in s tem zagotavljajo učinkovito upravljanje z vsemi razpoložljivimi viri in ponori energije. Takšen pristop zahteva sistemsko načrtovanje ravnanja z energijo v lokalni skupnosti, ki temelji na podrobni prostorski analizi obstoječega stanja in prihodnjega razvoja. V prispevku je predstavljen koncept prostorske analize rabe in oskrbe s toploto z uporabo orodij geografskega informacijskega sistema v Mestni občini Maribor (MOM).

Ključne besede: • trajnostne rešitve • ogrevanje • hlajenje • prostorska analiza • geografski informacijski sistem •

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Concept of Conducting a Spatial Analysis of Heat Consumptionand Supply in the City Of Maribor

JURE ČIŽMAN, DAMIR STANIČIĆ, MATJAŽ ČESEN, MIRAN ROŽMAN, LJUBO GERMIČ & FILIP KOKALJ

Abstract Sustainable heating and cooling solutions are based on modern technologies and increasing integration of various sectors of energy consumption and energy production – buildings, industry, electricity generation, and transport. District heating and cooling systems enable integration of various sectors, thus allowing for efficient management of all available energy sources and sinks. When planning energy management in a local community, such solutions require a systemic approach based on thorough spatial analysis of the current state and future development. The paper introduces the concept of conducting a spatial analysis of heat consumption and supply by using geographic information system tools of the City of Maribor.

Keywords: • sustainable solutions • heating • cooling • spatial analysis • geographic information systems•

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1 Uvod

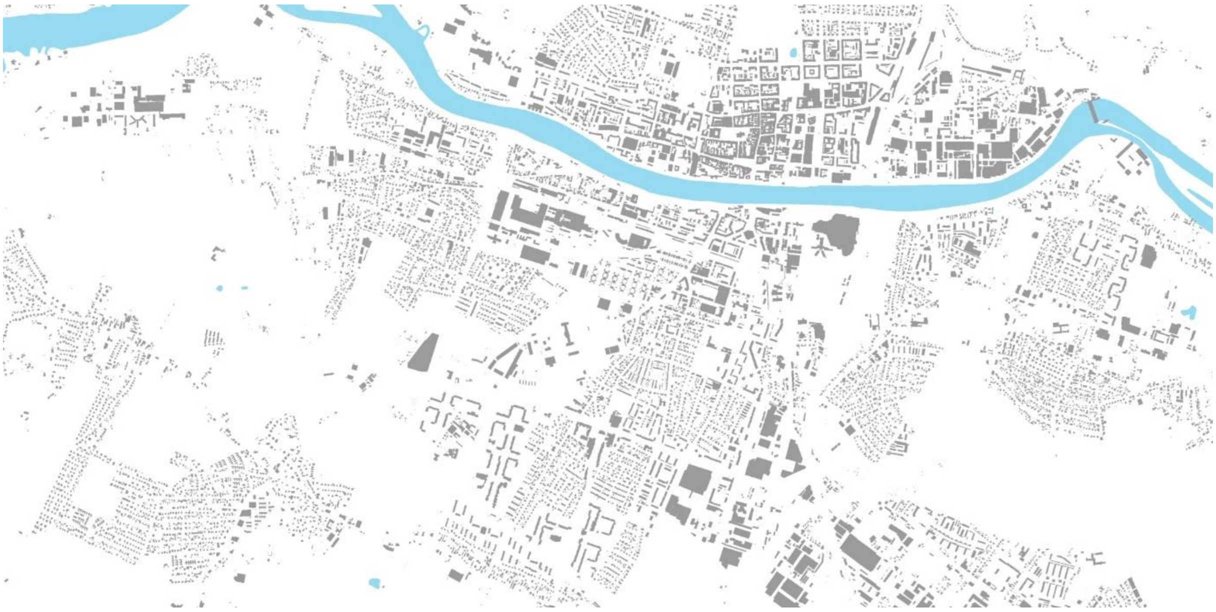
Sodobne trajnostne in učinkovite rešitve za ogrevanje in hlajenje temeljijo na sodobnih tehnologijah in vedno večjem povezovanju in integraciji različnih sektorjev rabe in proizvodnje energije, kar omogoča skupne pozitivne učinke ter učinkovito izkoriščanje in upravljanje vseh razpoložljivih virov energije. Sistemi daljinskega ogrevanja in hlajenja imajo pri tem posebno vlogo, saj omogočajo učinkovito povezovanje različnih sektorjev (industrija, proizvodnja električne energije, promet) pri zagotavljanju trajnostne in okolju prijazne oskrbe s toploto in hladom v urbanem okolju.

Navedene spremembe zahtevajo celovit in sistemski pristop pri načrtovanju ravnanja z energijo v lokalnih skupnostih (Lokalni energetski koncepti) in uvajanja novih pristopov prostorske analize (mapiranja, GIS orodja) rabe in možne oskrbe s toploto in hladom, ki na podlagi podrobne prostorske analize stanja, prihodnjega razvoja in potencialov omogočajo identifikacijo možnih trajnostnih in učinkovitih rešitev.

Za potrebe te študije so se za Mestno občino Maribor (MOM) izdelale osnovne energetske bilance proizvodnje in rabe toplote. V nadaljevanju se je ta analiza glede rabe toplote izvedla znotraj GIS. Na tej osnovi so se naredile potrebne projekcije razvoja do leta 2030. Vse to skupaj pa na osnovi naprej določenih kriterijev ponuja odgovor glede potrebnega prihodnjega razvoja energetske infrastrukture – daljinskega ogrevanja in zemeljskega plina.

2 GIS analiza trenutne rabe toplote v stavbah

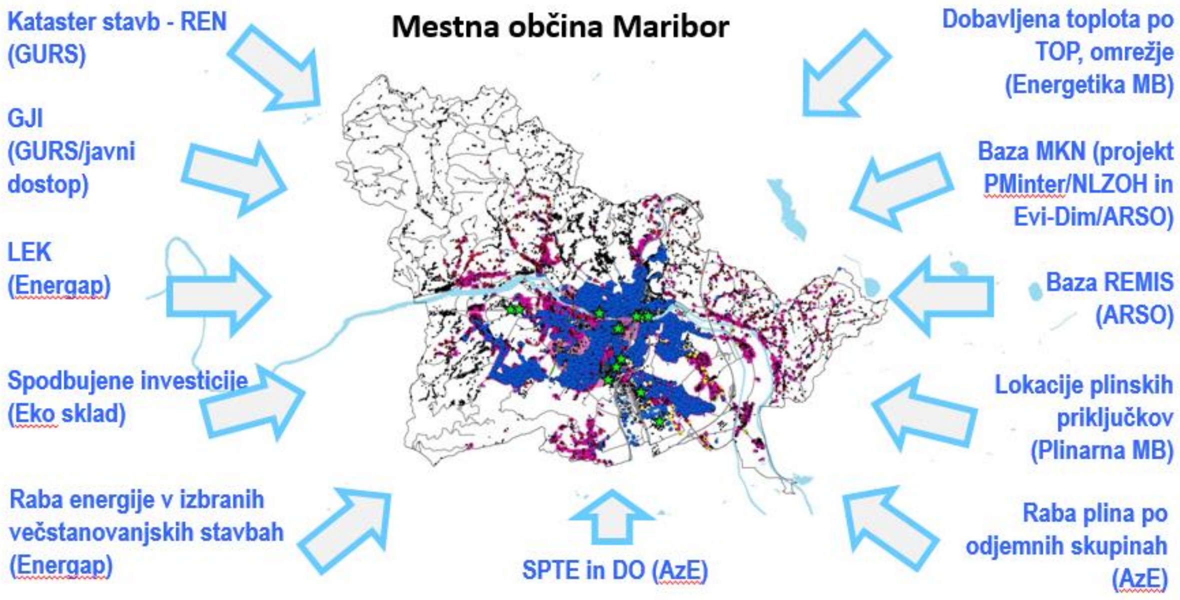
Osnova izvedbe naloge predstavlja popis in mapiranje stavbnega fonda v mestu. Informacije o stavbnem fondu so tiste, na katere so potem vezani vsi energetski in okoljski podatki. Mapiran stavbni fond je prikazan na sliki 2.1.



Slika 2.1: Stavbni fond Maribora

Na podlagi zbranih razpoložljivih podatkov (Energetika Maribor, dimnikarska baza, baze nepremičnin (GURS), EKO sklad in drugih v času izdelave razpoložljivih podatkov), kar je prikazano na sliki 2.2, je izdelan prostorski modelski izračun rabe toplote v stavbah:

- **točkovni izračun za vsako stavbo:** potrebna toplota, energent, ogrevalna naprava, ...
- **prostorski izračun:** prostorska gostota rabe toplote (različni kazalniki), skupna poraba in energentov (po posameznih območjih in skupno), ...

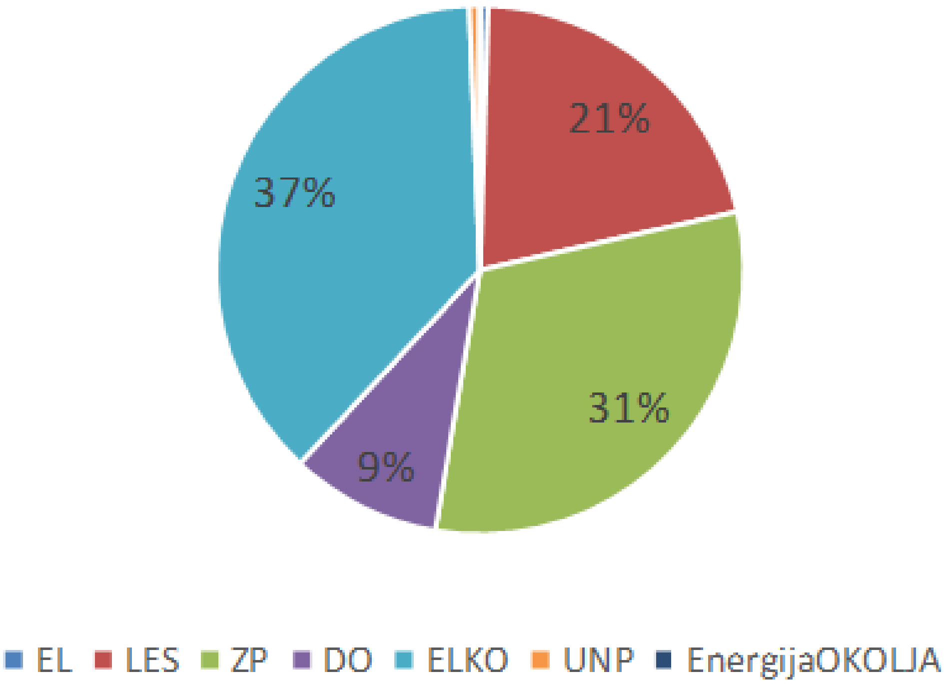


Slika 2.2: Podatki za izdelavo prostorske karte

Pri značilnosti stavb so se upoštevali tudi podatki o prenovah, ki so javno dostopne.

Pri pridobivanju potrebnih podatkov za našo analizo se je kot velik problem pokazal v dostopnosti in ažurnosti podatkovnih baz. Pokazalo se je, da se nekatere baze periodično osvežuje, nekatere pa niso osveževane. Do tovrstnih baz podatkov žal nimamo izdelane celovite nacionalne strategije, dejstvo pa je, da so takšni podatki izjemnega pomena za vse kvalitetne analize trenutnega stanja.

Stavbe so razvrščene v energijske razrede, za katere so v modelu izračunane specifične porabe energije za ogrevanje. V model so vključeni tudi podatki o rabi energentov po posameznih stavbah iz dimnikarske baze kurilnih naprav, podatki iz baze toplotnih postaj DO, podatki o porabi kurilnega olja v skupnih kotlovnicah, podatki o proizvodnji in dobavi toplote za DO, podatki iz baze odjemnih mest zemeljskega plina (ZP) ter podatki o distribuiranih količinah ZP po odjemnih skupinah. Parametri modela so bili po vključitvi vseh zgoraj navedenih podatkov kalibrirani tako, da je bila bilanca rabe energije za stavbe v MOM skladna z dejanskimi podatki o rabi energentov.



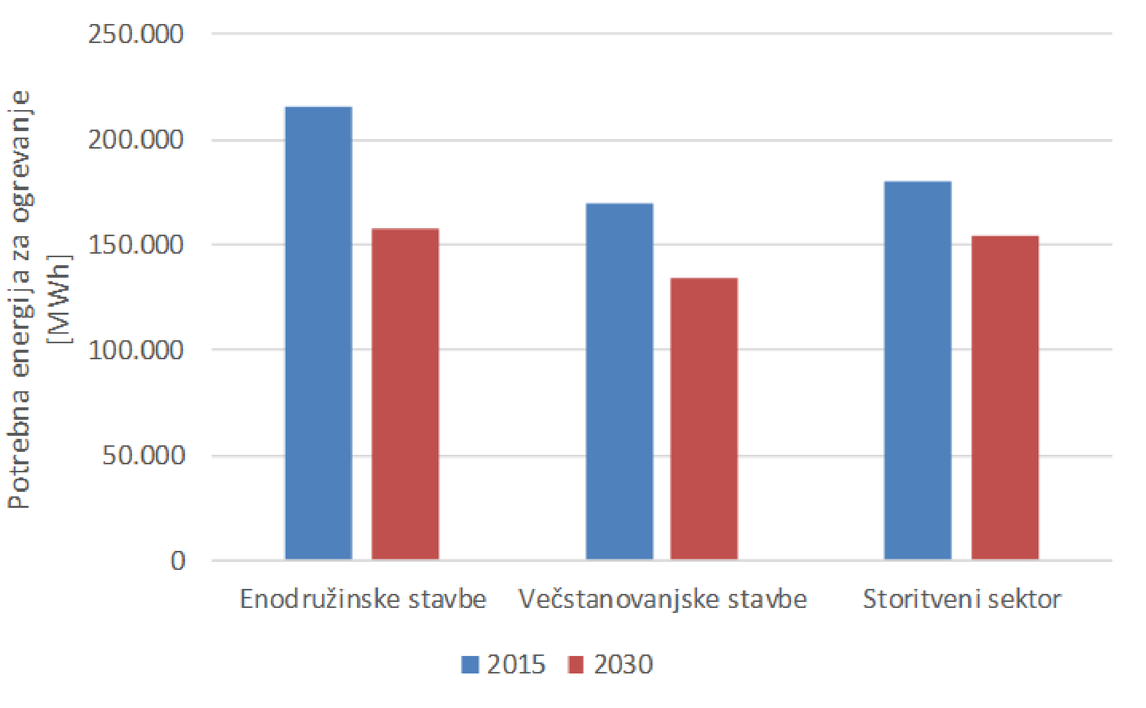
Slika 2.3: Končna raba energije za ogrevanje in toplo vodo v letu 2015

Trenutno stanje porabe energije (izračun za leto 2015) za ogrevanje in toplo vodo znaša slabo 1 TWh. Večina ogrevanja v Mariboru je še vedno na ekstra lahko kurilno olje (ELKO), nato so zemeljski plin (ZP), les in daljinsko ogrevanje (DO). Ostalih energentov, kot so električna Energija (EL), utekočinjen naftni plin (UNP) in toplotnih črpalk (EnergijaOKOLJA) je relativno malo. Odstotki posamezne rabe glavnih energentov so prikazani na sliki 2.3.

3 GIS analiza prihodnje rabe toplote za obdobje do leta 2030

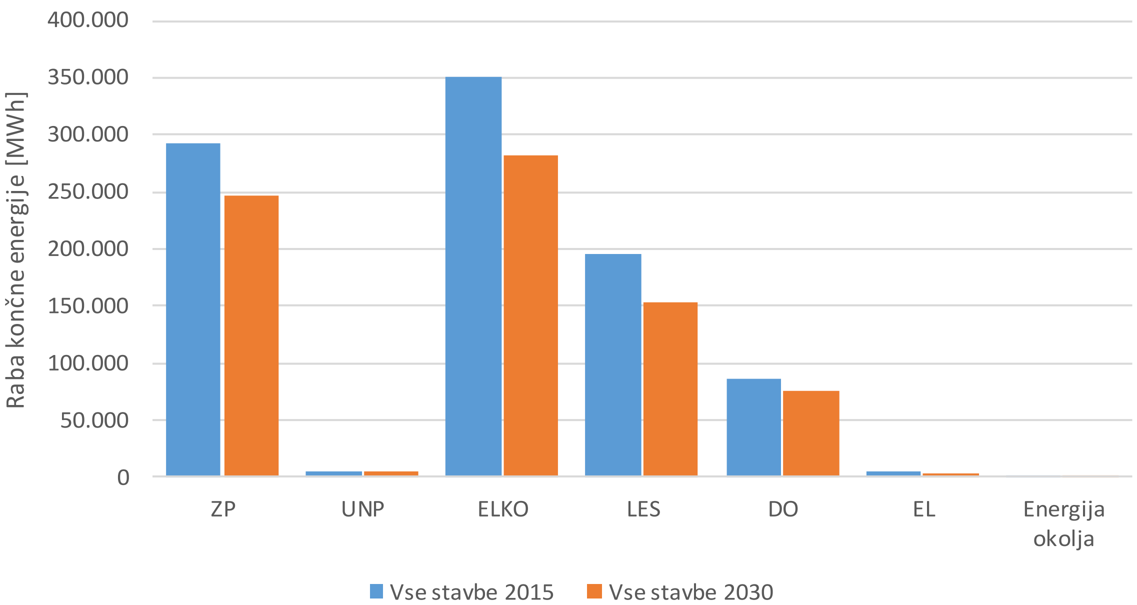
Ocena stanja v letu 2015 je služila za izhodišče za pripravo projekcij izvedbe ukrepov URE na stavbah do leta 2030. Predpostavljene so bile enake stopnje obnov kot v Dolgoročni strategiji za spodbujanje naložb energetske prenove stavb.

Slika 4 prikazuje projekcijo spremembe rabe toplote. Ta je oblikovana na osnovi podatkov o stavbah in predpostavki, da bo v naslednjih 15. letih prenovljenih 2,7 % enodružinskih stavb in 2,5 % večstanovanjskih stavb. Nekoliko nižji odstotek zmanjšanja rabe toplote je predviden za storitveni sektor.



Slika 2.4: Projekcija spremembe rabe toplote do leta 2030

Slika 2.5 prikazuje projekcijo spremembe rabe energije glede na posamezni energent. Vidimo lahko, da so zmanjšanja predvidena pri vseh energentih. Država in lokalna skupnost bi morala z aktivno energetsko in okoljsko politiko zmanjševati vire, ki imajo velik okoljski vpliv oziroma precej vplivajo na podnebne spremembe.

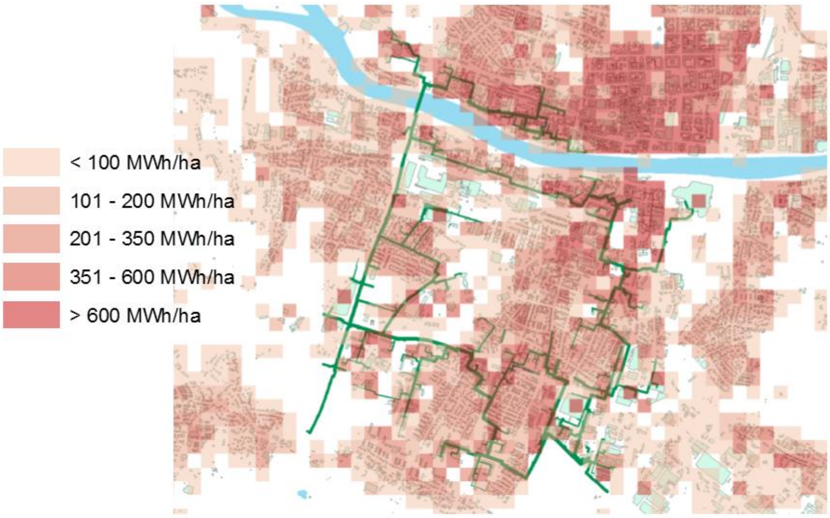


Slika 2.5: Projekcija spremembe rabe posameznega energenta do leta 2030

4 Mapirana energetska poraba toplote za leto 2015 in 2030

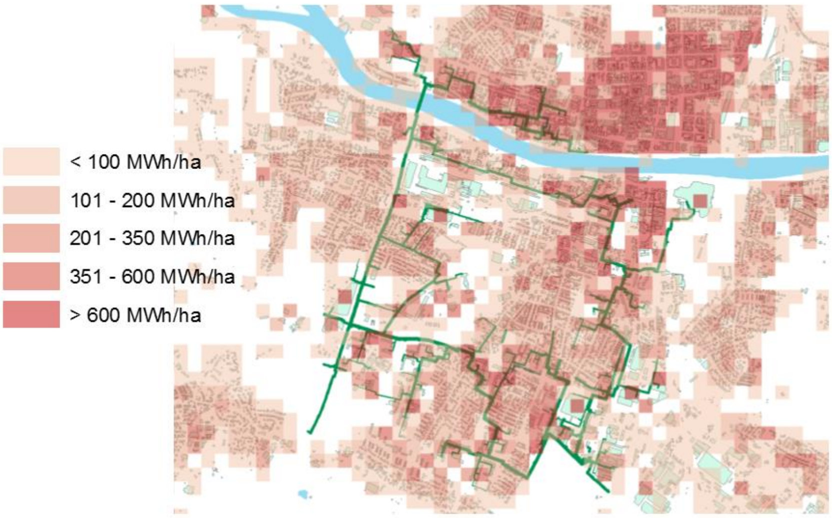
Na podlagi vseh zbranih rezultatov so re rezultati posamezne stavbe locirale v prostoru in izdelana je mapa porabe toplote v mestu. Iz slike 2.6 je razvidno, da so v mestu območja, kjer je letna poraba toplote na hektar preko 600 MWh, so pa tudi območja, kjer je poraba nižja od 100 MWh oziroma je praktično nična. Z zelenimi črtami so na sliki označeni glavni vodi daljinskega omrežja.

Vrednosti izbranih parametrov modela so pripisane vsaki stavbi, kar je omogočilo natančno prostorsko identifikacijo potencialov rabe toplote na nivoju posamezne stavbe ter določitev karakterističnih območij z uporabo GIS orodij.



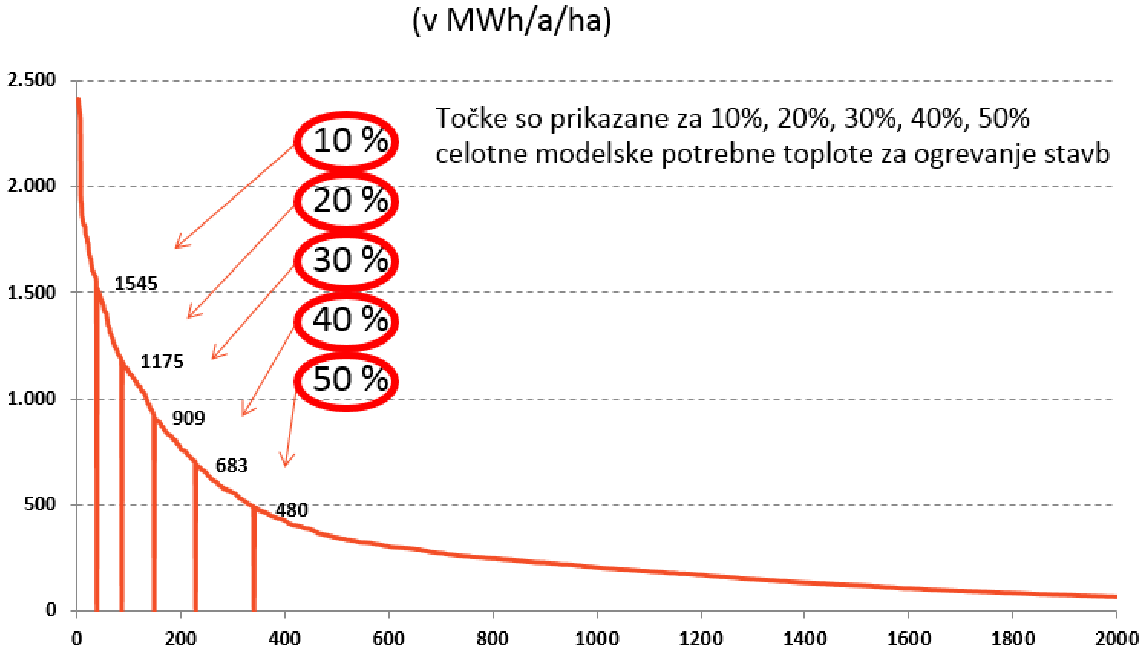
Slika 2.6: Mapirana raba toplote v MOM za ogrevanje stavb in pripravo tople sanitarne vode v letu 2015

Na sliki 2.7 pa so mapirani podatki projektije za leto 2030. Pri tem so upoštevani vsi ukrepi URE, ki naj bi bili izvedeni do takrat in so opisani v prejšnjem poglavju.



Slika 2.7: Mapirana raba toplote v MOM za ogrevanje stavb in pripravo tople sanitarne vode v letu 2030

Slika 2.8 prikazuje porabo toplote posameznih stavb in njihovo razporeditev v prostoru. Razberemo lahko, da je v MOM kar nekaj stavb gosto postavljenih in predstavljajo veliko porabo na hektar.



Slika 2.8: Porazdelitev zgradb glede na letno porabo toplote na hektar

5 Opredelitev kriterijev za nadaljnji razvoj gospodarske javne infrastrukture

Prostorska analiza rabe toplote daje jasne podlage komunalnim odločevalcem o načrtovanju bodoče nove gospodarske javne infrastrukture. Na ta način je je le-ta lahko s pomočjo ekonomskih, energetskih, okoljskih in prostorskih kriterijev grajena na trajnosten in ekonomski vzdržen način. Takšno načrtovanje zagotavlja potrebno gostoto odjema glede na površino oz. dolžino razvoda, kar se mora upoštevali pri določanju območja prihodnjega razvoja teh sistemov.

Območja so opredeljena tako z vidika ocenjevanja prihodnje rabe toplote, načrtovanja in nadaljnjega razvoja energetske infrastrukture, ter integracije z drugimi sistemi in načini ogrevanja, pri čemer so upoštevani še okoljski vidiki, in sicer struktura virov emisij trdnih delcev.

Na podlagi izdelanih kriterijev je s tem orodjem mogoče izdelati in preveriti:

- prostorski prikaz možnega prihodnjega razvoja omreži in drugih alternativ,
- možnosti povezovanja sektorjev (odpadna toplota, shranjevanje toplote, ...).

6 Zaključek

Analiza prostorske rabe in proizvodnje toplote je bila izvedena z namenom, da nudi objektivno in jasno osnovo za razvoj nizkoogljičnih in nizkoemisijskih energetskih projektov in tudi na ta način omogoči socialno sprejemljiv trajnostni razvoj lokalne skupnosti.

Z uporabo GIS so se vsi zbrani podatki mapirali. To omogoča precejšnjo kontrolo pridobljenih podatkov in daje jasen prostorski vpogled v ta segment komunalne energetike in njegovega vpliva na okolje.

Z zbirom vseh posameznih podatkov se lahko opredeli lokalni prispevek z vsem nacionalnim ciljem in mednarodnim zavezam, ki jih je sprejela naša država. To velja ne samo za rabo OVE za potrebe ogrevanja, ampak tudi za celotno področje komunalne energetike in varstvo okolja. Lokalnim strokovnim in političnim odločevalcem pa rezultati te študije dajejo možnost načrtovanja mestne energetske in okoljske politike ter spremljanje njenega izvajanja.

Vključevanje odjemalcev v programe prilagajanja odjema z uporabo dinamičnega tarifiranja v sklopu Evropskega projekta Flex4Grid

KRISTIJAN KOŽELJ, ANTON KOS & DAMJAN BOBEK

Povzetek Podjetje Elektro Celje, d.d. je kot član mednarodnega konzorcija uspešno kandidiralo na razpisu evropskega programa za razvoj in inovacije Horizon 2020 s projektom Flex4Grid, ki se nanaša na rešitve, ki bodo omogočale upravljanje prožnosti uporabnikov tako pri porabi kakor tudi pri proizvodnji električne energije.

Evropski razvojni projekt Flex4Grid se osredotoča na razvoj odprtega tehnološkega sistema za upravljanje podatkov in zagotavljanje storitev, ki bodo omogočale upravljanje prožnosti uporabnikov - prosumerjev distribucijskega omrežja tako pri porabi kakor tudi pri proizvodnji električne energije. Prožnost uporabnika pomeni, da je le-ta sposoben prilagajati porabo ali proizvodnjo potrebam drugih deležnikov v sistemu in bi lahko bil za svoje prilagajanje nagrajen. Storitev bo potekala v računalniškem oblaku, kjer bodo zbrani anonimizirani podatki. Razvili bomo nove poslovne modele in predstavili spodbude za sodelovanje odjemalcev v takšnih projektih.

Ključne besede: • Horizont 2020 • Flex4Grid • upravljanje podatkov • zagotavljanje storitev • distribucijsko omrežje •

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1 Uvod

Pojav razpršenih virov, kot so fotovoltaika, vetrna energija in ostali viri, je bil povod za nove uporabnike električne energije, t. i. »prosumerje« (proizvajalci in odjemalci v enem), ki proizvajajo in porabljajo električno energijo vzporedno. Poraba in proizvodnja električne energije prosumerja je zelo spremenljiva in kot taka lahko v večjem obsegu vpliva na omrežje ter deležnike na trgu z električno energijo, vendar se lahko prosumerji v določeni meri fleksibilno prilagodijo in s tem preprečijo svoj morebiten negativni vpliv [1].

Evropski razvojni projekt Flex4Grid se osredotoča na razvoj odprtega tehnološkega sistema za upravljanje podatkov in zagotavljanje storitev, ki bodo omogočale upravljanje prožnosti/fleksibilnosti uporabnikov - prosumerjev distribucijskega omrežja, tako pri porabi kakor tudi proizvodnji električne energije. Prožnost/fleksibilnost uporabnika pomeni, da je sposoben prilagajati porabo in/ali proizvodnjo potrebam drugih deležnikov v sistemu. Za svoje prilagajanje bi načeloma moral biti nagrajen. Elektrodistribucijska podjetja bodo lahko to prožnost izrabila za zniževanje koničnih obremenitev omrežja ter zmanjšanjem razkoraka med porabo in razpršeno proizvodnjo električne energije. Drugi oz. novi udeleženci pa bodo lahko na trgu električne energije ponujali storitve na osnovi podatkov in odprtih vmesnikov tehnološkega sistema Flex4Grid. Sistem bo zgrajen iz obstoječih komponent IKT, ki so jih partnerji konzorcija razvijali že več let v prejšnjih raziskovalnih projektih, kar pomeni, da ima projekt veliko možnosti, da se hitro implementira v praksi.

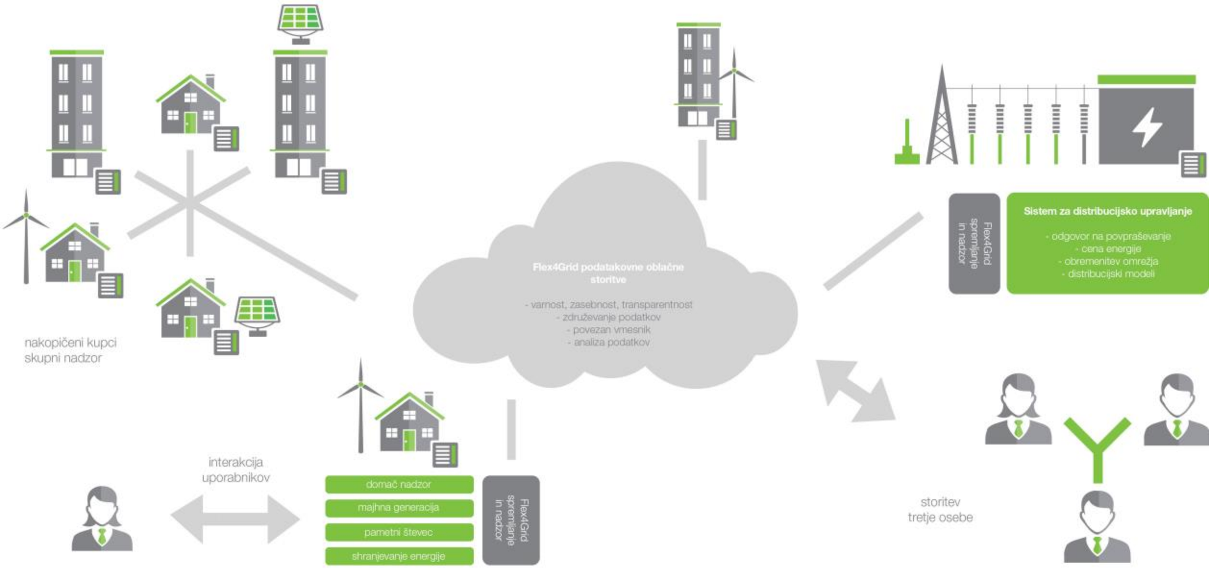
Flex4Grid bo vključeval:

a) storitev podatkovnega oblaka z anonimiziranim vmesnikom, kjer bodo uvedeni napredni mehanizmi varnosti in zasebnosti za izmenjavo podatkov in upravljanje storitev,
b) fleksibilnost prosumerja na področju proizvodnje in porabe električne energije in fleksibilnost odjemalca na področju porabe električne energije ter
c) izvedljiv poslovni model, ki lahko hitro zaživi v praksi.

Validacija sistema bo izvedena v realnem okolju - piloti v treh evropskih distribucijah z različnimi scenariji. Zadnji večji pilot bo v Sloveniji na distribucijskem območju Elektro Celje in bo lahko obsegal participacijo 8.700 uporabnikov oz. odjemalcev omrežja v pilotnem projektu dinamičnega tarifiranja.

Projekt se je začel izvajati 1. januarja 2015, ko je bila podpisana pogodba z Evropsko komisijo. V projektu Flex4Grid sodeluje osem partnerjev, ki prihajajo iz Slovenije, Finske, Slovaške ter Nemčije in so mešanica institucij znanja oziroma raziskovalnih inštitutov, distributerjev električne energije ter industrijskih partnerjev. Med njimi so tudi trije iz Slovenije, kjer poleg Elektra Celje, d.d., sodelujeta še podjetje Smart Com, d.o.o. in Inštitut »Jožef Stefan«. Projekt, katerega vrednost znaša nekaj manj kot 3,2 milijona evrov in ga Evropska komisija financira skoraj v celoti, bo trajal 36 mesecev (končanje projekta bo 31.12.2017), poteka pod koordinacijo finskega raziskovalnega inštituta VTT.

Koncept



Slika 3.1: Namen aktivnosti v Flex4Grid

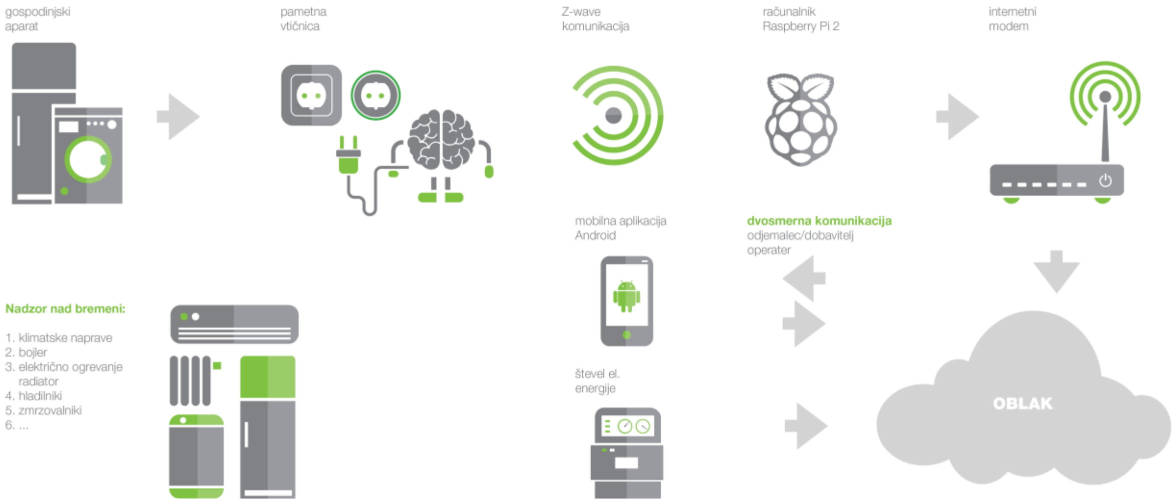
Namen aktivnosti v Flex4Grid (Slika 3.1) je zagotoviti sistem za nove udeležence na trgu, ki bodo lahko ponujali analize agregiranih podatkov za potrebe napovedi električne energije. Ideja je, da se predvidi vpliv porabe in proizvodnje na distribucijskem omrežju (najbolje čimbolj lokalno v distribucijskem omrežju). S takšnim napovedovanjem bi se v prihodnosti izognili morebitnim izpadom električne energije (kritične storitve najvišje prioritete v kritični infrastrukturi vsake države) zaradi preobremenitev ter energetske neuravnoteženosti porabe in proizvodnje v energetsko kritičnih točkah omrežja.

Flex4Grid ponuja celovit sistem za upravljanje s podatki z rešitvami za pametna omrežja, ki združuje izmenjavo podatkov med upravljavcem distribucijskega omrežja in njegovimi uporabniki z vključevanjem različnih dopolnilnih komponent, ki jih prispevajo ostali partnerji v projektu. Skupaj z izgradnjo centralnega oblačnega sistema za energetsko upravljanje, pametnim števcem električne energije ter pametnimi merilno–krmilnimi napravami, podprtimi z mobilno aplikacijo, bo imelo za posledico učinkovito upravljanje omrežja v smislu t. i. pametnega omrežja na najnižjem nivoju, torej v samem gospodinjstvu.

2 Vloga podjetja Elektro Celje d.d. v projektu

Znotraj projekta bodo v letu 2017 postavljeni tudi trije glavni piloti in sicer dva v Nemčiji ter eden na distribucijskem področju Elektra Celje, v katerega bo vključenih do 8.700 gospodinjskih odjemalcev električne energije. Za razliko od nemških pilotov, kjer bodo obravnavani prosumerji v manjšem številu, bodo v Sloveniji zaradi regulativnih ovir glede omejevanja proizvodnje pri proizvajalcih električne energije, v pilotni projekt vključeni samo odjemalci, ki pa bodo izbrani na relativno velikem vzorcu (pilot velikih razsežnosti).

Izvedba



Slika 3.2: Povezava komponent in storitev v Flex4Grid

Udeleženci pilota v Sloveniji bodo prejeli merilno-krmilno napravo, sestavljeno iz centralne enote Raspberry Pi z dodanim Z-wave brezžičnim komunikatorjem ter dve pametni vtičnici, preko katerih bodo priključili gospodinjske aparate (Slika 3.2). S pomočjo tega kompleta bodo odjemalci preko mobilne aplikacije krmilili ter spremljali stanje porabe električne energije izbranih gospodinjskih aparatov. Prav tako bodo lahko na mobilni napravi spremljali skupno porabo električne energije v njihovem gospodinjstvu in tako ugotavljali, kateri porabniki porabijo več v odvisnosti od skupne porabe. Vsake toliko bodo na mobilne naprave dobili obvestilo, da za kratek čas zmanjšajo porabo električne energije.

Za upravljanje s porabo niso zanimivi vsi porabniki, ampak predvsem tisti, ki v veliki meri ne zmanjšujejo ugodja bivanja odjemalcev, če jih za kratek čas izključimo, kot npr. hladilniki, električno ogrevanje, novejše klimatske naprave, bojlerji ter zamrzovalne skrinje. Ti aparati v gospodinjstvu predstavljalo večje porabnike, ki bi lahko bili za kratek čas izklopljeni in bi imeli določen vpliv na celotno porabo. Na drugi strani navedeni porabniki akumulirajo toploto ali hlad za dalj časa, zato njihov izklop za kratek čas ni problematičen.

Elektrodistribucijsko podjetje bo v okviru zakonskih omejitev ponujal program upravljanja s porabo in prilagajanja odjema. Program upravljanja s porabo bo ciljno usmerjen k zmanjševanju porabe v kriznih trenutkih oziroma trenutkih konične obremenitve sistema ter izboljšanju energetske učinkovitosti.

Kljub temu odjemalci morda ne želijo sodelovati v programih prilagajanja porabe, ker si nočejo zmanjševati ugodje bivanja, ali pa se s prilagajanjem ne želijo obremenjevati. Omejitvam navkljub verjamemo, da v kolikor želimo, da odjemalci znižajo oz. prilagajajo porabo, lahko to naredijo samo takrat, ko svojo porabo dobro poznajo. Z nameščanjem pametnega kompleta odjemalci spoznajo svojo porabo in se lažje odločajo. Vendar samo poznavanje svoje porabe ni dovolj, pomembno jim je dati tudi finančno spodbudo.

3 Testiranje učinkovitosti aktivnega vključevanja odjemalcev v programe prilagajanja odjema z uporabo dinamičnega tarifiranja

Glede na to, da je eden izmed ciljev pilotnega projekta Flex4Grid znižanje koničnih obremenitev za 3 % na določeni točki omrežja, bo ta cilj zelo težko doseči. Glavna omejitev je, da se projekt fokusira samo na gospodinjstva, ki so zelo razpršena in katera porabijo samo tretjino celotne energije. Omejitev predstavljajo tudi finančne spodbude za odjemalce. Z odprtjem trga z električno energije in EU zahtevo so se operaterji in dobavitelji električne energije v Sloveniji ločili. Na strani distribucijskih podjetij oz. operaterjev omrežja je možnosti za spodbud zelo malo, ker je dejavnost zelo regulirana, za razliko od dobaviteljev, ki pa so na področju cen z električno energijo zelo fleksibilni in lahko ponudijo več.

Kljub temu je Elektro Celje d.d. izrabila zakonsko priložnost testiranja izvedbene spodbude, ki je bila uvedena 1. 1. 2016 s sprejetjem Akta o metodologiji za določitev regulativnega okvira in metodologiji za obračunavanje omrežnine za elektrooperaterje (Uradni list RS, 66/15, 105/15) [2]. Izvedbene spodbude so v veljavnem regulativnem obdobju osredotočene na testiranje učinkovitosti aktivnega vključevanja odjemalcev v programe prilagajanja odjema z uporabo dinamičnega tarifiranja. Potrditev projekta Flex4Grid s strani regulatorja omrežja Agencije za energijo je podlaga za uporabo pilotne dinamične tarife iz 123. člena Akta, ki je omejena izključno na odjemalce električne energije, ki bodo prostovoljno pristopili v program prilagajanja odjema v okviru projekta.

123. člen Akta govori o pilotni kritični konični tarifi in je namenjena dinamični preusmeritvi končnih odjemalcev iz obremenitve sistema v času konic na obremenitev zunaj konic ob upoštevanju razpoložljivosti energije iz obnovljivih virov energije, energije, pridobljene v soproizvodnji električne energije in toplote z visokim izkoristkom, in porazdeljenega pridobivanja električne energije.

Kritična konična tarifa (KKT) [3] je poskusna omrežninska tarifa za distribucijski sistem s posebno tarifno postavko za preneseno delovno energijo (kWh), ki odstopa od običajne tarifne postavke in velja v času trajanja konične obremenitve omrežja (kritični dogodek). Za izvajanje te tarife je vnaprej omejeno število kritičnih dogodkov v določenem časovnem obdobju, njihovo trajanje ter časovni pogoji obveščanja odjemalcev o nastopu kritičnih dogodkov. Distribucijsko podjetje mora o nastopu ter času trajanja KKT obvestiti končnega odjemalca najmanj 24 ur vnaprej. Isto informacijo mora istočasno objaviti na svojih spletnih straneh. Število ur KKT v koledarskem letu je 50.

Tarifne postavke za omrežnino za distribucijski sistem na prevzeto električno energijo (kWh), ki so vključene v pilotni projekt, so določene na način, da se ob neodzivnosti odjema končnega odjemalca v obdobju KKT, obračuna v obdobju enega leta enaka omrežnina kot v primeru, če bi distribucijsko podjetje končnemu odjemalcu obračunal omrežnino za distribucijski sistem na podlagi običajnih tarifnih postavk. KKT tarifna postavka nastopa v času kritične konične tarife, ki lahko nastopi v času višje tarife (VT) ali manjše tarife (MT) in je za 10 krat višja od običajne tarifne postavke višje tarife (VT). V času izven KKT pa je cena višje tarife (VT) ali manjše tarife (MT) za 13% nižja od običajnih tarifnih postavk.

4 Zaključek

Električna energija je po svoji naravi specifično tržno blago, saj se je ne da ustrezno skladiščiti oziroma je njeno skladiščenje povezano z visokimi stroški. Zaradi tega mora biti proizvodnja električne energije vedno takšna, da pokriva celoten odjem. V časovnih obdobjih, ko je poraba električne energije visoka, je cena njene proizvodnje prav tako visoka, saj podjetja, ki proizvajajo električno energijo postopno, z večanjem obremenitve, zaganjajo proizvodne enote z višjimi proizvodnimi stroški [4].

Prav tako je v teh obdobjih elektroenergetsko omrežje bolj obremenjeno, kar lahko vodi do zamašitev in ogrozi stabilnost sistema. Elektroenergetska omrežja se načrtujejo na osnovi koničnih moči, to so najvišje moči, ki se navadno pojavljajo v omrežju zgolj nekajkrat v letu. Nova omrežja ter ojačitve obstoječega omrežja sodijo med stroškovno zahtevne investicije, ki bremenijo vse odjemalce električne energije ter imajo nezanemarljiv vpliv na okolje.

Prilagajanje odjema električne energije s strani odjemalcev pomeni, da odjemalci svoj odjem prilagajajo različnim cenam električne energije v časovnih intervalih ali se za prilagoditev odjema odločajo zato, ker jih v to spodbujajo programi, katerih cilj je znižati odjem v času višjih veleprodajnih cen (dobavitelji) ali v času, ko je elektroenergetski sistem ogrožen (operaterji omrežja).

S programi prilagajanja odjema električne energije bodo odjemalci svojo porabo premikali le, če bodo dobro poznali svojo porabo in če jih bodo uspele pritegniti nove inovativne ugodnejše tarife. S postopnim uvajanjem teh programov se želi pri odjemalcih vzpostaviti večja prožnost porabe električne energije. Hkrati pa je to priložnost, da raziščemo potencial dinamičnega tarifiranja električne energije pri gospodinjskih odjemalcih in skušamo odgovoriti na vprašanja ali so odjemalci pripravljeni prilagajati porabo, za kakšno ceno ter v kakšnem obsegu. Je pa to tudi priložnost, da s pomočjo pridobljenih rezultatov izboljšamo sam model dinamičnega tarifiranja v Sloveniji.

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[2] Akt o metodologiji za določitev regulativnega okvira in metodologiji za obračunavanje omrežnine za elektrooperaterje (Uradni list RS, 66/15, 105/15).

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[4] https://www.agen-rs.si/

University of Maribor Press

Involving Consumers in the Programmes of Consumption Adjustment by Using Dynamic Tariffing Within the European Project Flex4Grid

KRISTIJAN KOŽELJ, ANTON KOS & DAMJAN BOBEK

Abstract The distribution company Elektro Celje d.d. as a member of the International Consortium has successfully applied for the European Programme Tender on Research and Innovations Horizon 2020 with Flex4Grid project focusing on solutions that would allow flexibility management of users – the so-called prosumers of the distribution network in the field of consumption as well as power generation.

Flex4Grid, a European Development Project, focuses primarily on the development of an open technological system for data management and service provision which would allow managing user or prosumer flexibility of the distribution network in respect of their power consumption as well as power generation. Prosumer flexibility is a capability of prosumers to adjust their consumption or power generation to the needs of other stakeholders within the system, and could be rewarded for such adjustment. The service will be offered in a computer cloud where anonymised data will be collected. Some new business models will be developed and some new incentives for prosumer participation in such projects will be introduced.

Keywords: • Horizon 2020 • Flex4Grid • data management • service provision • distribution networks •

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1 Introduction

The emergence of diffuse sources, such as photovoltaics, wind energy and other sources, has given rise to new users of electricity, the so-called ‘prosumers’ (i.e. a producer and consumer as one person), who generate and consume electricity in parallel. Power consumption and generation of a prosumer is very variable and as such it may on a larger scale affect the network and the stakeholders in the electricity market. However, the prosumers may to a certain extent be flexible and thereby prevent their eventual negative impact [1].

Flex4Grid, a European Development Project, focuses primarily on the development of an open technological system for data management and service provision which would allow managing prosumer flexibility/adaptability of the distribution network in respect of their power consumption as well as power generation. Prosumer flexibility/adaptability is a capability of prosumers to adjust their consumption and/or power generation to the needs of other stakeholders within the system. Principally, the prosumer is supposed to be rewarded for providing such flexibility. Power distribution enterprises will be able to use such flexibility to reduce peak loads of the network and to narrow the gap between the consumption and the diffuse power generation. Other or new participants will be allowed in the electricity market that will offer services based on the data and open interfaces of Flex4Grid technological system. The system will be built with the use of the existing ICT elements which were being developed by the members of the consortium for several years within previous research projects. This means this project has a lot of potential to be rapidly implemented in practice.

Flex4Grid will include the following:

a) data cloud service with the anonymised interface with advance security and privacy mechanisms designed for data exchange and service management,
b) prosumer flexibility in the field of power generation and consumption, and consumer flexibility in the field of power consumption, and
c) a viable business model that can easily be applied in practice.

The system validation will be performed in real environments - pilot projects in three European distribution systems with different scenarios. The last major pilot project will be carried out in Slovenia in the distribution area of Elektro Celje d.d. with its potential participation of 8,700 users or consumers of the power distribution network within the pilot project of dynamic tariffing.

The project was launched on 1 January 2015 when the contract was signed with the European Commission. Flex4Grid project involves eight partners coming from Slovenia, Finland, Slovakia and Germany that are a mix of knowledge and research institutes, power distributors and industrial partners. Among them there are three Slovenian partners: Elektro Celje d.d., Smart Com d.o.o. and Jožef Štefan Institute. The project value amounts to nearly 3.2 million euros and is almost entirely funded by the European Commission. The duration of the project is 36 months (finishing on 31 December 2017) and is coordinated by VTT Finnish research institute.

The Concept

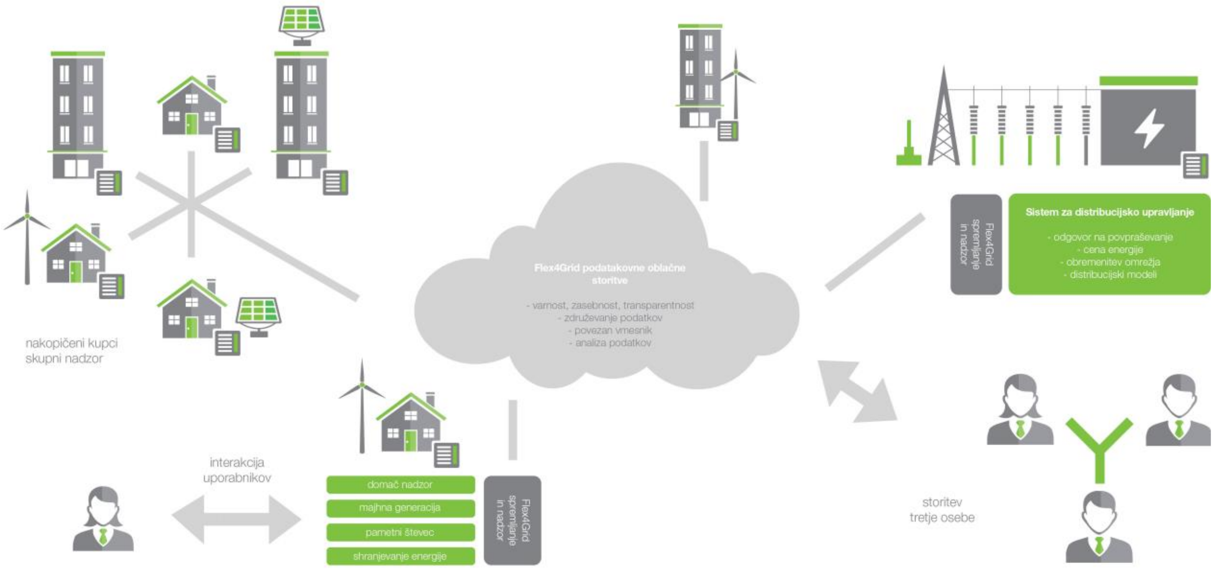

Figure 4.1: The aim of Flex4Grid activity

The aim of the activity within Flex4Grid (see Figure 4.1) is to assure the system to include new participants in the electricity market who will be in position to provide aggregate data analyses for forecasting electricity demand. The main idea is to anticipate the effect of power consumption and generation in the distribution network (most locally in the distribution network). By using such forecasts we will be able to avoid any potential power failures (critical services of the highest priority in critical infrastructure of each country) due to overload and imbalanced power consumption and generation in some energy-related critical points in the network.

Flex4Grid offers a comprehensive system of data management with solutions for intelligent networks, which integrates data exchange between the distribution network operator and its users by incorporating various complementary components contributed by other project partners. The construction of the central cloud system for energy management along with a smart electrical meter, smart measuring and control devices supported by a mobile application shall result in an effective network management in the sense of the so-called intelligent network at the lowest level, i.e. in households.

2 The role of Elektro Celje d.d. in the project

There will be three main pilot projects established within the project in 2017; two in Germany and one in the distribution area of Elektro Celje d.d. with up to 8,700 household consumers of electricity. Unlike the German pilot project implementations, where prosumers will be treated in a smaller number, the Slovenian pilot project will not include prosumers due to regulatory restrictions that apply to power generated by power producers. The project will only include consumers of electricity which will be selected in a relatively large sample (a large scale pilot project).

Implementation

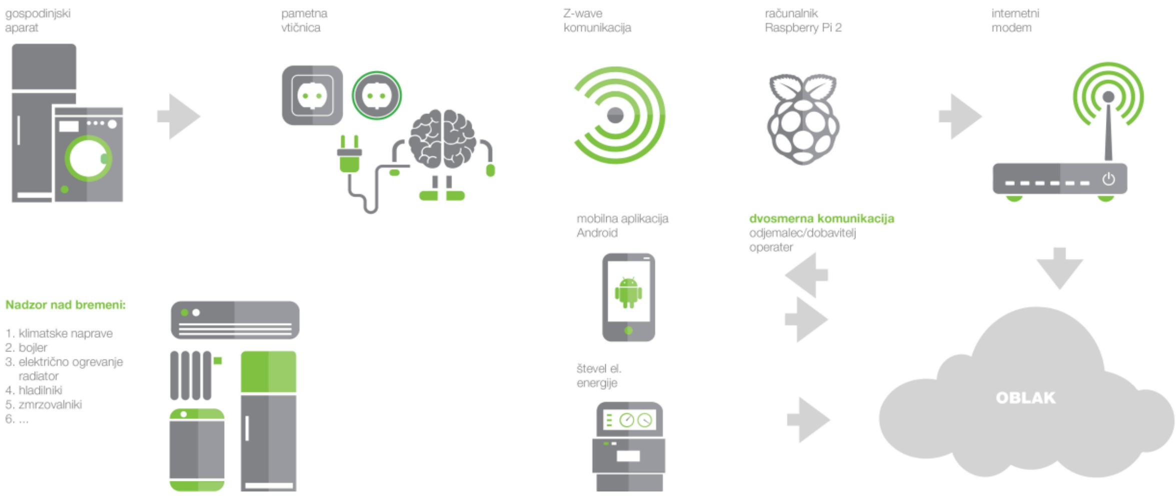

Figure 4.2: Flex4Grid integration of components and services

The pilot participants in Slovenia will receive a measuring and control device consisting of a central unit Raspberry Pi with the addition of Z-wave wireless communicators and two smart outlets to be used to plug in household appliances (Figure 4.2). By using this kit, consumers will be able to control the power consumption of their household appliances via the mobile application. They will also be able to control the total electricity consumption in their household via the mobile application, and to make comparison which electric appliances consume more electricity depending on the total electricity consumption. From time to time, they will receive a note on their mobile appliances to reduce the electricity consumption for a shorter period of time.

In terms of power management, not all electric appliances are of interest. However, of particular interest are those appliances that do not substantially reduce the comfort level of living in case they are disconnected for a shorter period of time, such as refrigerators, electrical heating, more recent air conditioning devices, boilers and freezers. Those household appliances are major electrical appliances that could be disconnected for a shorter period of time and could have a significant effect on the total electric consumption. On the other hand, those electric appliances accumulate heat or cold for a longer period of time. For this reason, their disconnection from the network is not considered problematic.

Power distribution company will, within the applicable legal restrictions, provide the programme on power management in respect of power consumption and its adjustment. The power management programme will be target-oriented in reducing power consumption in critical moments or in the moments of peak load of the system, and in improving energy efficiency.

Consumers may nevertheless not want to participate in programmes of power consumption adjustment, since they do not wish to diminish their comfort level of living, or they may not want to be burdened with adjustment of their power consumption. Despite all those limitations, we believe that if we want for the consumers to reduce or adjust their consumption, they can do so only when they know their consumption really well. Consumers take such decisions much easier when they learn about their consumption after the smart kit is installed in their homes. However, only knowing about their consumption is not enough; they also need a financial incentive.

3 Testing The Effectiveness Of Active Participation Of Consumers In The Programmes Of Consumption Adjustment By Using Dynamic Tariffing

Taking into account that one of the targets of Flex4Gripd pilot project is reducing peak loads by 3% at a specific network point, such objective will be hard to achieve. The main limitation is focusing only on widely dispersed households which consume only one third of the total energy. The limitation is also included in financial incentives for consumers. Upon opening the electricity market and with the EU requirement the operators and suppliers of electricity in Slovenia separated. There are only a few incentives provided by power distribution enterprises or network operators since this business activity is highly regulated in Slovenia, unlike the activity of supply, where suppliers are very flexible when setting their prices for electricity consumption, and thus can offer more.

Irrespective of the above mentioned restrictions, Elektro Celje d.d. has used the statutory opportunity of testing the implementation incentive which came into force on 1. 1. 2016 when Act on methodology for setting the regulatory framework and the methodology for calculating network charge for network operators (Official Gazette of the RS 66/15, 105/15) was adopted [2]. The implementation incentives are in the current regulatory period focused on testing the effectiveness of active participation of consumers in the programmes of consumption adjustment by using dynamic tariffing. The approval of Flex4Grid project by Energy Agency, the network regulator, forms the basis for the use of pilot dynamic tariff from Article 123 of the above mentioned Act, which is limited solely to electricity consumers who will voluntarily join the programme of consumption adjustment within this project.

Article 123 of the Act applies to a pilot critical peak rate and is intended for a dynamic redirection of final consumers from the peak system load to the off-peak system load with regard to the availability of renewable energy sources, energy generated in combined heat and power generation (CHP generation) with high efficiency, and distributed generation of electricity.

The critical peak pricing rate (CPPR) [3] is a trial network tariff for the distribution system with a special tariff rate of transferred active energy (kWh) which deviates from the usual tariff rate, and is valid during the time of peak system load (a critical moment). To perform such tariff, there is a pre-determined limited number of critical moments in a specific time period, their duration and time conditions of informing the consumers about the occurrence of such critical moments. Power distribution company shall inform its final consumers about the occurrence and the time of CPPR at least 24 hours in advance. At the same time such information shall be published on the website of the distribution company. The number of CPPR hours in one calender year is 50.

Tariff rates for network charge for the distribution system of the transferred electricity (kWh) included in the pilot project are determined in the way that in case of consumption unresponsiveness of the final consumer in the period of CPPR, the network charge for the period of one year will be equally calculated as in the case of the network charge for the final consumer based on normal tariff rates. The CPPR tariff rate occurs in the time of critical peak pricing rate, which can occur in the time of the higher tariff (HT) or the smaller tariff (ST) and is 10 times higher than the common higher tariff rate (HT). Out of the times of critical peak pricing rates the higher tariff (HT) or the smaller tariff (ST) is 13% lower than common tariff rates.

4 Conclusion

Electricity is a specific commodity in its nature since it cannot be stored properly or its storage is related to high storage costs. For this reason, power generation must always be implemented in the way to provide or cover the entire consumption. In the times when power consumption is high, the price of its production is also high, since enterprises that gradually, with increasing load, generate electricity, run their production units with higher production costs [4].

In such periods of time, the power distribution network is much more loaded which may give rise to network failure which can jeopardise the whole system stability. Power distribution networks are planned on the basis of peak power, i.e. the maximum power, which normally occurs in the network only a few times during the year. New networks and reinforcement of the existing network belong to demanding investments in terms of costs, which are borne by all consumers of electricity, and have quite a significant effect on the environment.

Consumption adjustment of electricity by consumers means that consumers adjust their power consumption to different electricity rates in specific time intervals and take decisions on their consumption adjustment mostly because they are encouraged by the programmes providing lower prices of their consumption in the times of higher wholesale prices (suppliers) or in the time when the energy distribution system is jeopardised (network operators).

With the programmes of power consumption adjustment, consumers will adjust their power consumption only in case they will know their actual consumption well and in case they will be successfully encouraged by new innovative cheaper electricity tariffs. With gradual introduction of such programmes we wish to establish bigger flexibility of the consumers when making decisions on their power consumption. On the other hand, this is a great opportunity to explore the potential of dynamic electricity tariffing for household consumers, and to answer the questions related to consumer willingness to adjust their electricity consumption, at what price and to what extent. This is also an opportunity to improve the dynamic tariffing model in Slovenia based on the results obtained in the project.

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Analiza španskega trga z električno energijo in predlogi za nadaljnji razvoj

ESTER GETINO, EMILIO GARCÍA & KLEMEN DEŽELAK

Povzetek Električna energija ima dandanes pomembno vlogo pri zagotavljanju varnosti in stabilnosti posameznih držav tako na ekonomskem, kakor tudi na socialnem področju. Na področju energetske liberalizacije je vloga uvedbe trga z električno energijo ključnega pomena. V članku so obravnavani določeni problemi trga z električno energijo v Španiji ter cilji v bližnji prihodnosti. Podobno kot vse članice Evropske Unije se tudi Španija sooča s priporočili in zahtevami s strani Evropske komisije.

Ključne besede: • trg z električno energijo • liberalizacija • Španija • proizvodnja • prenos • razdeljevanje•

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Analysis of the Spanish Electricity Market and Proposals for Future Development

ESTER GETINO, EMILIO GARCÍA & KLEMEN DEŽELAK

Abstract Nowadays the electricity is found in any daily activity, while a state can not develop its economic and social potential without a consolidated electricity system. In sense of the liberalized electrical systems, the figure of an electric market becomes fundamental. This paper shows an overview of the Spanish electricity market, involving its problems and future objectives. Spain as a member of the European Union faces the demands proposed by the European Commission. The European challenge is not an individual challenge for individual member but requires the cooperation of all member states, moving towards an energetically integrated European Union.

Keywords: • electricity market • liberalization • Spain • generation • transportation • distribution •

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1 Introduction

The supply of electric energy constitutes a service of general economic interest because economic and human activity can not be understood today without its existence [1]. That is why, the electric sector can be understood as a tool for the economic and social development of a country. This can be seen by analyzing the variation of electricity consumption in the years before and after the economic crisis, as reflected in data on electricity consumption in Spain in 2009, which are 4.7 % lower than the previous years [2].

Since the liberalization of the electricity sector in 1997, this is structured into four major activities: generation, transportation, distribution and commercialization. Of which, generation and retail are carried out under free competition, and transportation and distribution under a natural monopoly. In short, the customer is entitled to a free contract.

One of the factors that has limited economic development in Spain is the scarcity of energy resources and therefore the high foreign dependency from energy, being, according to data of the European Statistical Agency Eurostat, like the second great country of the European Union (EU) with more primary energy dependence from abroad with a total import in the year 2014 of 72.9 % of the energy resources used this year [3].

This fact explains the nature of the Spanish energy mix, composed mostly of nuclear plants (21.8 %) and coal (20.3 %) power plants, as reflected in Fig. 1 [4] conforming an installed power capacity of 101,027 MW.

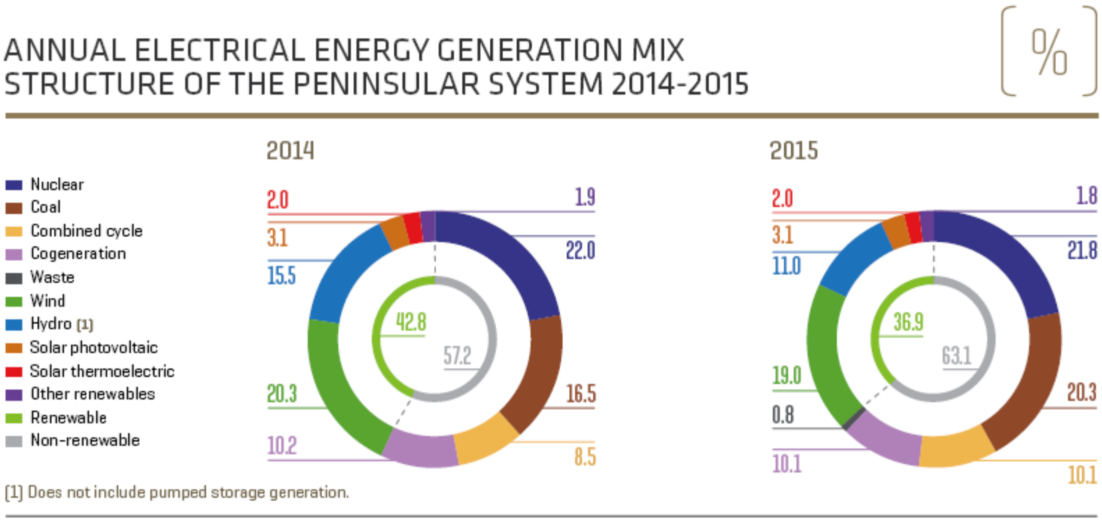

Figure 5.1: Spanish energy mix of the electrical energy generation [4]

In view of Figure 5.1, it is observed that renewable technologies, especially wind and hydro, represent 36.9 % of total energy generation by 2015.

In 2015, electricity demand in Spain reached 262,931 GWh, an increase of 1.9 % over the previous year, with an instantaneous maximum demand of 40,726 MW. This demand came from 63.1 % of the industry, 27.2 % from the services sector and 9.7 % from others such as mining, construction and the primary sector [4].

Due to its geographical location, Spain has interconnections with France, Portugal and Morocco. Figure 5.2 shows the scheduled energy exchanges by interconnection of the year 2015 [4].

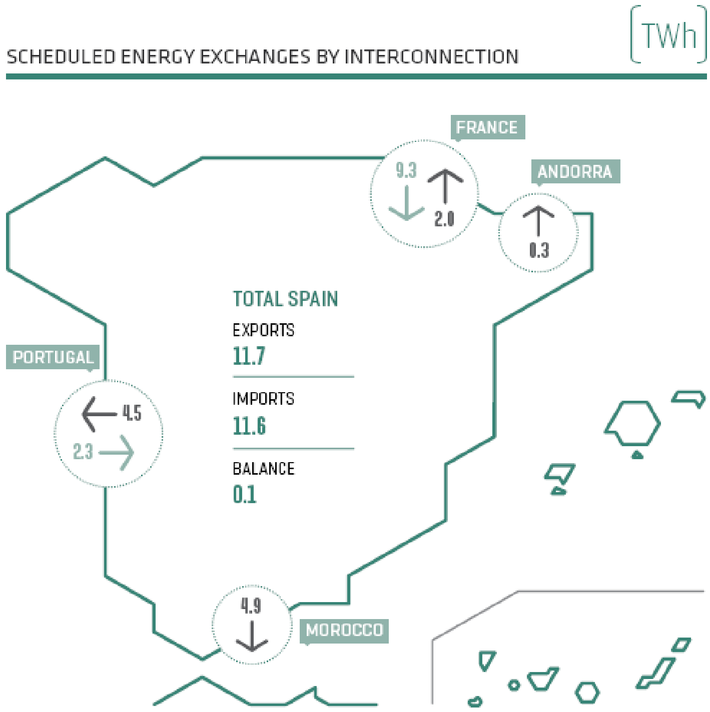

Figure 5.2: International connections of Spanish power system [4]

2 Historical review of the electricity market in Spain

Until 1997, the electricity sector in Spain was a sector regulated by the State, creating in 1944, during the dictatorship, the UNESA Association as a group of 18 electrical companies that represented 80 % of the total production of the sector. This meant the beginning of the unified exploitation, so that the facilities of each company were put at the service of supplying the country's demand, as if it were a single company. In 1951, the Unified Top Rates were approved, which established the unification of electricity prices for the entire Spanish territory. In 1985, Red Eléctrica de España (REE) was created, which involves the nationalization of the transport network [5].

In 1997, Law 54/1997 of the electricity sector was approved, whose basic purpose is to establish the regulation of the electricity sector, differentiating itself with previous laws in which this law is based on the conviction that guaranteeing the electricity supply, its quality and its cost does not require more state intervention than the specific regulation itself supposes [1].

This law therefore implies the liberalization of the sector and the creation of an Electricity Market, giving rise to the current structure of the Spanish electricity sector. This law also creates the figures of the National Energy Commission, the System Operator and the transport network manager (REE) and the Electricity Market Operator (OMEL) .

In Spain, final energy prices in 2011 reached one of the highest levels in the EU, so, final prices for residential domestic consumers reached high values in comparison with neighboring countries, such as France and Portugal, in the European ranking with a price of electricity 0.195 €/kWh, according to EU statistics, as reflected in the Table 5.1 [6].

Table 5.1: Electricity prices in Euro area in the year 2011 [6]

EU-27 Euro area	Households 2011 [€/kWh]
Belgium	0.214
Bulgaria	0.083
Czech Republic	0.150
Denmark	0.291
Germany	0.253
Estonia	0.097
Ireland	0.190
Greece	0.125
Spain	**0.195**
France	0.138
Italy	0.201
Cyprus	0.205
Latvia	0.117
Lithuania	0.121
Luxembourg	0.168
Hungary	0.168
Malta	0.170
Netherlands	0.174
Austria	0.199
Poland	0.147
Portugal	0.165
Romania	0.108
Slovenia	0.144
Slovakia	0.168
Finland	0.154
Sweden	0.209
United Kingdom	0.143

The tariff deficit arose; the government recognized fixed costs associated with electric energy, and what was entered in did not cover these fixed expenses. A debt of 10.000 million euros per year is reached, putting in danger of bankruptcy to the electrical system in the year 2013, reason why it publishes the Royal Decree 9/2013 by which urgent measures are adopted to guarantee the financial stability of the electrical system [7]. In this law, the most harmed technologies are those under the special regime (state program of economic incentives to renewable generation proposed in Sapin in the year 1998 in order that renewable energy could compete on equal terms with other technologies), being no longer primacy and adapting to a regime of free competition.

To date, the Spanish electricity system continues to face the tariff deficit, with impact on the final price of electricity for customers.

3 Current situation and operation of the electricity market in Spain

As mentioned above, the Spanish electricity system was liberalized in 1997 giving rise to a regime of free competition both in generation activity and in the commercialization activity. So, we should speak of the Electric Market as a competition free and unregulated market, differentiated into the wholesale and retail markets.

The wholesale market consists of the set of transactions derived from the participation of the market agents in the forward, daily and short-term market sessions. The liberalization of the electricity market establishes the right of free installation of electricity generation, opening the door to any private investor that wants to compete in the generation activity. This activity stopped being compensated by technology, with the elimination of the special regime established for renewable energies, to compete in price in the wholesale market [8]. The Spanish electricity market integrates with the Portuguese electricity market the Iberian Electricity Market (MIBEL) since 2008. Within this group, the Spanish daily market operators (OMIE) and Portuguese (OMIP) are integrated into the forward markets, and the Operators of the system, REE in the Spanish case and REN in Portugal. Within the wholesale market three markets are distinguished:

a) Forward Market

This group belongs to all those markets in which the contract has a delivery time greater than 24 hours.

b) Daily market

It is carried out by OMEL and consists of matching the generation offers with the demand for each of the 24 hours of the following day. This market is characterized by being a marginal market [8], in which all matched generators perceive the same price. This price is determined by the crossing point between the supply and demand curve and reflects the opportunity cost, that is, the revenues that generators give up for not producing, as shown in Figure 5.3 [8].

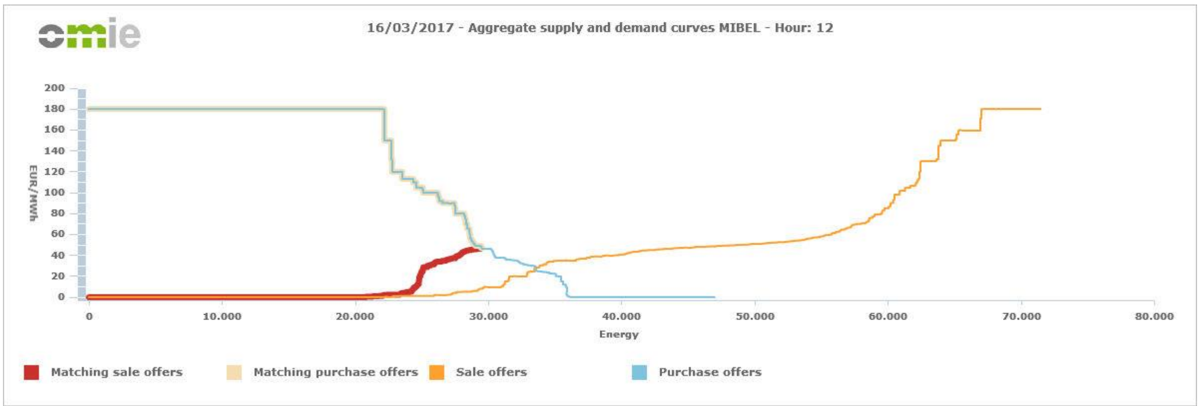

Figure 5.3:Agreegate supply and demand curves for a random day [8]

c) Short term markets

They are characterized to take place during the day of the dispatch.

Within the retail market is the sales activity, which consists of the delivery of energy to the final customers in exchange for an economic consideration. In Spain, this activity is exercised by mercantile companies under a competition regime. These companies acquire energy in the wholesale market and deliver it to the final consumer by hiring and paying tolls for access to the transmission and distribution networks, which subsequently have an impact on the consumer´s electric bill. These grid fees are regulated by the Ministry of Industry, Energy and Tourism [5].

4 Problems and proposals for the electricity market in Spain

The main problem currently facing the Spanish electricity sector is the eradication of the tariff deficit, which as mentioned above has placed Spain in the highest positions in the ranking of EU electricity prices [6], [9].

Currently, thanks to measures taken by the government, such as the application of a stable, objective and transparent remuneration to regulated activities, resulting from a valuation of standard projects applied to generation through renewable energy sources, cogeneration and waste; transport and distribution and operation of the system, as well as measures to reduce the cost of generation in non-mainland electric systems and the revision of energy planning, have allowed the tariff deficit to be (consequently) reduced for the first time in 2015 [10].

In this situation, although to a lesser extent, other EU countries especially affected by the economic crises such as Portugal, France, Greece, Bulgaria, Malta and Romania are facing to the same problem [11]; (countries with a delicate economic situation could suffer the higher tariff deficit as explained in the reference [10], [11].).

The European Commission (EC) says in its technical reports that a high percentage of renewables increases the probability of a tariff deficit, because their support, in the majority of cases, have shown to be (very) expensive [10]. Despite these results, Spain faces compliance with the EU Horizon 2020 strategic plan, which is based on increasing renewable generation in member countries. In a country like Spain where more than 38 % of national energy coverage comes from non-renewable sources and with the weight of the economic crisis behind them, the Spanish electricity system faces a new challenge in which to achieve the objectives of the European program with the improvement of the current financial situation [12].

The possible future development facing both Spain and the EU is the integration of a single European electricity market. This is a complex task since each member state is part of a different situation and with different rules for its electricity market. However, this may be the solution to be able to incorporate non-manageable renewable energy into European electricity systems, due to the variability in renewable generation and the dificulty to predict their availability [13].

5 Conclusions

The liberalization of the electricity sector in Spain led to the creation of the electricity market and the benefits of an unregulated free competition regime. However, despite being one of the major advances in the sector, some research has shown a sharp change in the liberalization process as an influential factor in the financial instability of the current system. Spain must continue betting on renewable energy generation together with the incorporation of measures that allow the reduction of the tariff deficit, approaching the European objectives of Horizon

2020. The increase in research and development investments in the sector is one of the greatest challenges facing Spain in the future years.

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Kakšna je vrednost? Določitev kapitala evropskih rek in praga hidroelektrarn

PETRA GSODAM & HEINRICH STIGLER

Povzetek Za osnovna sredstva elektroenergetskih podjetij sta značilna dolga življenjska doba in visoki investicijski stroški. Zgodovinsko gledano so osnovna sredstva prikazana v bilancah elektroenergetskih podjetjih s prenizko vrednostjo: realna vrednost osnovnih sredstev ni prikazana zaradi nominalnega višanja cen. Alternativo za prikaz realne vrednosti osnovnih sredstev predstavlja koncept kapitala, ki temelji na nadomestnih vrednostih zmanjšane amortizacije (neto kapitalska vrednost). Za izračun vrednosti osnovnih sredstev je potrebno poznati podatke o višini vložka v času gradnje v vsaki elektrarni (zgodovinska nabavna vrednost) kakor tudi skupno izhodiščno leto (nadomestne vrednosti). V članku je prikazano, kako oceniti ne-standardne naložbe v hidroelektrarne ter kako izračunati kapital pretoka reke in prag hidroelektrarne. Dolgoročna sredstva v obliki pretočnosti reke in pragu hidroelektrarne so primerjana na osnovi zgodovinskih stroškov in nadomestnih vrednosti. Ugotovljeno je, da je mogoče, glede na nominalno povišanje cen za nadomestne naložbe, kot je to primer z hidroelektrarnami z dolgo življenjsko dobo, zagotoviti ohranitev vrednosti premoženja družbe le z uporabo amortizacije na osnovi nadomestne vrednosti.

Ključne besede: • osnovna sredstva • elektroenergetska podjetja • bilanca stanja • kapitalska vrednost • amortizacija •

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What is it Worth? Determining the Capital Stock of European Hydropower Plants

PETRA GSODAM & HEINRICH STIGLER

Abstract High lifetimes and high capital intensities characterize fixed assets of electric utilities. The historical cost concept implicate that long-lasting fixed assets are shown too low in balance sheets of electric utilities: the real value of long-lasting assets is not shown because of nominal price increases. An alternative to show the real value of long-term assets represents the capital stock concept based on replacement values less depreciations (net capital stock). To calculate the capital stock, information regarding the level of investment in each power plant at the time of construction (historical acquisition values) and with regard to a common base year (replacement values) is necessary. This paper shows how the not-standardized investments in hydropower plants can be estimated and how the capital stock of run-of-river and threshold hydropower plants can be calculated. Long-term assets in the form of run-of-river and threshold hydropower plants are compared based on historic costs and replacement values. The paper concludes that given nominal price increases for replacement investments, as is the case with long-lasting hydropower plants, only depreciations based on replacement values can ensure preservation of the company's assets.

Keywords: • fixed assets • electric utilities • balance sheet • capital stock • depreciation •

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1 Introduction

One of the principles of proper accounting is the historical cost concept. On the basis of this principle, which is mandatory in the individual financial statements under commercial law, the cost of acquisition or production represent the upper limit for assets in the balance sheet (§ 203 para. 1 UGB). This aims at preserving a company's nominal capital, whereby monetary fluctuations and changes in replacement values over time are not considered [1]. The historical acquisition values as upper limit for the valuation lead to an undervaluation of long-lasting assets and hidden reserves are created within the company. As a consequence, the equity of a company appears too low than it is actually [2]. Ensuring a company's long-term viability as a superior corporate objective for capital-intensive companies with long-lasting assets is not possible with nominal capital preservation. Instead, such companies need to focus more on preserving a company's assets rather than a company's nominal capital. Therefore, the valuation of long-lasting assets in the balance sheet has to consider replacement values instead of historical acquisition values. The valuation based on replacement values was already taken up by Schmidt [3]. Schmidt's theory of the organic balance sheet includes price increases and, consequently, considers replacement values instead of historical acquisition values. The organic balance sheet is oriented towards preserving a company's assets. This theory was developed at times with high annual nominal price increases (hyperinflation in Germany). The International Financial Reporting Standards (IFRS) also addressed the issue of undervaluation (or overvaluation) of fixed assets. Therefore, there are two options for the valuation within the consolidated financial statements where companies can choose between the use of historical acquisition values and the fair value [1].

Depreciations consider impairments of fixed assets arising e.g. through use and aging. From an economic point of view, a constant depreciation based on historical acquisition values during the average useful life (straight-line depreciation) is common. Depreciations are part of the cash flow and should be used for replacement investments [2]. Depreciations based on historical acquisition values are – for long-lasting assets – due to nominal price increases too low to ensure adequate replacement investments at the end of a power plant's life. Long-lasting assets in capital-intensive industries, such as the electricity industry, require depreciations based on replacement values to preserve a company's assets. Preserving a company's assets is not possible with depreciations based on historical acquisition costs [3].

The fixed assets are particularly important for electric utilities due to the longevity of the power plants. The determination of the actual value of fixed assets is, however, difficult. In sectors with high asset turnover, the value of fixed assets is shown in the balance sheets of the companies. This is not the case in the electricity sector, since this sector faces a rather low asset turnover and nominal price increases, which have a great impact on long-lasting assets, are not considered. Therefore, an alternative method has to be used to determine the actual value of fixed assets [4]. One method is to determine the net capital stock, which shows the fair value of the fixed assets at a specified reference day. The net capital stock is calculated based on the gross capital stock (capital stock at replacement values) less cumulated depreciations [5]. Since the net capital stock is based on the gross capital stock and, therefore, on replacement values, it is important to determine accurate replacement values. Hydropower plants are specific regarding their investment costs. Thermal power plants are standardized and power plants of the same technology are similar to each other. The investment costs for a thermal power plant can be estimated based on other projects with known investments. On the contrary, hydropower plants vary from site to site and investment costs can only be estimated with uncertainty.

Investment costs depend on local environmental factors and geographic circumstances, such as gradient or average annual discharge of the river. Therefore, it is difficult to make generalizations regarding the investment costs of run-of-river and threshold hydropower plants.

Compared with other electricity generation technologies, run-of-river and threshold hydropower plants have a very high useful life. The comparatively old hydropower plants are shown in the balance sheets of the companies with their historical acquisition values. These values do not reflect the actual value of the power plants. A 40-year-old run-of-river hydropower plant produces too low depreciations due to annual nominal price increases, so that there is insufficient capital for replacement investments in the capital-intensive power plants available. An overview of the age structure of run-of-river and threshold hydropower plants of selected countries is shown in Figure 6.1. Figure 6.1 shows that a large part of hydropower plants was built between 1950 and 1990. Given an assumed economic useful life of 50 years, many of these power plants are already fully depreciated.

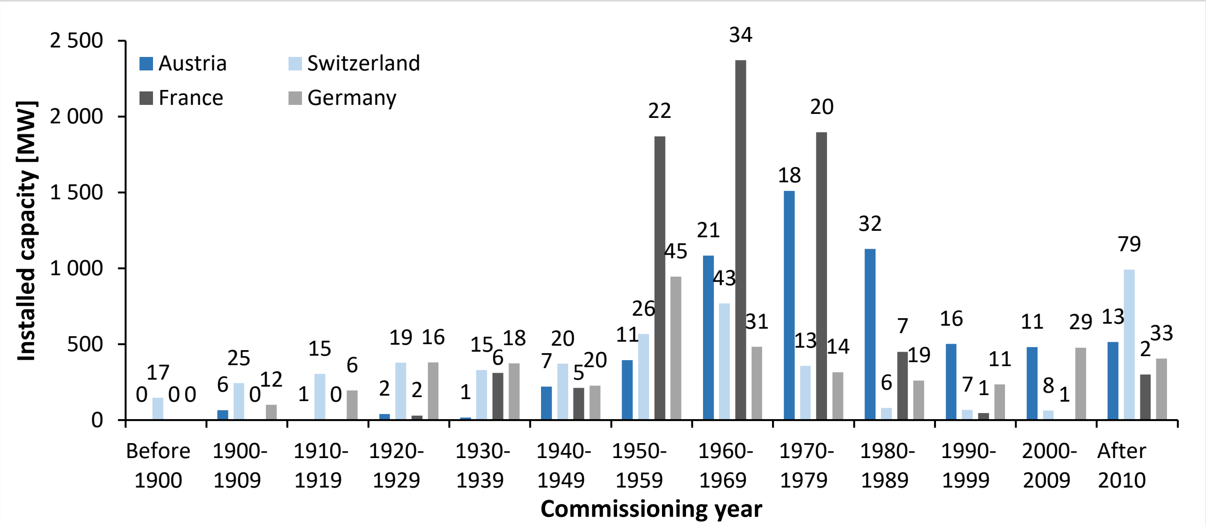

Figure 6.1. Age structure of run-of-river and threshold hydropower plants in selected countries (Source: own representation, based on the Institute's database).

Against this background, the following research questions arise:

- How can bandwidths for the specific investment costs of run-of-river and threshold hydropower plants be determined and how high are the resulting bandwidths?
- How do the fixed assets of electric utilities change if replacement values instead of historical acquisition values are used to determine the value of fixed assets?

1.1 The capital stock in the electricity sector

In this paper, the term capital stock refers to all non-financial assets that are used for more than one year for electricity production (i.e. power plants). The stock of fixed assets based on replacement values without consideration of depreciations at 2015 prices is referred to as gross capital stock; with consideration of depreciations the stock of fixed assets is referred to as net capital stock. The gross capital stock is based on replacement values. The price for all fixed assets is referred to a specific base year, resulting in constant prices for the replacement. The gross capital stock is the basis for the net capital stock – the cumulated depreciations are subtracted from the gross capital stock and the depreciated capital stock is shown [5]. The economic useful live used to calculate depreciations and residual book values in accounting is not equal to the technical lifetimes. Therefore, the net capital stock, which should represent the actual value of the fixed assets, is calculated based on the higher technical lifetimes.

The ratio of gross to net capital stock is called degree of modernity. This ratio provides information on how much of the historic investments are not yet depreciated; the ratio informs about the aging process of the fixed assets [6]. Another key performance indicator based on the capital stock is the capital intensity. This indicator represents the ratio between capital stock and number of employed people, whereby the average employment of capital per employee is measured. Both key performance indicators are quite high in the electricity sector compared to other sectors, e.g. the manufacturing sector [4, 7].

One method to determine the fixed assets of a sector is to sum up the fixed assets shown in balance sheets of individual companies. However, this is not very effective in sectors with long-lasting assets and high capital intensities. This would result in a distorted picture of reality; due to nominal price increases the value of fixed assets would be too low. The actual value of fixed assets cannot be determined from the balance sheets due to long technical lifetimes and depreciations based on historical acquisition values [4]. For all those reasons it is of particular importance to apply the capital stock concept to the electricity sector and to determine the gross capital stock and the net capital stock of this sector.

In order to determine the capital stock, time series of the investments in fixed assets as well as their economic useful live and technical lifetimes are necessary [6]. A part of the required information can be derived directly from the Institute’s simulation model ATLANTIS [8]. The missing element is investment in each power plant at the time of construction and based on a common base year for the replacement values. One possibility to determine the missing information for run-of-river and threshold hydropower plants is presented in the next section.

2 Methodology

The determination of the gross capital stock and the net capital stock requires information about the investment in each power plant. Data on investment costs of Austrian run-of-river and threshold hydropower plants are the basis for determining unknown investment costs. A large part of these data were taken from [9].

Investment costs in hydropower plants are highly depending on local environmental factors and geographic circumstances. Therefore, the Austrian power plants are grouped according to the river on which they were built. The considered power plants are located on the following rivers: Danube, Drava, Enns, Inn, Mur, Salzach, and Traun. The specific investment costs of the power plants, determined through extensive research, on the above mentioned rivers are shown in Figure 6.2. Figure 6.2 shows the entire bandwidth for each river as well as the bandwidth excluding minimum and maximum values. Within each box, the mean for each river is indicated. The specific investment costs are shown in constant prices for 2015 per annual kilowatt hour (kWh_a).

Based on the 10 % quantile as lower limit and the 90 % quantile as upper limit, the statistical bandwidths and the mean values of the adjusted specific investment costs in EUR_{2015} based on the annual production capacity (APC) are shown in Table for each river. The 10 % quantile and the 90 % quantile are used to eliminate minimum and maximum values.

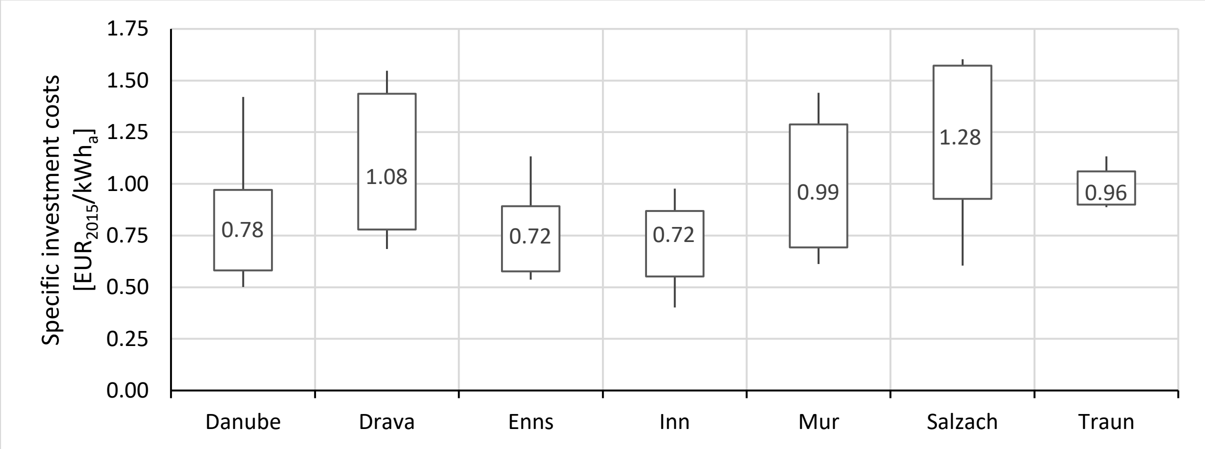

Figure 6.2. Boxplot of the specific investment costs based on the APC (Source: own representation).

The bandwidths shown in Table 6.1 are used to determine the unknown investment costs of run-of-river and threshold hydropower plants. For this purpose, the bandwidths for each river are distributed linearly over a period of 95 years, from 1920 to 2015, with the 10 % quantile reflecting the specific investment costs of 1920 and the 90 % quantile the specific investment costs of 2015. This is based on the assumption that first the particularly attractive hydropower plants were built on each river, followed by more expensive alternatives, so that at the end only comparatively expensive power plants remain. Potential cost savings resulting from technological progress in the construction of run-of-river and threshold hydropower plants are offset by the construction of power plants at unfavourable locations as well as increasing environmental requirements.

Table 6.1: Bandwidths of the specific investment costs based on the 10 % quantile and the 90 % quantile as lower and upper limit (Source: own representation).

River	**Specific investment costs [EUR_{2015}/kWh_a]**	**Mean [EUR_{2015}/kWh_a]**
Danube	0.581–0.971	0.75
Drava	0.779–1.436	1.08
Enns	0.577–0.892	0.72
Inn	0.552–0.869	0.72
Mur	0.692–1.288	0.99
Salzach	0.927–1.572	1.28
Traun	0.900–1.060	0.93

The lower limit for the specific investment costs for all power plants on a river is the 10 % quantile. Specific investment costs in constant prices cannot be below this limit. The year 1920 as lower limit is chosen since only few European countries built hydropower plants before this year. This is illustrated in Figure 6.3. Among the continental European countries, Switzerland has the most (large) run-of-river and threshold hydropower plants with a commissioning year before 1920 (59), followed by Germany (19) and Italy (13).

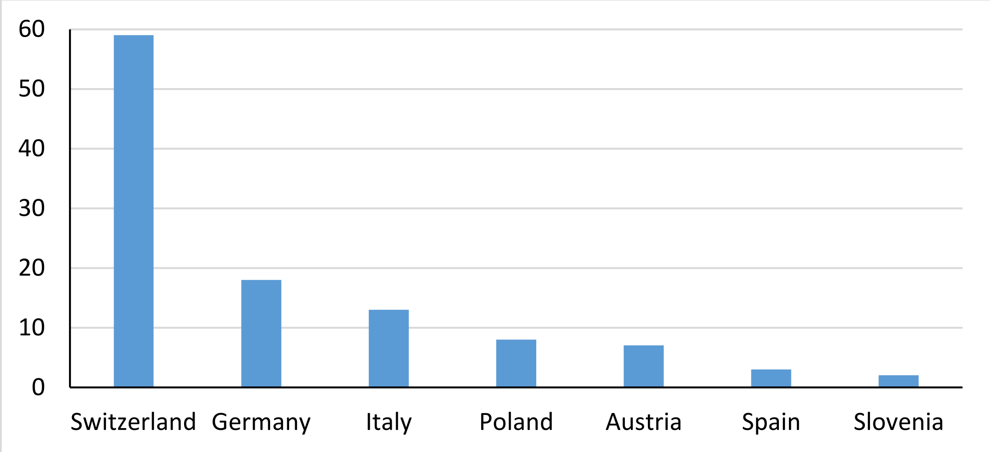

Figure 6.3. Run-of-river and threshold hydropower plants with a commissioning year before 1920 in selected European countries (Source: own representation, based on the Institute's database).

In order to calculate the total investment costs in constant prices ($TIC_{COP\ 2015}$) based on specific investment costs ($SIC_{COP\ 2015}$), it is necessary to relate the specific investment costs to the APC of the power plant. This is shown in (1).

$$TIC_{COP\ 2015}\ [EUR] = SIC_{COP\ 2015} \left[\frac{EUR}{kWh_a}\right] \times APC\ [kWh_a] \qquad (1)$$

Next, the $TIC_{COP\ 2015}$ are converted into current prices (TIC_{CUP}) – i.e. prices at the time of construction – using an index for price increases, in order to determine the actual historical acquisition values that had to be paid in the commissioning year, see (2). This is the value of the power plants of which depreciations and the depreciated book values are calculated. Data on average annual inflation in Austria (consumer price index, CPI) are provided by [10]. The CPI is chosen because it presents – among all European countries – the longest available time series to measure price increases. For calculating historical acquisition values of very old run-of-river and threshold hydropower plants (commissioning year before 1948), an average annual price increase of 2 % is assumed. Before 1948 no data on CPI in Austria is available. 2 % is chosen because this represents the ideal annual inflation according to European Central Bank, the Federal Reserve and many others.

$$TIC_{\ CUP}\ [EUR] = TIC_{COP\ 2015} [EUR] \times \frac{CPI_{Commissioning\ year}}{CPI_{2015}} \qquad (2)$$

Based on the data of the Austrian run-of-river and threshold hydropower plants, the unknown investment costs of run-of-river and threshold hydropower plants built in other European countries are determined. It is assumed that rivers with similar geographic circumstances, like gradient and water volume, have similar specific investment costs and differ only regarding the price level of the countries. In order to represent the price levels correctly, data from [11] are used. In this work, price levels for 2015 are used because the common base year for the replacement values in constant prices is the year 2015. Information like length, gradient, average annual discharge and others, are collected for each river or river section on which run-of-river and threshold hydropower plants were built according to the Institute's database. Furthermore, the geographic situation (river in the mountains, lowlands) is taken into account via Google Earth. Based on this information, the rivers are compared and an Austrian "reference river" is assigned to each river. If a river does not show significant similarities with any of the Austrian rivers, the mean of all analysed Austrian rivers for the commissioning year of the considered power plant is used. The conversion from constant to current prices is based on the CPI for the respective country, to calculate the historical acquisition values, see (2). The CPI of a country is provided by national statistical offices and the OECD statistics database. For some countries, such as most Balkan countries, it is not possible to find complete historical time series back to 1948 and before 1948. Missing data are filled with the "2 %-assumption", same as for Austria before 1948. Many countries had to cope with runaway inflation (10–50 %) or even hyperinflation (> 50 %) in the past. After periods with runaway inflation or hyperinflation, a monetary reform is usually unavoidable. Therefore, it is assumed that the index after this period is just slightly above the index before. These high price increases are adjusted and the assumption is made that the average annual inflation rate during these years was 2 %.

3 Results

Based on the method presented in Section 2, the capital stock (replacement values) and the value of fixed assets shown in the balance sheets of the companies (historical acquisition values) were calculated for 28 continental European countries (excluding Scandinavia, Ukraine, Moldova, Belarus and Russia). Data are shown in Table. The depreciated values (net capital stock and depreciated book values) were calculated using the economic useful life and the technical lifetimes, respectively. The net capital stock is based on the technical lifetime (assumption: 80 years), while the depreciated book values are based on the economic useful life (assumption: 50 years). At the end of 2015, the considered countries show a gross capital stock at replacement values of 158.5 bn EUR for electricity production out of run-of-river and threshold hydropower plants. Gross capital stock less depreciations with a technical lifetime of 80 years results in 70.8 bn EUR for the net capital stock at replacement values. On the basis of the historical acquisition values – the prices that had to be paid in the commissioning year – the fixed assets of the companies amount to 57 bn EUR. Less depreciations with an economic useful life of 50 years the depreciated book values shown in the balance sheets of companies amount to 26.7 bn EUR. At the end of 2015, the considered countries have in total about 1 600 run-of-river and threshold hydropower plants (microgeneration units were combined to aggregates for each country) with an installed capacity of about 50 GW.

It can be seen from Table 6.2 that the net capital stock based on depreciated replacement values is higher than the fixed assets without depreciations based on historical acquisition values. The degree of modernity shows the ratio between the gross capital stock and the net capital stock and provides information on how much of the investments are not yet depreciated. The degree of modernity for the above-mentioned capital stock is 45 %. This means that 45 % of the capital stock based on replacement values are not yet depreciated through use and aging with an assumed technical lifetime of 80 years. Considering historical acquisition values and an economic useful life of 50 years, the degree of modernity for the fixed assets is 47 %. The degree of modernity for the investigated countries was high in Estonia (88 % and 82 %, respectively) and Greece (87 % and 84 %, respectively), while this indicator was low in Bulgaria (29 % and 14 %, respectively) and Lithuania (36 % and 15 %, respectively). The degree of modernity in Slovenia is 43 % and 51 %, respectively.

Table 6.2: Capital stock (replacement values) and fixed assets (historic acquisiton values) of run-of-river and threshold hydropower plants (Source: own representation).

Country	Gross capital stock (RV[1])	Net capital stock (RV[1])	Fixed assets (hist. AV[2])	Depreciated book values (hist. AV[2])
Albania	757 162 913	436 403 076	392 820 643	201 677 087
Austria	25 804 920 759	13 915 808 433	10 798 748 392	5 168 883 020
Belgium	233 962 135	103 176 333	74 116 424	22 107 525
Bosnia and Herzegovina	1 218 549 134	888 083 921	863 203 273	635 159 890
Bulgaria	360 196 605	103 803 122	94 172 806	13 415 958
Croatia	1 762 895 487	855 416 617	643 186 293	172 163 339
Czech Republic	991 561 465	435 505 894	352 220 967	54 950 337
Denmark	11 095 804	1 803 068	1 128 676	–
Estonia	13 535 401	11 953 955	10 461 580	8 582 995
France	32 344 531 744	12 474 351 151	8 502 937 629	2 347 318 857
Germany	16 483 897 919	6 891 692 608	6 836 624 590	3 348 803 966
Greece	673 600 549	583 961 232	546 196 215	459 229 570
Hungary	90 497 153	37 474 718	17 277 922	2 499 998
Italy	19 319 917 659	7 668 547 347	6 537 097 141	3 465 777 568
Latvia	862 787 482	380 454 644	292 023 805	36 465 132
Lithuania	262 172 125	94 791 775	91 285 235	13 473 818
Luxembourg	106 325 828	44 630 530	28 322 769	7 850 439
Macedonia	75 925 097	38 388 742	36 174 501	14 974 122
Montenegro	130 534 258	118 160 891	118 195 347	111 144 718
Netherlands	132 685 493	89 653 346	80 789 381	38 929 487
Poland	489 865 918	198 152 752	143 593 843	28 609 846
Portugal	9 140 474 058	5 589 838 649	4 739 452 161	3 172 744 354
Rumania	5 740 163 974	3 365 748 785	2 469 970 897	1 103 089 093
Serbia	3 330 417 842	1 786 833 943	1 243 327 443	534 865 489
Slovakia	4 345 973 004	2 785 747 568	1 207 506 927	683 797 681
Slovenia	3 493 633 101	1 508 623 873	922 735 976	470 722 255
Spain	6 439 903 796	3 353 746 340	2 465 744 039	1 322 216 834
Switzerland	23 889 455 797	6 992 514 096	7 614 920 640	3 213 682 084
Total	**158 506 672 502**	**70 755 267 409**	**57 124 235 515**	**26 653 135 462**

[1] Replacement values
[2] Historical acquisition values

Due to nominal price increases the differences between historical acquisition values and replacement values is highest for rather old hydropower plants. Figure 6.4 and Figure 6.5 present a comparison of the investment costs of hydropower plants on the Drava and Sava river. The oldest hydropower plant is Fala on the Drava river with a commissioning year of 1918. In contrast, the youngest hydropower plant is Krško on the Sava river with a commissioning year of 2012. Figure 6.4 and Figure 6.5 show the historical acquisition values and the replacement values as well as the respective depreciated values. All values are referred to the replacement value of 2015 for each power plant. The historical acquisition values only account for a small portion of the replacement values due to nominal price increases. This is illustrated best for the rather old hydropower plants, like Fala, Medvode or Dravograd. Those power plants are also already above their economic useful life of 50 years. Considering the historical acquisition values, they are already fully depreciated. In the balance sheets of the companies such power plants are represented with a value of 1 EUR, so that they are still visible and listed but without any economic value. Considering the replacement value and the technical lifetime of 80 years, all power plants – despite Fala – still show a depreciated replacement value.

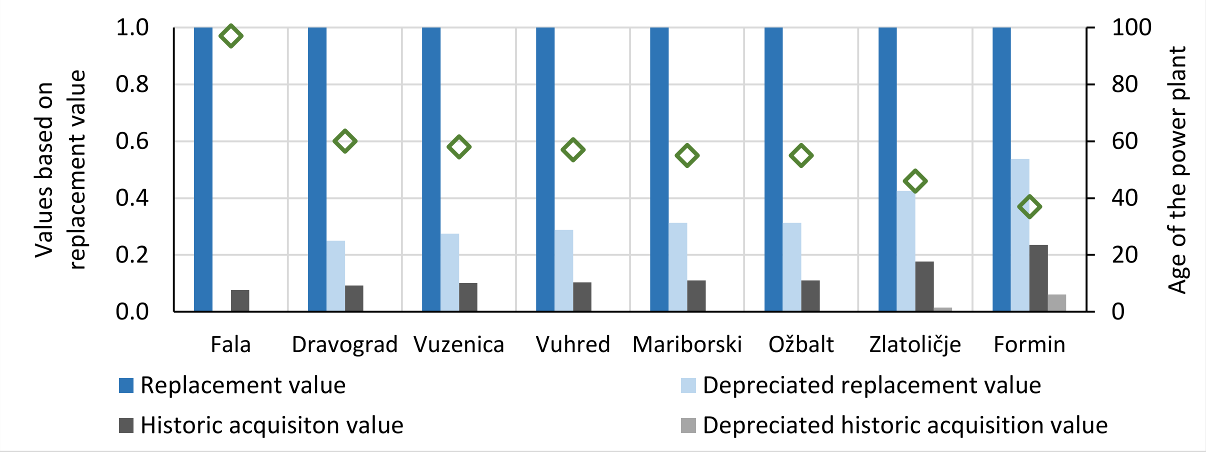

Figure 6.4. Comparison of the investment costs of hydropower plants on the Drava river. Values are referred to the replacement value (Source: own representation).

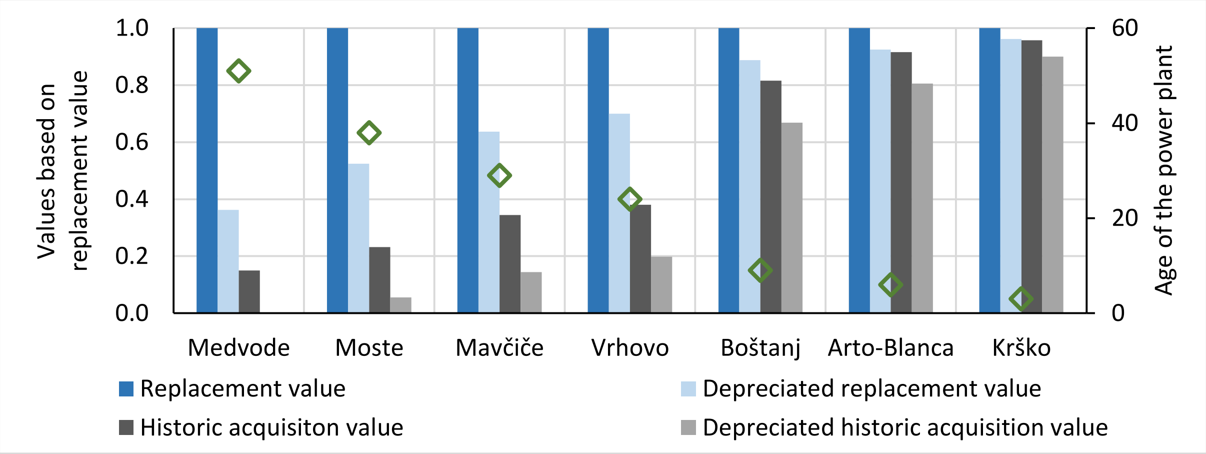

Figure 6.5. Comparison of the investment costs of hydropower plants on the Sava river. Values are referred to the replacement value (Source: own representation).

Figure 6.6 illustrates the investment costs in absolute numbers of the three youngest large hydropower plants in Slovenia, all of them located on the lower Sava river. Also these rather young hydropower plants already show some differences between the replacement values and the historical acquisition values due to nominal price increases. For all three power plants, the depreciated replacement value is higher than the historic acquisition value.

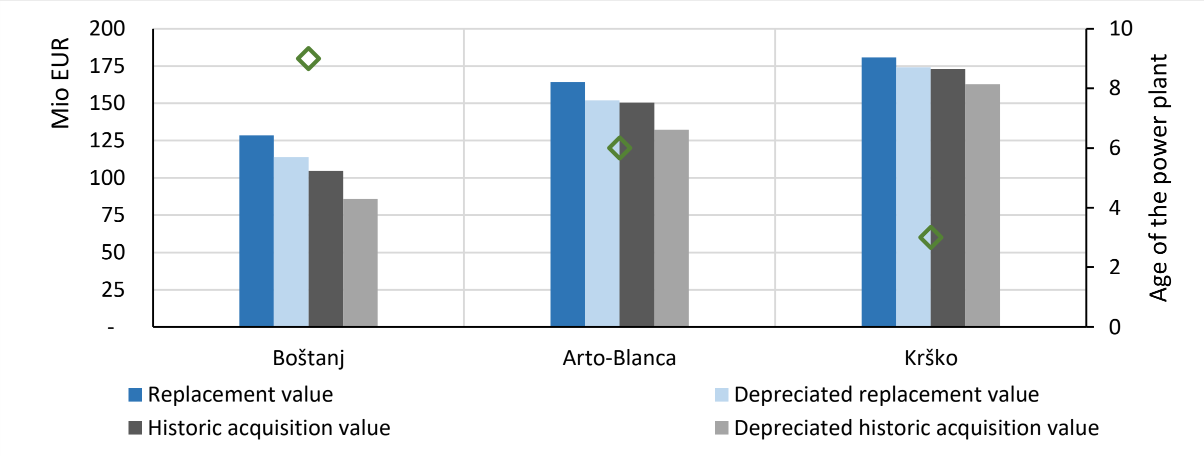

Figure 6.6. Comparison of the investment costs of the three youngest large hydropower plants. The secondary axis shows the age of the power plant (Source: own representation).

4 Discussion and conclusion

The net capital stock based on replacement values is about 2.75 times higher than the depreciated historical acquisition values. When looking at the gross capital stock and the historical acquisition values, the same picture can be observed. In companies with low asset turnover, high capital-intensities and long-lasting assets, the fixed assets are undervalued in the balance sheets of the companies due to historical acquisition values as upper limit for the valuation and nominal price increases. The actual value of fixed assets (capital stock) is higher as shown in the balance sheets. Furthermore, the economic useful life is not equal to the technical lifetime. The net capital stock based on replacement values is perceived to be a suitable method to show the real value of electric utilities' fixed assets. Due to nominal price increases, it is not possible to finance new power plants by using the part of the cash flow which consists of depreciations. Depreciations resulting from the historical acquisition values are not sufficient for preserving a company's fixed assets and provide insufficient financial resources for investments. The determination of the gross capital stock and the net capital stock based on replacement values as well as the determination of the (depreciated) historical acquisition values shown in the balance sheets of the companies provide relevant information on a sector. On the one hand, the actual value of the fixed assets of the companies is shown (capital stock). On the other hand, there are various key performance indicators for productivity analysis, such as capital productivity, capital intensity or degree of modernity.

Investments in run-of-river and threshold hydropower plants are difficult to determine due to plant-specific features and location-specific costs. The method shown in Section 2 is a possibility for the determination of the non-standardised investment costs in run-of-river and threshold hydropower plants. A large part of the investment costs of these hydropower plants consist of the costs for dykes and the dam. These costs depend on the gradient and water volume of the river. Therefore, those characteristics of a river can be used to determine the investment costs in hydropower plants. The calculated investment costs represent an estimate in order to determine the actual value of the electric utilities' fixed assets. Plant-specific features that lead to a reduction in investments during construction cannot be taken into account accurately.

Finally, we can draw the following conclusion. Preservation of a company's fixed assets can only be ensured by deprecations based on replacement values. Depreciations based on historic acquisition values lead to a lack of capital for replacement investments in capital-intensive and long-lasting assets. Furthermore, a valuation based on the historical cost concept does not show the actual value of long-lasting assets due to nominal price increases. The capital stock concept can be used to determine the actual value of long-term fixed assets.

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Ovrednotenje modelov verjetnostne porazdelitve napake napovedi proizvodnje vetrnih elektrarn

BOŠTJAN POLAJŽER & DUNJA SRPAK

Povzetek V članku so obravnavani različni modeli verjetnostne porazdelitve napake proizvodnje vetrnih elektrarn. Poleg modelov, znanih iz literature (beta, Weibull, gamma), so obravnavani modeli z razširjeno nesimetrično posplošeno normalno porazdelitvijo. Obravnavan je tudi model s t.i. verzatilno verjetnostno porazdelitvijo, ki je občutljiv na valovitost empirične porazdelitve, vendar omogoča analitičen izračun percentilne funkcije. Dobljeni rezultati kažejo, da modeli z beta, Weibull in gamma verjetnostno porazdelitvijo ne dajejo dobrih rezultatov, bistveno bolj ustrezni so modeli z nesimetrično posplošeno normalno verjetnostno porazdelitvijo.

Ključne besede: • model • verjetnostna analiza • porazdelitev napake • proizvodnja • vetrne elektrarne •

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Evaluation of Probability-Distribution Models for Wind-Power Forecast Error

BOŠTJAN POLAJŽER & DUNJA SRPAK

Abstract This paper discusses different probability-distribution models for wind-power forecast error. Models known from the literature (beta, Weibull, gamma) are discussed along with the models with extended-skew generalized-normal distribution. Furthermore, a versatile model is discussed, which enables analytical calculation of the percentile function; however, it is sensitive to wavelets in the probability distribution. Obtained results show that beta, Weibull and gamma probability distributions do not capture the actual (empirical) one; far more adequate are models with skew generalized-normal probability distribution.

Keywords: • model • probability • error distribution • generation • wind power •

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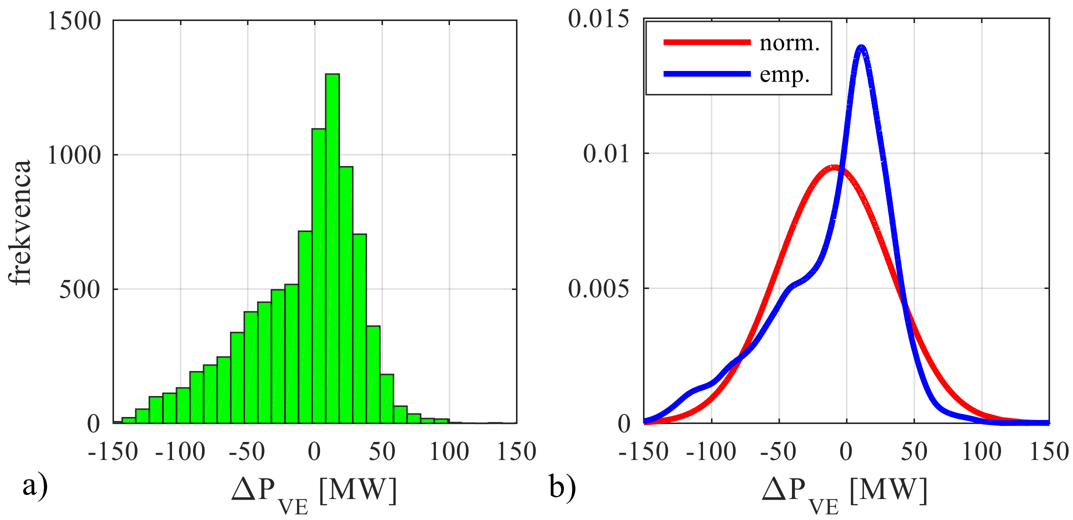
1 Uvod

Spremenljivost proizvodnje vetrnih elektrarn (VE) v elektro energetskem sistemu (EES) povzroča dodatna neravnotežja med proizvodnjo in porabo električne energije, kar pomeni dodatne zahteve po regulacijski rezervi (RR). Zaradi znatne napake napovedi proizvodnje VE je pri določitvi RR potrebno upoštevati ustrezne modele verjetnostne porazdelitve. Modeli z normalno verjetnostno porazdelitvijo praviloma niso dovolj točni, zato se uporabljajo modeli, ki temeljijo na beta (β) porazdelitvi [1], hiperbolični in Weibullovi (WB) porazdelitvi [2], kakor tudi gamma porazdelitvi (γ) [3]. Poleg omenjenih modelov je v tem članku obravnavan tudi model z razširjeno-nesimetrično posplošeno-normalno (RNPN) porazdelitvijo [4]. Vendar je uporaba omenjenih verjetnostnih porazdelitev pri dinamičnem določanju RR lahko omejena, saj določitev zbirne funkcije verjetnosti zahteva tako numerično integracijo, kakor tudi aproksimacijo. Zaradi tega je obravnavan tudi t.i. verzatilni (VER) model, ki temelji na predpostavljeni zbirni funkciji verjetnosti in omogoča analitičen izračun inverzne (percentilne) funkcije [5]. V članku sta podrobneje opisana RNPN in VE modela verjetnostne porazdelitve, predstavljeni so tudi postopki določitve parametrov. Za podatke iz hrvaškega EES za leto 2013 je izvedena primerjava rezultatov dobljenih z obravnavanimi modeli (β, WB, γ, RNPN in VER) z rezultati empiričnega modela, pri čemer so za vsak model ovrednotene razlike funkcije gostote verjetnosti in izbranih percentilov.

2 Napaka napovedi prozvodnje vetrnih elektrarn v Hrvaškem EES

Napaka napovedi proizvodnje VE je definirana z razliko napovedane in izmerjene delovne moči. Negativna vrednost napake torej pomeni premajhno vrednost napovedi, pozitivna pa preveliko. V članku so uporabljena urna povprečja napovedane in izmerjene delovne moči VE hrvaškega (HR) EES za leto 2013. V tem letu se je instalirana moč VE povečala iz približno 140 MW na 250 MW. Trend rasti instalirane moči VE je v HR EES izrazit, saj je v letu 2016 le-ta znašala že 420 MW, kar predstavlja približno 10 % skupne instalirane moči. Slika 7.1a prikazuje histogram napake napovedi, slika 7.1b pa primerjavo funkcije gostote verjetnosti za normalno porazdelitev in za empirično (neparametrično) porazdelitev z Gaussovim glajenjem. Poleg izrazite leve nesimetrije in valovitosti verjetnostne porazdelitve (moment 3. stopnje znaša -0,72) je opazna tudi sploščenost, saj je moment 4. stopnje za 0,41 večji kot pri normalni porazdelitvi. Srednja vrednost napake napovedi proizvodnje VE znaša -9 MW, standardni odklon pa kar 42 MW.

Za določitev RR je potrebno upoštevati tudi napako napovedi obremenitve, ki je glede na povprečno obremenitev (2000 MW) relativno majhna. Srednja vrednost napake napovedi obremenitve za obravnavano časovno obdobje znaša -21 MW, standardni odklon pa 62 MW. Korelacija med napakama napovedi proizvodnje VE in napovedi obremenitve je zanemarljivo majhna. Poudarimo, da se v tem članku omejujemo samo na modeliranje verjetnostne porazdelitve napake napovedi proizvodnje VE.



Slika 7.1: Histogram in funkciji gostote verjetnosti za normalno in empirično porazdelitev napake napovedi proizvodnje VE

3 Modeli verjetnostne porazdelitve

V tem poglavju so podrobneje opisani modeli RNPN in VE verjetnostne porazdelitve. Ostale obravnavane porazdelitve (β, WB in γ) so splošno znane, njihova uporaba pri modeliranju napake napovedi proizvodnje VE pa je podana v literaturi [1-3].

3.1 Razširjena-nesimetrična posplošena-normalna porazdelitev

Funkcija gostote verjetnosti, ki opisuje RNPN porazdelitev, je za slučajno spremenljivko x podana z izrazom

$$f_{\mathrm{RPNN}}\left(x \mid \lambda_1, \lambda_2, \lambda_3\right) = 2\phi(x_s)\Phi\left(\frac{\lambda_1 x_s}{\sqrt{1+\lambda_2 x_s^2 + +\lambda_3 x_s^4}}\right)\frac{1}{\sigma} \tag{1}$$

kjer $\phi(\bullet)$ in $\Phi(\bullet)$ označujeta funkcijo gostote verjetnosti in zbirno funkcijo verjetnosti za normalno porazdelitev. x_s je standardizirana slučajna spremenljivka, ki je definirana kot $x_s := (x-\mu)/\sigma$, pri čemer je μ srednja vrednost, σ pa standardni odklon. λ_1, $\lambda_2 \geq 0$ in $\lambda_3 \geq 0$ so parametri oblike, ki vplivajo na nesimetrijo in sploščenost verjetnostne porazdelitve. Parametri (μ, σ in λ_i) se določijo z numerično maksimizacijo funkcije verjetnosti [4].

Tabela 7.1: Vpliv parametrov oblike λ_i

λ_1	λ_2	λ_3	porazdelitev	nesimetrija	sploščenost
$\neq 0$	$= 0$	$= 0$	NN	DA	NE
$\neq 0$	> 0	$= 0$	NPN	DA	DA
$\neq 0$	> 0	> 0	RNPN	DA	DA

3.2 Verzatilna porazdelitev

Funkcija gostote verjetnosti, ki opisuje VER porazdelitev, je za slučajno spremenljivko x podana z izrazom

$$f_{\mathrm{VER}}\left(x \mid a,b,c\right)=\frac{ab\exp\left(-a\left(x-c\right)\right)}{\left(1+\exp\left(-a\left(x-c\right)\right)\right)^{b+1}} \tag{2}$$

Parametri a, b in c so določeni z aproksimacijo zbirne funkcije verjetnosti [5], ki je podana analitično z izrazom

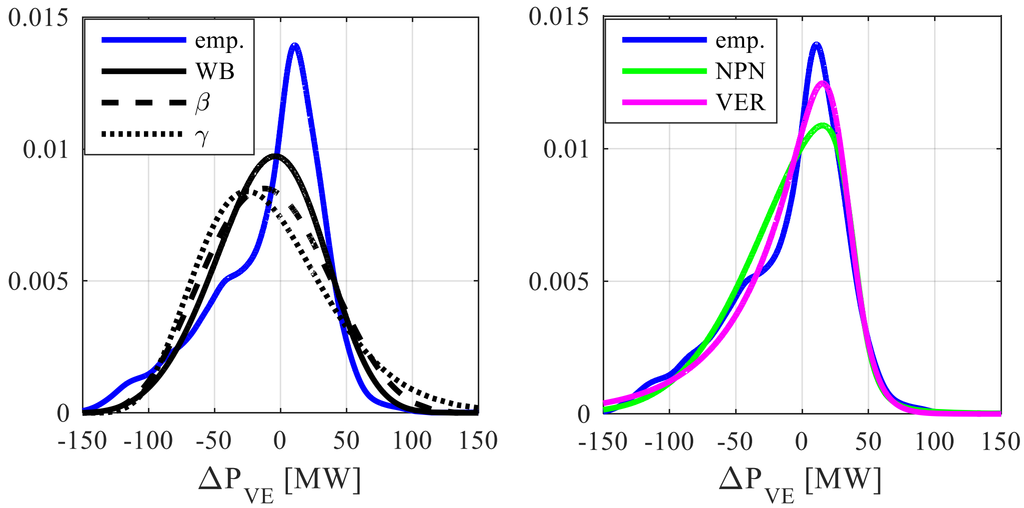
$$F_{\mathrm{VER}}\left(x \mid a,b,c\right)=\left(1+\exp\left(-a\left(x-c\right)\right)\right)^{-b} \tag{3}$$

Tudi inverzna (percentilna) funkcija je podana analitično, in sicer je za p-ti percentil

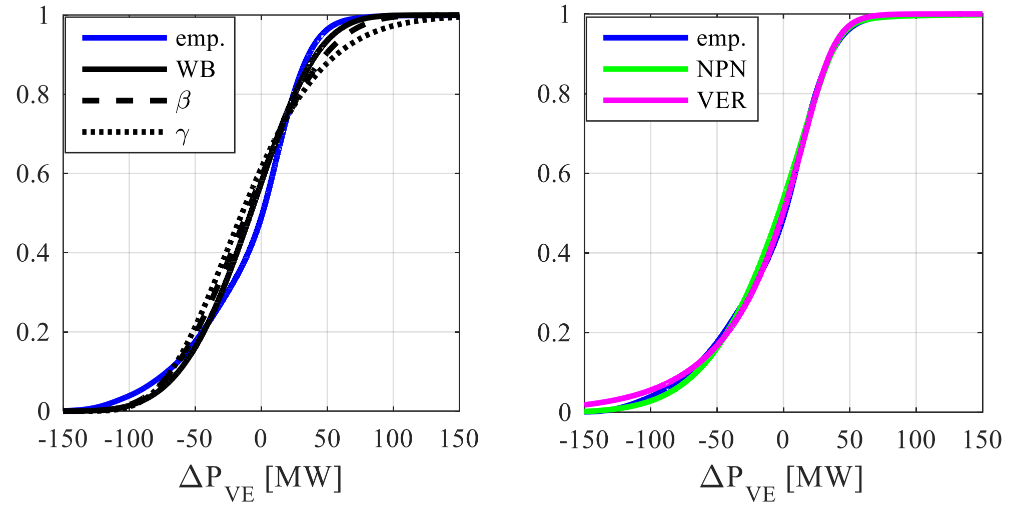
$$F_{\mathrm{VER}}^{-1}\left(p \mid a,b,c\right)=c-\frac{1}{a}\ln\left(\left(0{,}1p\right)^{-1/b}-1\right) \tag{4}$$

4 Rezultati

Sliki 7.2 in 7.3 prikazujeta funkcije gostote verjetnosti in zbirne funkcije verjetnosti napake napovedi proizvodnje VE v HR EES za leto 2013. Modeli z β, WB in γ porazdelitvijo so bili določeni z uporabo Matlabove funkcije »histifit«. Parametri RNPN, NPN in NN modelov so bili določeni z maksimizacijo funkcije verjetnosti, z uporabo diferenčne evolucije, ki je bila uporabljena tudi za določitev parametrov VER modela. Dobljene funkcije gostote verjetnosti so za obravnavane modele ovrednotene z efektivno vrednostjo razlike s funkcijo gostote verjetnosti empiričnega modela (tabela II). β, WB in γ verjetnostne porazdelitve kažejo največja odstopanja, medtem ko so odstopanja najmanjša za model s NPN verjetnostno porazdelitvijo.



Slika 7.2: Funkcije gostote verjetnosti za obravnavane modele porazdelitve napake napovedi proizvodnje VE



Slika 7.3: Zbirne funkcije verjetnosti za obravnavane modele porazdelitve napake napovedi proizvodnje VE

Tabela 7.2: Efektivna vrednost razlike funkcije gostote verjetnosti obravnavanih modelov in funkcije gostote verjetnosti empiričnega modela

β [%]	WB [%]	γ [%]	VER [%]	NN [%]	NPN [%]	RNPN [%]
52	36	45	26	22	19	32

Obravnavani modeli verjetnostne porazdelitve so ovrednoteni tudi z izbranimi percentili; 1%, 5%, 10%, 90%, 95% in 99%. WB porazdelitev za obravnavane percentile odstopa od empirične za približno 15%, podobno tudi β in γ porazdelitvi, vendar samo v levem delu (percentili 1%, 5%, 10%). V desnem delu (percentili 90%, 95%, 99%) znaša odstopanje β porazdelitve med 30 in 40%, odstopanje γ porazdelitve pa kar med 60 in 95%. Tudi odstopanje RNPN porazdelitve je v desnem delu večje in znaša med 20 in 30%, v levem delu pa znaša približno 10%. NPN in NN porazdelitvi najmanj odstopata od empirične, odstopanja obeh so v celotnem področju manjša od 10%. Tudi model z VER porazdelitvijo daje dobre rezultate, saj so odstopanja manjša od 10%, vendar na skrajnem levem robu odstopanja narastejo tudi do 40%, kar je posledica valovitosti empirične porazdelitve.

Tabela 7.3: Izbrani percentili določeni z obravnavanimi modeli

p	β [MW]	WB [MW]	γ [MW]	VER [MW]	NN [MW]	NPN [MW]	RNPN [MW]	emp. [MW]
1%	-105,5	-105	-101	-177	-122	-122,5	-111	-124
5%	-82	-78	-81	-104,5	-85	-85	-81	-93
10%	-67	-62	-68	-73	-65,5	-65,5	-63	-71
90%	48,5	41,5	57	35	39	36	44	36
95%	64	54,5	82	44	49	45	58	46
99%	91	77	130	61	68	70	86,5	67

5 Sklep

Dobljeni rezultati za HR EES v letu 2013 kažejo, da modeli, ki se v literaturi pogosto uporabljajo za verjetnostno porazdelitev napake proizvodnje VE, niso najbolj ustrezni. Predvsem β in γ porazdelitvi v desnem delu izrazito odstopata od empirične porazdelitve. Rezultati, dobljeni z modelom z WB porazdelitvijo, so sicer zelo podobni rezultatom dobljenim z modelom z RNPN porazdelitvijo, vendar so odstopanja od empirične porazdelitve znatna. Boljše rezultate daje VER model, a samo na desni strani porazdelitve. Na skrajnem levem robu so odstopanja velika, kar je posledica valovitosti empirične porazdelitve. Z izbiro ustrezne aproksimacijske funkcije bi bilo možno izboljšati rezultate VER modela. Najboljše rezultate dajeta modela z NN in NPN verjetnostno porazdelitvijo.

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Praktičnost pasovne obnovljive energije v Indiji

KARTHIK SUBRAMANYA BHAT & UDO BACHHIESL

Povzetek Indija se, tako kot mnogo drugih držav po svetu, kjer postaja eden pomembnejših dejavnikov energetska tranzicija s čim manj škode za gospodarstvo. Indijski energetski sektor je zelo ogljično intenziven, saj zagotavljajo 70% celotne proizvedene električne energije v termoelektrarnah na premog. Obnovljivi viri zavzemajo okoli 15% celotne energije. Dostopnost energetov, skupaj s številnimi drugimi dejavniki, predstavlja glavno oviro za prehod v uporabo čiste energije. Zaradi majhnih sezonskih nihanj v porabi električne energije za pokrivanje pasovne energije skrbijo s poceni energijo iz premogovnih termoelektrarn, medtem ko za pokrivanje konic skrbijo plinske elektrarne. Mit, da z obnovljivimi viri ni mogoče zadostiti potrebam po pasovni energiji, se je razširil in sprejel predvsem zaradi nestalne narave obnovljivih virov. V nekaterih študijah je prikazan optimističen prehod na 100% energije iz obnovljivih virov v prihodnjih desetletjih. V energetskem sektorju, ki v večini temelji na ogljiku, kot je to primer v Indiji, je pojem »pasovne energije« velika in močna ovira, saj zagotavljanje pasovne energije predstavlja pomemben dejavnik, ki neposredno vpliva na gospodarstvo države. V prispevku so prikazana razmišljanja, ali je v Indiji mogoče zagotavljati pasovno energijo iz obnovljivih virov, in izzivi, povezani s tem.

Ključne besede: • Indija • pasovna energija • obnovljivi viri • energetska tranzicija • ogljično intenziven •

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Practicality of Base Load Renewable Generation in India

KARTHIK SUBRAMANYA BHAT & UDO BACHHIESL

Abstract India, among several other countries globally, now faces a unique situation where managing the energy transition process without hurting the economic development becomes the highlight of its policies. The Indian power sector is highly carbon intensive, with coal based power providing 70% of the total electricity generated. Renewable energy occupies around 15% of the capacity mix. Energy access along with several other challenges, pose an obstacle to the needed transition to clean energy. As the seasonal load variations in India are not prominent, cheap coal based power supplies most of the load profile, while gas power plants are used for peak loads. The myth that renewable energy sources cannot meet baseload demand has become widely accepted and wide-spread, given their fluctuating nature. Several studies demonstrate an optimistic transition to 100% renewable sources might just be possible in the coming decades. In a carbon-rich power sector like India, the 'base load' mind set is a pretty big and powerful hurdle, as ensuring base load generation becomes a major issue with implications directly affecting the country's economy. In this study, an effort has been made to discuss whether base load renewable generation in India is feasible, and the challenges involved.

Keywords: • India • base load • renewable generation • energy transition • carbon intensive •

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1 Introduction

India is a country globally known for its diversity and size, on the other hand is also known for its energy related emissions. An overview of the primary energy usage deeply highlights the role of fossil fuels, mainly coal and oil. Moreover, the Indian fossil fuel balance shows that there is an import dependency of the country for both coal and oil, implying a direct relation to the country's economy. Most of the electricity in India comes from coal based power plants (up to 60% installed capacity), while renewables in the share are relatively less. Considering the steep increase in annual electricity demand growth and that a large part of the country's population lack electricity access, a large scale capacity expansion is necessary to ensure energy access. India plans to install 175 GW of solar PV and wind power by the year 2025, to achieve complete energy access and to significantly reduce its carbon footprint. Though the plans seem entirely over-optimistic, when and if achieved, it would solve much of the country's energy-related problems. However, having such a high penetration of renewable energy in the energy system leads to many significant problems, and a strategy for effective integration into the system becomes necessary.

'Base load' generation in India since a few decades has been done by coal based thermal power plants, given their reliability and cheap electricity generation prices. In the past, several possibilities for nuclear energy to take up the role of coal in the base load generation were considered, but were not realized as obstacles due to the non-participation in the Non-proliferation treaty and failed attempts to join the Nuclear Supply Group arose. However, the country now has the chance to shift the base load generation from coal based technology to renewable energy, considering the significant capacity expansion goals and available technical potential. Though the mind-set of the country's power sector seems to be inclined towards coal being never replaced by any technology in the near future, many initiatives like subsidy schemes, energy-savings initiatives and other energy efficiency improvement strategies have been proposed, in support of the much needed energy transition. These initiatives ensure lesser demand while in turn also assuring a possibility of large scale renewable electricity generation to take up the role.

2 Base load and base load power plants in India

Base load fundamentally means the load which can be expected throughout the 24 hours in a day, throughout the year. This would mean that the minimum electricity demand of the country over a year would form the base load. In a country with almost 330 million people without continuous access to electricity, base load satisfaction is given the utmost importance, next to only its economic development. India is predominantly focused on building such 'base load' power plants, to secure its minimum electricity requirements. It seems pretty reasonable that policy-makers in India usually have a lot of focus on 'base load' power, as the country's need for a source of 'reliable' power that is available throughout the year is uniquely high. With this special need to ensure sufficient energy supply, after the drastic economic reforms in the early 1990s, an almost continuous addition of coal based capacities has been observed in the country, with every consecutive year [1]. An illustration of the load variation in the year 2011, and the corresponding load duration curve is as shown in the accompanying Figure 8.1., where the base load is highlighted.

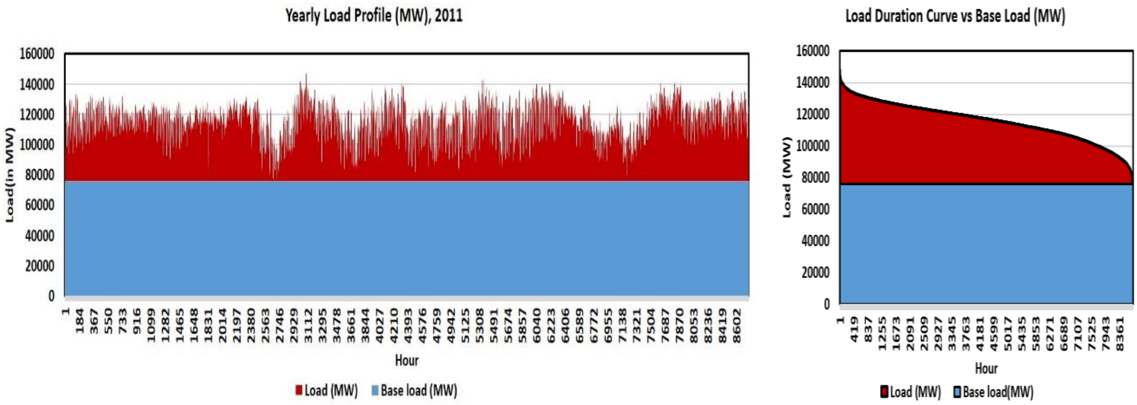
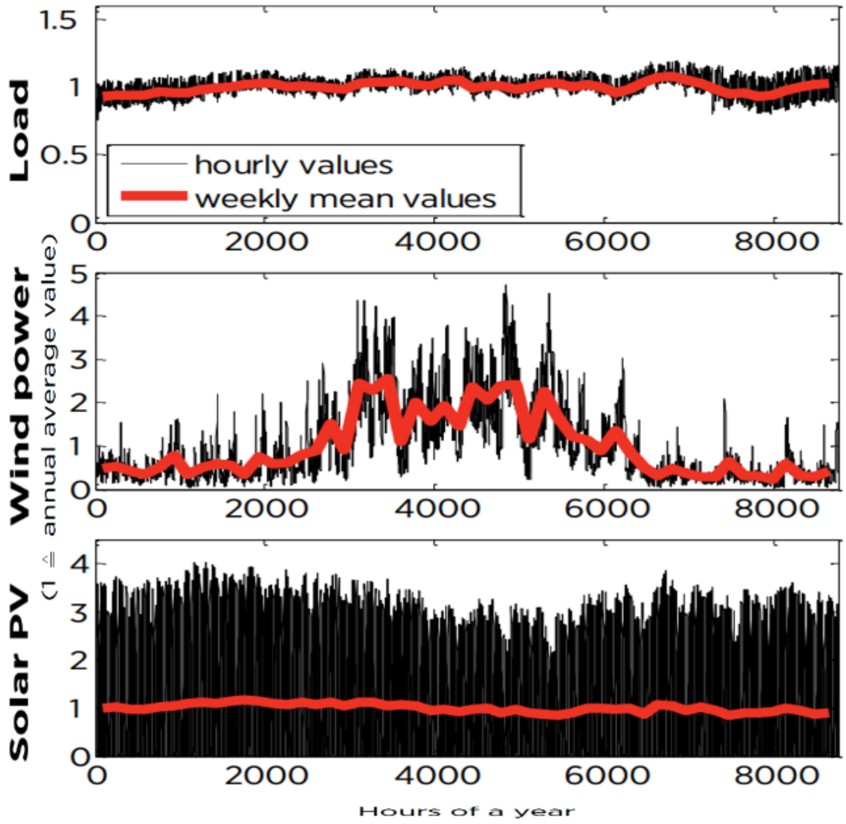


Figure 8.1. Electrical load profile in India for the year 2011

It can be observed that the electrical load in India has no such predominant seasonal variations throughout the year, the base load roughly accounting for around 52% of the yearly peak. This would mean that the base load constitutes for more than half of the total annual electricity demand. The intermediate and the peak loads are usually shared mostly by commercial and industrial sectors, while the industrial and domestic sectors which usually involve continuously operated processes, majorly occupy the base load region. It can also be observed here that the base load is a characteristic of electricity demand, rather than a necessity of the supply side [2].

The base load in India is traditionally covered by the so-called 'base load' power plants such as coal based or nuclear power plants which have higher availability factors and a steadier power output than many other power plant technology. Such power plants are usually characterized by high capital costs and lower variable costs. The intermediate load is usually covered by combined cycle gas plants, and the peak loads by gas and oil power plants. It is generally accepted that these 'peak load' power plants have lower capital costs, but comparably very high variable costs. By the end of the year 2016, India had an installed capacity of 186 GW of coal and 5.78 GW of nuclear thermal power plants. Also, a capacity of 24.5 GW gas and 994 MW of oil thermal power plants is expected to cover the intermediate and peak loads [3] (iv). Recent developments in the energy sector have shown a significant growth in the renewable energy, accounting up to 43 GW (excluding hydro power) of installed capacity. The added renewable capacity constitutes of mainly on-shore wind and solar PV capacities, and a small portion of biomass. A Figure 8.2. illustrates the fluctuating nature, with a comparison of the average load, wind and solar PV temporal variations over a year.



Source: adapted from Ueckerdt et al., 2014.

Figure 8.2. Comparison of average electrical load, wind and solar PV temporal variations in India [2][5]

For now, even with lesser flexibility, the role of the 'base load' power plants is significantly large, due to their constant output. But with a higher share of renewable energy in the future, the Indian power system would require a higher level of flexible interplay [4] between its components. Thus it cannot be completely guaranteed that any technology will run at a high utilization rate or even provide a constant output. Subsequently, the significant role of such base load power plants is more likely expected to decrease. Additionally, as electrical load is inherently variable, the fact that a heterogeneous mix of different generation technologies, by bringing in different degrees of variable costs would be a sensible option, and also be more cost effective with higher flexibility in output.

3 Challenges for renewable energy in the indian energy sector

India must not only change its focus on building base load power plants, but also change its objective in supplying all parts of the load i.e., from base load to peak load, in a cost effective and a much reliable way. When this mind-set is in play, renewable energy technology plays a big part in the realization of such an objective. The already large share of base load power plants, when further increased, might not only cause 'lock-ins', which are observed with power systems dominated by dependence on conventional plants, but could even endanger the required transition towards renewables[2]. Thus, several challenges for renewable energy exists, some of which are identified in this study.

a) Increasing demand and transmission losses: increases the base load value
b) Variable nature of renewables vs the 'base load' mind-set
c) Integration costs of large scale renewable energy

Many countries have similar challenges to the integration of renewable energy, and solutions can be derived from a general comparison of the global electricity sector.

a) Increasing demand and transmission losses

India is characterized by a huge electricity demand growth rate of 6.9% p.a.[1], and this situation elevates the risk of energy scarcity with every consecutive year. This abnormal electricity demand growth is due to the increase in population (consumers) and rapid industrialization. The Government of India (GoI), while only focusing on economic development created by the industry boom, takes up the task of building cheap gas and oil power plants with smaller capital costs but higher variable costs, as a temporary short-term solution. For long term planning, several coal power plants with higher capital costs and much-lower variable costs are proposed. Considering that coal power plants lack the flexibility to ramp at high rates to follow the variable intermediate and peak loads, the expensive gas or oil power plants are also run. This creates a situation where renewable power plants are utilized only to a minimum, and lose their relevance in the energy system.

A viable solution to this problem would be to improve the energy efficiency of the system by introducing several energy efficiency directives in all sectors. This would put a stop to the increasing of the demand, which would in turn, to some extent reduce the inclination of the power sector on coal capacity expansion. Base load is usually created from continuously operated processes, examples include industrial processes like smelting of aluminium, or other residential applications such as lighting, electronic equipment, refrigerators, freezers et cetera. By increasing the energy efficiency, pro-active maintenance and scheduled energy auditing of such processes, the base load value can also be inherently decreased.

Additionally, the efficiency of the distribution networks managed by the state owned distribution companies (DisCom) has been low, resulting in serious losses. In 2013, India's Transmission and Distribution (T&D) losses accounted to almost 23%, and the Aggregate Technical and Commercial losses (AT&C) almost 25.4% [6], must be identified as major problems. In simple terms, this loss rate would mean that the electricity generators would have to generate up to four units of electricity for every three units they sell to their retail and industrial customers. This creates a financially unfavourable situation (v)for the energy utilities due to severe lack of returns on the investment. A significant loss in transmission and distribution could only cause major problems in meeting the on-grid consumer demand, even with the availability of centrally generated power. The Figure 8.3. describes the demand projections and grid losses through the years.

Figure 8.3. Electrical demand increase, grid losses, and the demand shares by sector in India

b) Variable nature of renewable energy sources vs 'base load' mind-set

Based on the nature of electricity generation output, two distinct categories of generation from renewable energy sources can be defined: 'variable' and 'dispatch-able'. While the generation from Variable Renewable Energy (VRE) sources cannot be significantly controlled given the highly intermittent nature, 'Dispatch-able' renewable power generators are able to control their generation output within a given specific range, similar to a conventional fossil fuel power plant. VRE sources include wind and solar irradiation. Reservoir hydropower plants, biomass power plants, and concentrated solar thermal power stations fall in to the dispatch-able category. The integration of dispatch-able renewable power plants normally does not pose any additional challenges to the power system [2]. In a country like India, where the concept of base load power is a significant factor, the VRE integration poses many challenges like geographical source dependency, over production, energy storage requirements and unreliability of power supply. Thus, a transformation towards renewables requires a rethinking of the concept of base load power plants in India

Comparing with the so called 'base load' power plants, power systems with a combination of VRE and dispatch-able renewable power plants could prove to be a feasible solution. VRE power plants could never cover base load power demands at all times. But this should not be considered as a disadvantage, since just covering the base load should not be the objective of the country. It must also be noted that the variability of VRE is the highest for an individual power plant, but when different VRE plants of the same type are combined across the country, the overall variability decreases considerably. Several countries have already proved that a mix of renewables can reduce the variability. In Germany, solar PV and off-shore wind power generation have been shown to complement each other due to opposite seasonal variations. Similarly, hydro power and wind energy complement each other in Brazil, where wind generation is at its peak during the dry season and hydro generation during the rainy season is at the maximum. The Figure 8.4. shows the nature of the average seasonal variation of the availability solar PV, off-shore wind and hydro power sources in India, in a year. The complementary nature is not easily observed, so a hybrid system including the conventional power plants have to be planned. Also, to avoid the stranding of the already available conventional fossil fuel power plant assets, a hybrid system has to be operated, to ensure both energy access and financial security of the private energy sector in India.

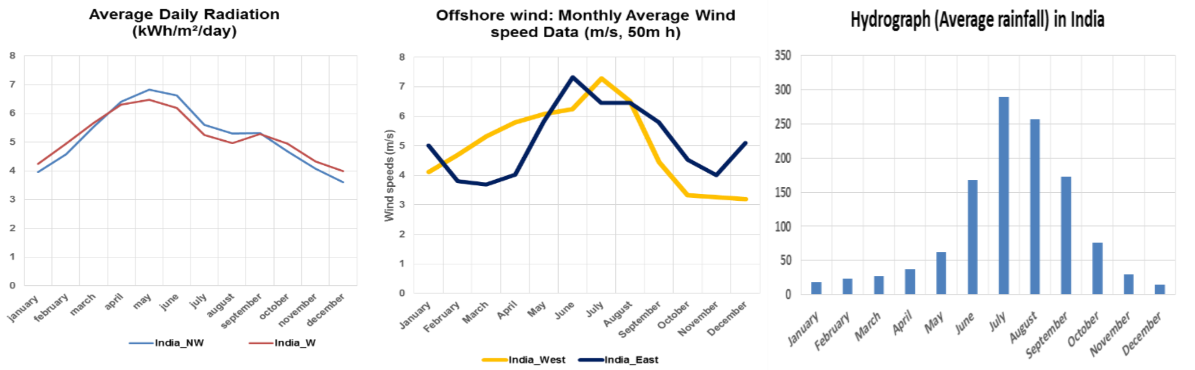


Figure 8.4. Seasonal variation of availability of solar PV, off-shore wind and hydro graph of India

Thus, as a solution, India must look at the options of a hybrid power system, with a generous mix of VRE, dispatch-able renewable energy and conventional power plants with high flexibility and relatively lower variable costs.

c) Integration costs of large scale renewable energy

Though India's interest in large scale renewable energy integration developed in the last few decades, the GoI has ambitious plans in this sector. After the Climate Change Conference in Paris 2015, the GoI revised its plans to increase its solar capacity fivefold from its initial target of 20 GW to an optimistic target of 100 GW by the year 2022. 75 GW of wind power has been planned to reach its renewable targets of 175 GW by 2022. Currently, around 7 % of the total electricity produced is from renewables (i)(ii). Wind energy in India is already considered competitive, as the Levelized Cost of Electricity (LCoE) from wind power was almost same or less than that from the fossil fuel. However, the LCoE from solar power was 11.79 % higher than imported coal in 2015 [7]. The cost is expected to decrease over time due to technological learning effects that drive the solar prices down while fossil fuels become more expensive. Solar power is projected to be cheaper than imported coal based power in 2019. The Figure 8.5. shows the calculated forecast for LCoE from imported coal, solar energy and wind energy in India.

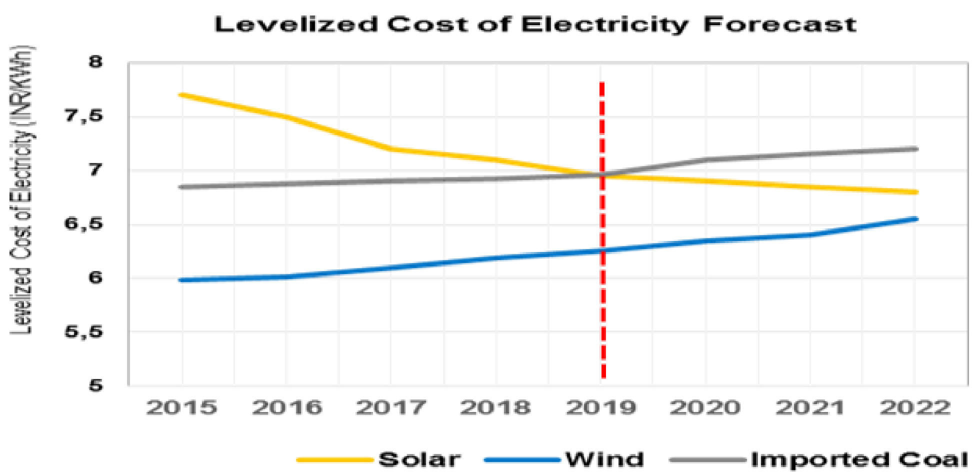


Figure 8.5. Levelized Cost of Electricity generation from coal, wind and Solar PV in India

A large scale integration of VRE power plants also inflicts so-called integration costs at the system level [9] [10]. These integration costs are just additional costs on the power system due to the integration of such power plants with uncertain and less predictable availability. Normally, VRE integration costs are low or even sometimes negative, when their share in the system is low [2]. This could mean that the integration would save costs on a system level. With higher shares of VRE integration, the concerned challenges technical obstacles due to fluctuation tend to decrease, but the integration costs are expected to increase. Due to the temporal variability of such sources, they cannot be relied upon during the peak load times. Thus, a considerable scale of renewable capacity would also need a considerable share of back up technologies like energy storage, and back-up conventional power plants. Unfortunately, energy storage is a relatively expensive option, which makes the integration less effective. The geographical dependency of VRE sources also create a need for investments in transmission and distribution networks, which also needs a lot of initial capital.

The level of integration costs of VRE is usually highly dependent on the characteristics of the power system involved. Thus, a solution for such an integration problem would be to make the Indian power sector to 'VRE friendly' by investing in flexible generation plants, strengthening the grid and flexible demand i.e., Demand Side Management (DSM). Also, the introduction of regulatory frameworks and innovative grid operation protocols could significantly reduce the integration costs by harnessing the potential for technical flexibility. To effectively reduce the system integration costs, it is necessary to shift from capital intensive base load power plants like coal power plants, to intermediate and peak load plants with higher flexibility and lower capital costs to complement the high VRE shares.

4 5-Point Check list as a solution

After the discussion and consideration of the challenges for renewable generation in the country, a unique five point check list is proposed in an effort to effectively strategize large scale renewable capacity expansion in India. These points in the checklist not only reflect the present situation of the country, but also provide an overview of the future of the electricity sector in India.

1. Energy Efficiency directives and Demand Side Management

Energy efficiency outside the power generation sector could effectively decrease the power demand by almost 20% [3] (vi), which means one unit in five could be shut down without any major repercussions. This would also act as a stop to the highly increasing demand growth rate, and would lessen the dependency on base load power plants. Demand Side Management would not only decrease the integration costs of the VRE power plants, but also encourage the consumer to play his part in the energy transition of the sector. Energy efficiency improvement should be given utmost priority, given the increasing nature of the country's overall electricity demand. India has already introduced energy efficiency directives for the domestic sector [11], and should focus on improvement of efficiency in the industrial and commercial sectors.

2. A more responsive power sector to improve transmission and distribution

The T&D and AT&C losses could not only severely hamper India's strategy to battle energy accessibility, but on a system level, add up to the increasing demand. Improvement and expansion of the transmission network should be considered also as a high-priority task, as a support to the large share of location specific VRE power plants in to the system. Meeting each of India's renewable energy integration challenges also depends on improving the efficiency of the transmission and distribution grids.

3. Investments in Peak and Intermediate load power plants

To significantly reduce the integration costs of VRE, and to provide flexibility to the generation side of the power system, the investments on Peak/Intermediate load power plants have to be encouraged. Such power plants need lesser capital than base load power plants like coal and thermal, and can be installed almost in any location, near the load centers. However, care must be taken to ensure cleaner operation of such power plants.

4. Distributed VRE generation, hand in hand with large scale renewable generation

Along with large scale VRE installations, small scale distributed VREs like urban rooftop PV, PV for agricultural use and wind installations in rural areas also have to be encouraged. Since the availability of solar irradiation almost everywhere in the country is evenly distributed, and that VRE technologies like Solar PV can be effectively integrated into urban infrastructure, the increase in awareness and encouragement towards such technologies have to be done, possibly by introducing lucrative support schemes

5. Promotion of energy efficient urbanization

Since almost half of India is considered yet to be built, an intelligent strategy for efficient urbanization has to be implemented. This not only helps decrease the increasing demand, but also helps effectively integrate VRE technology. Also, introduction of smart grids and electro-mobility [11] in developing areas could also be effective, as to support DSM initiatives and improved grid response when controlling the grid. Developing towns can be assigned Renewable Power Obligations (RPO) which would ensure that any new power plant built in this area would have to integrate a certain level of renewable power.

5 Conclusion

A brief study of the challenges involved with renewable integration in India provides us with an insight on whether the 'base load' renewable generation in the country is practical or not. Simply put in terms, the concept of 'base load' power plants have to be changed, for a transition in the Indian power sector. Also, for a sustainable renewable generation, India has to consider a hybrid system, renewables along with intermediate/peak load power plants, to be free of the base load mind set. Overall, it is definitely possible for India to replace its base load power plants with renewable energy, albeit with a diverse renewable portfolio (with both dispatch-able and VRE power plants). India's power system in the distant future would possibly be a combination of a high share of dispatch-able (hydro power and biomass), VRE (solar PV and Wind), and a significantly smaller share of combined cycle power plants

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Development Scenarios for E-Mobility in Europe

UDO BACHHIESL & NIKOLAS KORDASCH

Abstract This paper presents development scenarios for e-mobility in Europe. The analysis of the initial situation shows, that key factors such as climate change or dependence on oil in the mobility sector call for a promotion of e-mobility globally and in Europe. This development is influenced by given targets in the European Union regarding alternative mobility. Furthermore, the fundamental aspects of e-mobility like the advantages and disadvantages or the different types of vehicles are introduced. With the help of recent sales numbers the European EV market has been divided into battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) and has been analysed in detail for each country for the years 2011 to 2015. Based on this data, an in-depth research on the countries' promotion and support measures regarding e-mobility has been conducted. The global e-mobility targets (IEA2DS, IEA4DS, Paris Declaration) are converted into European targets and in relation to these targets three different scenarios (LOW, MEDIUM and HIGH) have been developed. These scenarios describe the growth of the EV market from 2016 to 2030 and are based on the actual numbers of EV. In addition, by using predefined average values for the EV the power consumption of the EV has been calculated and put in relation to the overall power consumption of the countries for every year until 2030. Concluding a summary of the present supporting measures of the investigated European countries for EV will be given in this paper.

Keywords: • e-mobility • Europe • development scenario • BEV • PHEV •

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1 Introduction

The energy economical world will have to change in the future in order to fight the ongoing climate change. A major cause for the climate change is the rising concentration of manmade greenhouse gases (GHG) in the atmosphere, mostly coming from burning of fossil fuels. Within the different GHG carbon dioxide (CO_2) plays beside of methane an important role. Figure 9.1 shows a comparison of the different major sources of CO_2 emissions on a global level and in Austria.

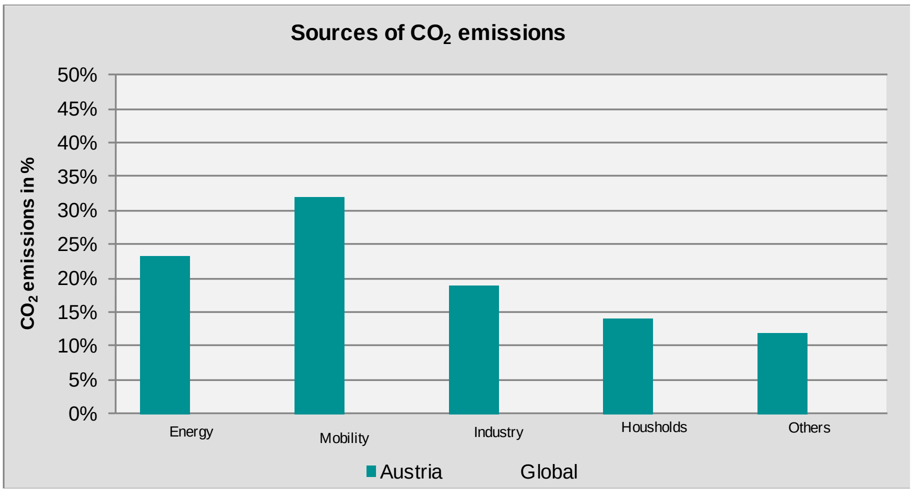

Figure 9.1. Sources of CO_2 emissions [1]

Figure 9.1 shows that at the global scale the energy sector is responsible for about 45 % of the CO_2 emissions, followed with nearly one quarter coming from the mobility sector and followed by industry and households. In Austria - because of the big share of electricity coming from hydropower plants - the situation differs and the mobility sector is with 32 % of the overall CO_2 emissions in the lead followed by the energy sector with 23 %. This short analysis shows, that the mobility sector will have to play an important role, if we want to reduce the CO_2 emissions substantially. The emissions will not remain stable at the present level, because it is to be expected, that especially the mobility sector is still growing rapidly especially in the BRICS (Brazil, Russia, India, China, South Africa) countries. Also according to the United Nations Framework Convention on Climate Change, 21st Conference of the Parties (COP21) it is expected that the emissions in this sector will rise about 20% up to the year 2030 and about 50% up to the year 2050. [2]

In the case of Austria, the emissions from the mobility sector account for about one third of the overall emissions of 67,9 million tonnes CO_2 equivalent, which corresponds to 32 million tonnes CO_2 equivalent. [3] Fig 2 shows the composition of the GHG emissions in Austria in 2014 and it can be seen that CO_2 emissions account for 85 % followed by the CH_4 emissions with 7 %.

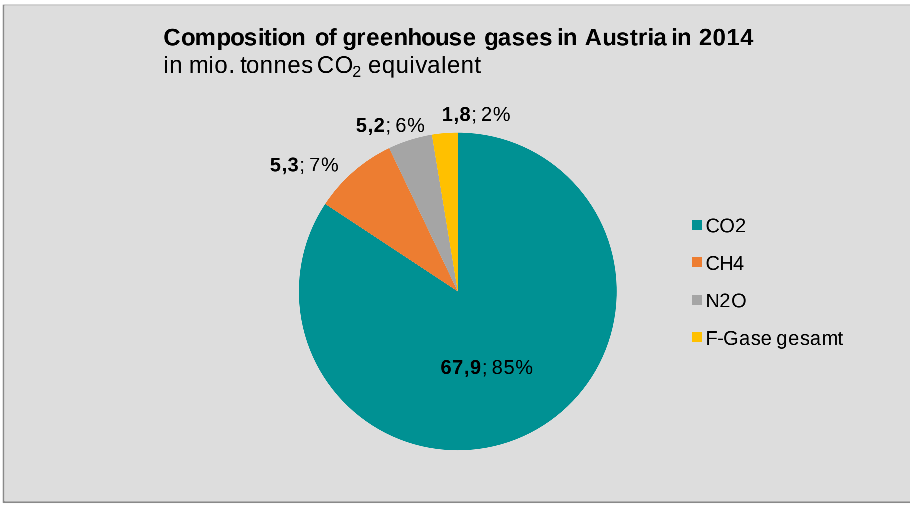

Figure 9.2. Composition of GHG emissions in Austria in 2014 [3]

Since several decades the world community has tried to react against the mentioned development, starting in 1979 with the first world climate conference and the following signature of the United Nations climate treaty in 1992. 1997 started the implementation of the Kyoto protocol which entered into force in 2005 and should cover the period from 1990-2012 but since a replacement treaty has been missing it has been prolonged to 2020. In 2015 the UN climate conference took place in Paris and the agreement has been signed by 175 states in April 2016 and with the coverage of 55 states and 55% of the global emissions it went into force in November 2016. The agreement should lead to a limitation of the global warming below 1,5°C, a complete decarbonisation until 2045-2060 with no burning of fossil fuels and 100% electricity from renewables from 2040 on.

As shown before the mobility sector is highly relevant for reaching the desired targets. One future option is the large-scale introduction of EV with an electricity supply based on renewable energies. Within the EU legislation exist different targets regarding the mobility sector, some of indirect and some of direct manner. The indirect targets cover the present targets of the energy strategy up to the year 2020 regarding GHG reduction (40%), the share of renewable energy (27%) and the improvement of energy efficiency (27%). As long term target a reduction of the GHG emissions of 80 to 95% up to the year 2050 has been settled. Direct targets are e.g. covered by the white book mobility of the European Commission [4]. The goals of the white book cover a bisection of the conventional vehicles for city logistics up to 2030 and up to the year 2050 no more conventional vehicles in the city logistics. There also exist passages within the Paris declaration on electro-mobility and climate change. According to calculations of the International Energy Agency (IEA) at least 20% of the fossil fuel based transport sector has to be switched to e-mobility in order to reach the 2 °C target. The overall share of EV has to reach 35 % up to the year 2030.

2 Fundamentals of E-Mobility

As has been shown in the first chapter, it will be only possible to reach the climate targets if we are able to reduce the emissions from the mobility sector worldwide. Figure 9.3 shows the average CO_2 emissions of new passenger cars in Europe and although the emission limits have been reduced since the last decades this measure alone will not be sufficient enough.

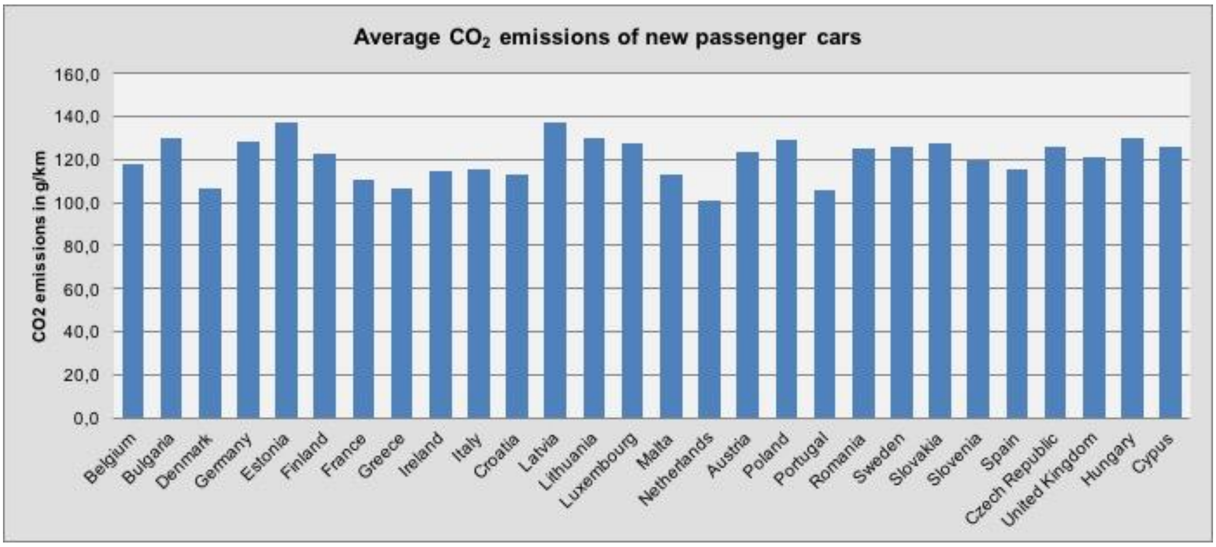

Figure 9.3 Average CO_2 emissions of new passenger cars in Europe

There are several alternatives for the future mobility which comprise biofuels, super ethanol, natural gas and CNG, hydrogen, hybrid concepts as well as pure EV. This paper focuses on EV and following some of the major advantages of EV will be given:

- Energy efficient drivetrain
- Reduction of local emissions
- Loudness
- Torque
- Simplicity of drivetrain
- Cheap operation and maintenance costs

Although there are several advantages one has to consider also the disadvantages of e-mobility and some of them are listed below:

- High initial investment costs
- Range
- Charging time
- Loudness

There are different options for using electricity in the mobility sector like Mild Hybrid Electric Vehicle (MHEV), Full Hybrid Electric Vehicle (FHEV), Plug-in Hybrid Electric Vehicle (PHEV), electric cars with range extender, Battery Electric Vehicles (BEV) or Fuel cell (FC) cars. Table 9.1 gives an overview of different properties of the mentioned driving options.

Table 9.1: Properties of different alternative propulsion systems

Type	Model	Power		Battery	Charging	Consumption	CO2 emission	Range		Price*
		Electric	Gasoline					electric	total	
		[kW]	[kW]	[kWh]		[l / 100 km]	[g/km]	[km]	[km]	[€]
Mild-Hybrid (MHEV)	Mercedes S 400	20	225	1	recup.	6	139	-	-	98550
Full-Hybrid (FHEV)	Toyota Prius	53	72	1,3	ICE, recup.	3	70	2	-	29900
Plug-In Hybrid (PHEV)	Toyota Prius PH	18	72	5	230V, recup.	2,1	49	30	-	37920
Range Extender	Opel Ampera	115	63	16,5	230V, ICE	1,2	27	40 - 80	500	38400
Battery electric vehicle (BEV)	Mitsubishi i-MiEV	49	-	16	230V, recup.	-	0*	160	160	34000
	Tesla Roadster	183	-	53	230V, recup.	-	0*	200-300	200-300	128000
Fuel Cell (FC)	Mercedes B (F Cell)	65	-	1,4	FC, recup.	3,3	0**	400	400	-

* if using renewable energies for electricity production

** produces H2 emissions

ICE…Internal combustion engine, FC…Fuel Cell, recup…Recuperation

Figure 9.4 shows the CO_2 emissions of the mentioned alternative driving technologies, assuming that the directly used electricity for charging comes from renewable energies without causing CO_2 emissions.

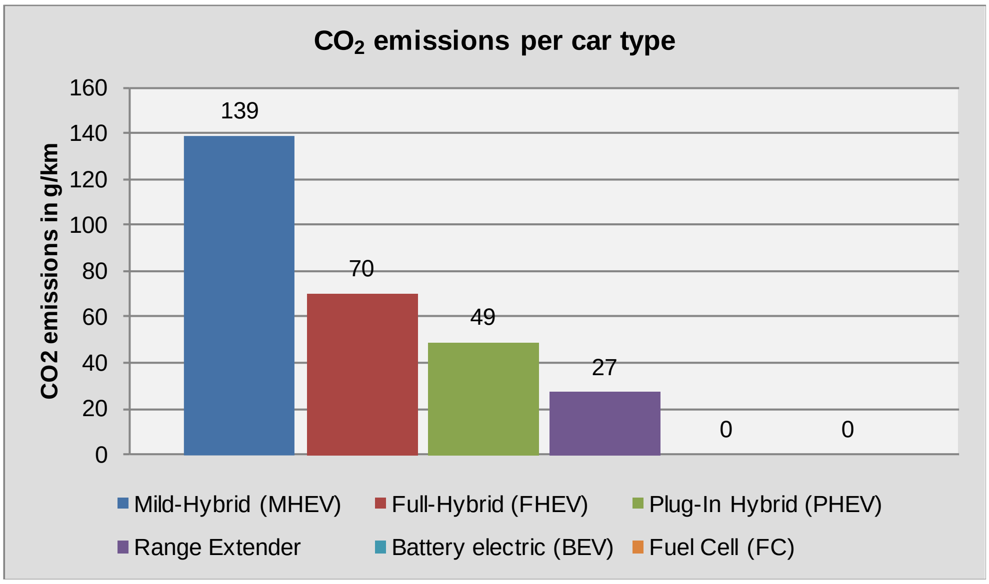

Figure 9.4 CO_2 emissions of the compared alternative driving technologies

3 Status of E-Mobility in Europe

This chapter gives an overview of the status of e-mobility in Europe. The analysis has been done for every single European country and is based on many different national sources and complemented by some general publications. Those publications are e.g. the “Global Electric Vehicle Outlook 2016” of the IEA [5], data from the European-Alternative Fuels Observatory Homepage [6] and permission data of the European Automobile Manufacturer Association [7]. The status in the single countries is very different reaches from nearly 0% to 2% and therefore the countries have been divided into two groups with less than 0,1% and more than 0,1% of market share. The result of this analysis is given in Table 9.2.

.

Table 9.2 Overview of the e-mobility status in Europe

EUROPE 2015					
	BEV	PlugIN	Total EV	Licensed	Market share
Liechtenstein	0	0	0	0	0,00%
Hungary	0	0	0	3.671.663	0,00%
Bulgaria	10	7	17	3.605.000	0,00%
Romania	31	47	78	5.915.630	0,00%
Turkey	119	108	227	15.143.756	0,00%
Poland	157	249	406	24.476.852	0,00%
Lithuania	29	20	49	2.151.813	0,00%
Caprus	4	29	33	583.692	0,01%
Greece	126	252	378	6.423.343	0,01%
Latvia	59	13	72	764.422	0,01%
Croatia	113	48	161	1.605.927	0,01%
Italy	3.802	1.256	5.058	41.905.560	0,01%
Czech Republik	623	179	802	5.766.175	0,01%
Slovakia	193	144	337	2.343.922	0,01%
Malta	56	5	61	324.360	0,02%
Spain	4.045	1.434	5.479	26.954.473	0,02%
Slowenia	193	67	260	1.174.723	0,02%
Portugal	1.215	711	1.926	5.635.860	0,03%
Finland	507	988	1.495	3.853.008	0,04%
Ireland	837	135	972	2.265.940	0,04%
Germany	29.374	18.519	47.893	48.202.108	0,10%
Belgium	3.582	3.924	7.506	6.391.644	0,12%
Austria	4.380	1.765	6.145	5.209.228	0,12%
United Kingdom	20.875	28.117	48.992	37.608.358	0,13%
France	43.863	9.023	52.886	38.521.667	0,14%
Estonia	1.053	25	1.078	780.016	0,14%
Luxembourg	541	224	765	425.571	0,18%
Switzerland	6.120	3.965	10.085	4.916.609	0,21%
Denmark	6.697	532	7.229	2.815.552	0,26%
Sweden	4.766	10.890	15.656	5.253.288	0,30%
Island	682	235	917	261.710	0,35%
Netherlands	9.970	78.260	88.230	9.342.400	0,94%
Norway	58.097	10.154	68.251	3.189.187	2,14%
Total	**202.119**	**171.325**	**373.444**	**317.483.456**	

In 2015 there have been in sum 202.119 BEV and 171.325 PHEV on the road in Europe which totally represents an overall share of just about 1%.

Aside the concrete numbers given in Table 9.2 Figure 9.5 shows a graphical representation of the results. In order to get a better overview, the classification has been redefined into five sections which are shown in different colours in the graph.

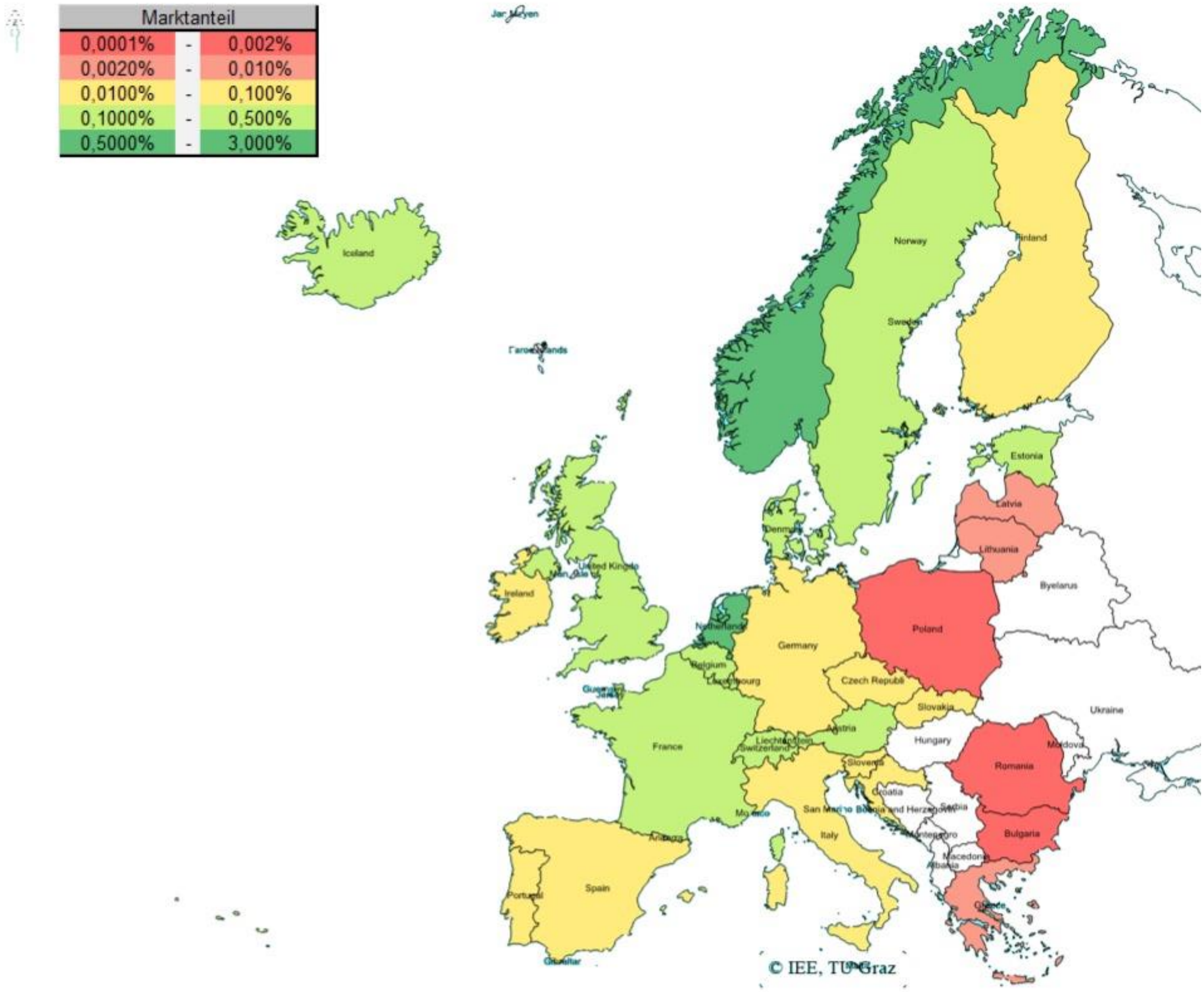

Figure 9.5 Graphical representation of the e-mobility shares in Europe

Summing up Figure 9.6 shows the cumulative development of EV in Europe between the year 2011 and 2015. In 2015 there have been already about 373.444 EV on the road in Europe, which is compared to the overall number of licensed cars still a small number, but marks the starting point for the future development of e-mobility in Europe

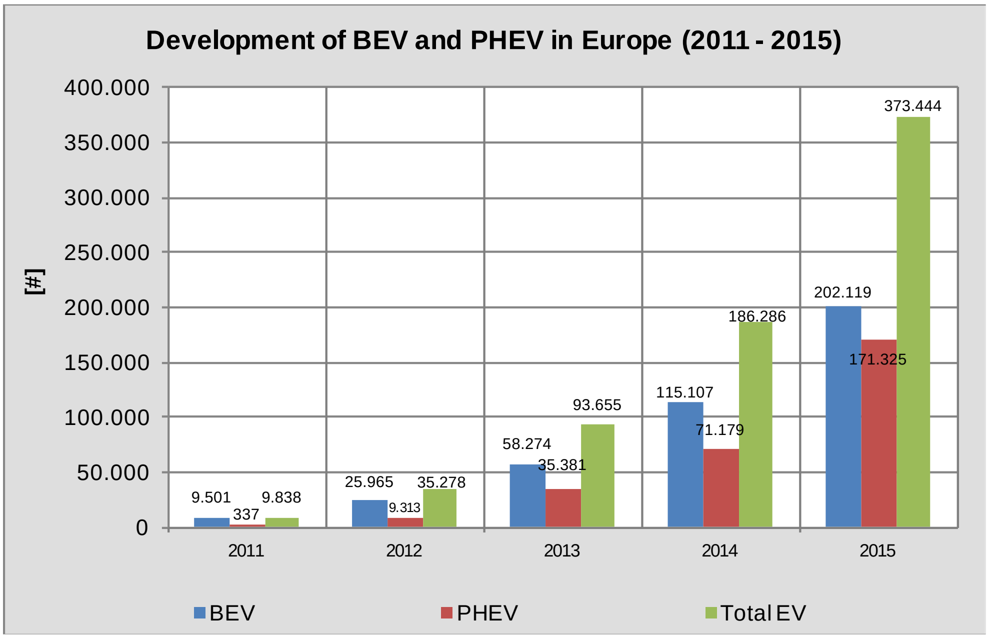

Figure 9.6 Development of EV in Europe 2011-2015

4 Scenarios for the Development of E-Mobility in Europe

Based on the investigation of the actual situation in Europe presented in chapter 0, this chapter deals with the future perspectives of e-mobility in Europe. A country based overall scenario for whole Europe does not exist so far in the literature and in order to adjust the developed scenarios, they are oriented on the global scenario from the IEA (see Figure 9.7) which includes also a path pointing in the direction of the goals of the afore mentioned Paris Declaration.

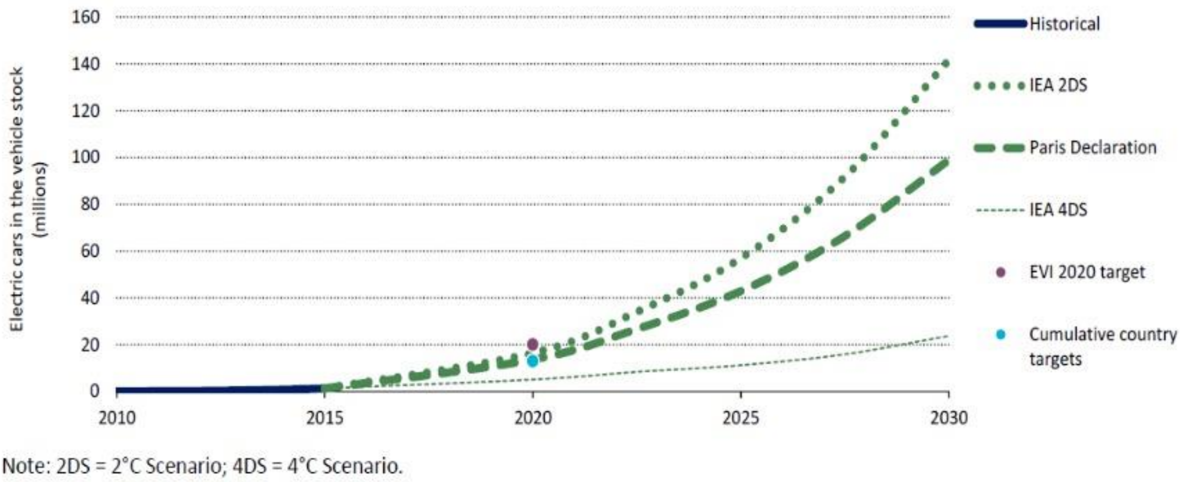

Figure 9.7 Global EV Scenario [6]

The IEA defined three different paths to 2030: The first scenario covers the needed EV in order to remain below 2°C global warming (100 million EVs), the second below 4°C (23 million EVs) and the third scenario describes a path in direction of the goals of the Paris declaration (100 million EV). This global scenario from the IEA forms the basis for the European scenario and it can be seen, that approximately 31% of the global market corresponds to Europe. Figure 9.8 shows the e-mobility goals for Europe based on the IEA scenario.

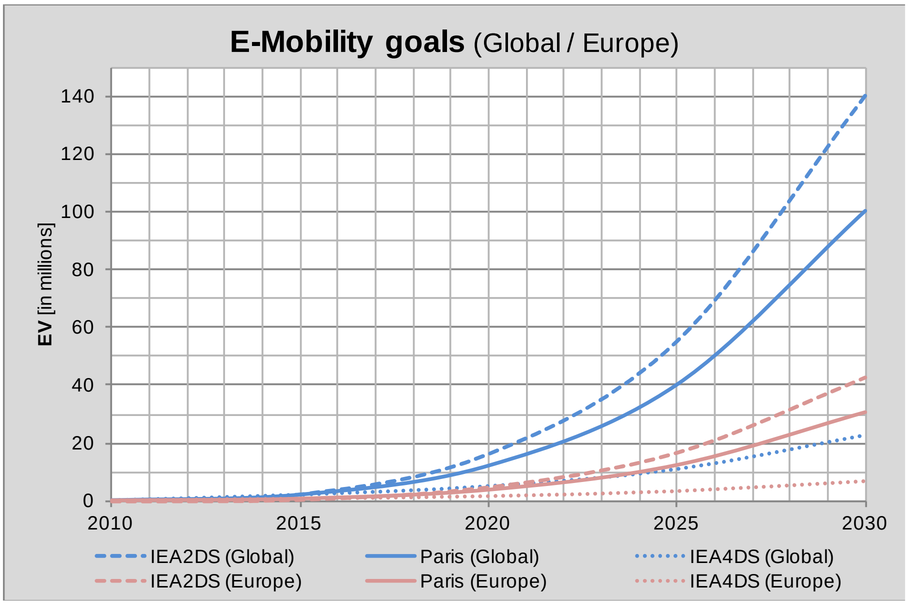

Figure 9.8: E-mobility goals for Europe based on the IEA scenario

Based on the derived boundary conditions for Europe up to the year 2030 three different scenarios have been generated: low, medium and high. The starting values have been taken from the presented investigations in chapter 0 and the development up to the year 2030 is based on the afore presented target values. Figure 9.7 shows the resulting values for Europe in the three different scenarios and shows also the percentage of the EVs in relation to the amount of totally running vehicles in 2030 (app. 382 million):

- Scenario LOW: In 2030 roughly 7 million EV will be seen in Europe corresponding to app. 1,8% of the European market
- Scenario MEDIUM: The target value for this scenario is 30 million EV in 2030 which corresponds to about 7,9% of the overall European market.
- Scenario HIGH: This scenario shows 43 million EV in Europe which equals 11,3% of the whole vehicle market.

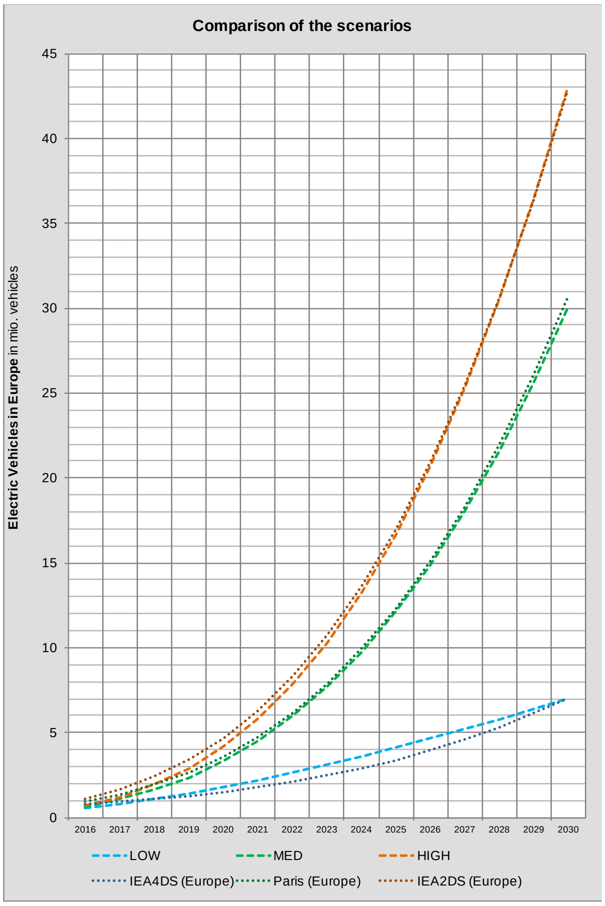

Figure 9.7 Overview of the derived scenarios

Regarding the energetic considerations some basic assumptions have been defined. Table 9.3 and Table 9.4 show an overview of present BEV and PHEV with their associated values. The tables also include the market share of the different models and based on those numbers a weighted average has been calculated, which is the basis for the following calculations.

Table 9.3 Data of present models BEV

Average values for BEV							
Ranking	Producer	Model	Distribution	technical data: electricity consumption	share driven electric	Battery capacity	Electric range
				kWh/100km	%	kWh	km
1	Renault	Zoe	27,35%	7,3	100	22	300
2	Nissan	Leaf	25,14%	16,9	100	27	160
3	Tesla	Model S	16,02%	16,0	100	85	530
4	Volkswagen	e-Golf	9,39%	12,7	100	24,2	190
5	BMW	i3	5,80%	11,0	100	33	300
6	Kia	Soul EV	4,97%	12,7	100	27	212
7	Mercedes	B250e	3,59%	14,0	100	28	200
8	Volkswagen	e-Up!	3,31%	13,4	100	18,7	140
9	Peugeot	iOn	2,49%	10,7	100	16	150
10	Citroen	C-Zero	1,93%	10,7	100	16	150
weighted average				**12,7**	**100%**	**34,3**	**271,4**
				kWh/100km	%	kWh	km

Table 9.4 Basic data for the PHEV reference car

Average values for PHEV									
				technical data					
Ranking	Producer	Model	Share	electricity consumption	fossil fuel consumption	share driven electric	Battery capacity	Electric range	Total range
				kWh/100km	l/100km	%	kWh	km	km
1	Mitsubishi	Outlander PHEV	24,81%	24,0	2	6%	12	50	800
2	Volkswagen	Golf GTE	12,92%	19,8	6	5%	9,9	50	939
3	Volkswagen	Passat GTE	11,89%	19,8	1,7	5%	9,9	50	939
4	Volvo	XC90 PHEV	11,63%	23,0	2,1	5%	9,2	40	850
5	Mercedes	C350e	9,82%	20,0	7	4%	6,2	31	850
6	Audi	A3 e-Tron	7,49%	18,3	1,7	5%	8,8	48	940
7	BMW	X5 40e	5,94%	29,0	10	4%	9	31	800
8	BMW	330e	5,43%	47,0	3,3	2%	10,8	23	1000
9	BMW	i3 Rex	5,17%	24,4	7	30%	22	90	300
10	BMW	225xe	4,91%	19,0	2	5%	7,6	40	800
weighted average				23,3	3,8	6%	10,4	45,8	840,7
				kWh/100km	l/100km	%	kWh	km	km

Based on the number of EV in the different scenarios and the definition of basic data for BEV and PHEV reference cars the needed electricity consumption has been calculated. In order to get a better overview of the value for the single countries, the calculated energy consumption for the EV is set in relation to the overall consumption of the regarded country. Figure 9.10 shows the results of the calculations and shows the share of electricity for EVs in relation to the total consumption per country for the three different scenarios. Based on the initial situation of the regarded countries the development is very different.

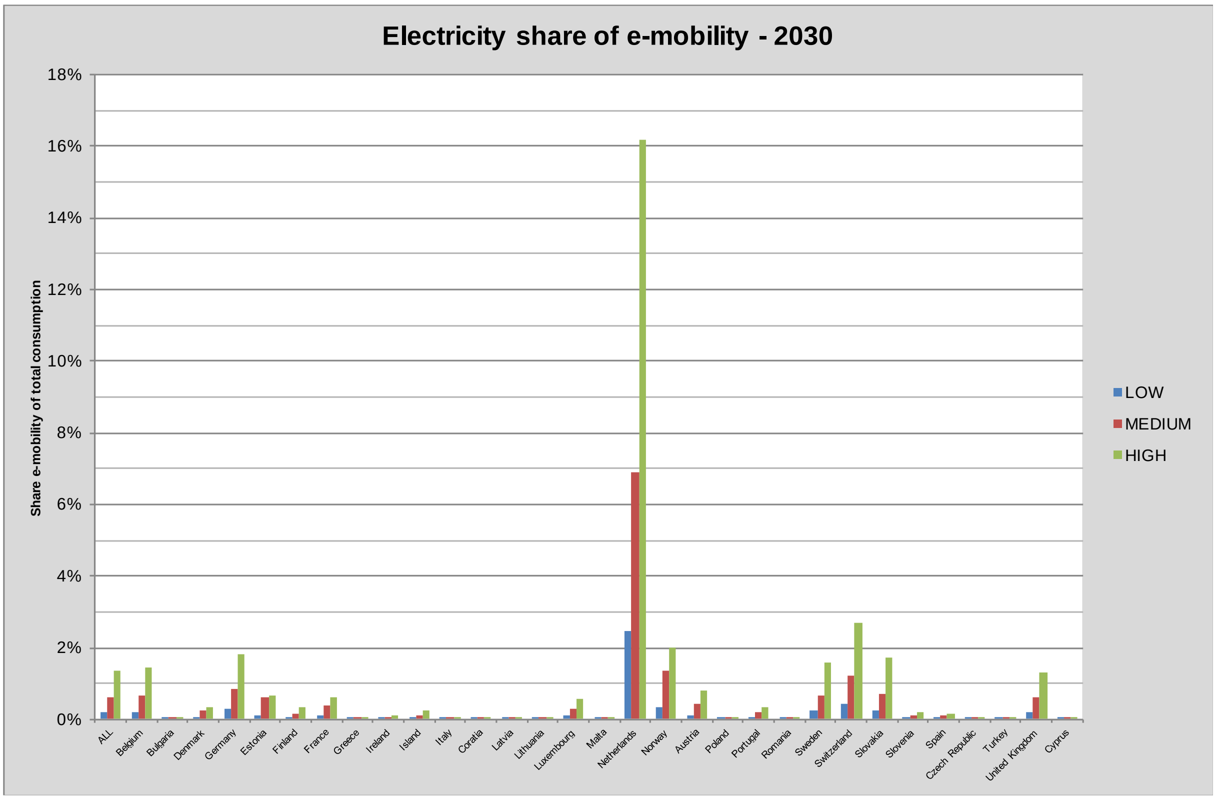

Figure 9.10 Share of electricity for e-mobility compared to total electricity consumption in 2030

Due to the fact, that EV hold already a prominent position in the Netherlands and it has been assumed that the Netherlands will follow this encouraged path also in the future.

5 Promoting Measures for E-Mobility

One key aspect for the future development of e-mobility concerns barriers and promoting measures. Within this work all European countries have been analysed regarding the status and future targets for e-mobility. A further aspect dealt with existing promotional measures as well as barriers in the different countries

Table 9.5 gives a summary of the different supporting measures, which exist in the different European countries at the moment.

Table 9.5 Overview of promotional activities for e-mobility

Category	Description
Support for the acquisition of vehicles	- Bonus in different heights - Saving of value-added tax - Often differences between BEV PHEV - BEV support often higher - Support often capped with list price - Scaling according CO_2 emission - Sharing of support between national an federal level
Cost of permission	- No cost for both BEV and PHEV - Sometimes just BEV exempt from permission cost - Reduction of permission cost - Scaling of permission cost according CO_2 emissions
Taxes on cars	Private consumer - no car tax for BEV - sometimes time limit for exception (5-10a) - Reduction for BEV - No engine based tax for BEV - No tax for BEV, 505 reduction for PHEV Companies - Tax deductibility for commercial vehicle - Scaling of tax according to CO_2 emission - No Tax for commercial vehicles - Other tax privileges
Local incentives	- Free parking or reserved parking lots - Usage of bus lanes - No road charges for towns - No road charges for highways
Infrastructural incentives	- Support for the erection of infrastructure - Public support for the building of fast battery chargers on main routes - Support for private chargers - Support for the installation of general charging points
Other incentives	- No import taxes or reduces import taxes

6 Conclusions and Outlook

In order to takle the future energy economic challenges – especially regarding the climate change – the mobility sector along with the energy sector will play an important role. Projections show, that the mobility sector is still growing, especially in the BRICS countries.

During the climate conference in Paris in 2015 (COP21) many countries agreed to fight against climate change and to present according measures. There are several options for the mobility sector like biofuels, hydrogen, but at the moment a strong tendency towards electro mobility can be seen. Electro mobility alone will not be the solution, but it offers the opportunity for reducing the carbon footprint in using renewable energies for producing the needed electricity. This paper gives a brief overview of the global situation and scenarios for EV and then focuses on the situation and development paths for Europe. The basic research comprised an in deep analysis for every single European country with a special focus regarding the situation of EV, supporting measures and the electricity demand. Due to limited available room within a paper the presentation of the results of every single country review is not possible, but the summarising figures are presented. Based on these analyses and already existing targets for e-mobility (e.g. IEA or Paris declaration) three development scenarios (low, medium, high) for the share of EV in the European countries have been built. Based on the present development state and the applied supporting measures in the different countries the scenarios show a distinguished development in the single countries. The range reaches from countries with an already remarkable share of EV and BEV like Netherlands and Norway to countries with very small amount of EV on the road like the Baltic states. The target values in the different scenarios for 2030 reach in the LOW-scenario from 7 million EV (app. 1,8% market share) and in the MEDIUM-scenario 30 million EV (app. 7,9% market share) to the HIGH-scenario with 43 million EV (app. 11,3% market share). Based on the derived scenarios a calculation of the needed additional electricity consumption for the EV has been done and the results have been presented in relation to the electricity consumption of every single regarded country. The last section of this paper presents a summary of the different promotional activities based on the single country analysis and lists further barriers which have to be overcome in order to reach the goals for e-mobility.

Summarising it can be stated that there are promising developments going on in the field of e-mobility in Europe but there are still some challenges (battery technology, range, loading infrastructure, vehicle cost, power management) to solve for the integration of a high amount of EV.

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Izzivi trajnostne rabe fosforja

DEAN ČERNEC

Povzetek Večanje števila prebivalstva in porabe hrane zahtevata vedno večje količine fosforja. Še do nedavnega je veljalo prepričanje, da je zalog fosforja dovolj še za mnogo prihodnjih generacij. Na podlagi dognanj v zadnjih letih pa postaja jasno, da so zaloge fosfatne rude kot glavnega vira fosforja omejene. Pričujoči prispevek povzema te ugotovitve in predstavi možne alternative pridobivanja fosforja iz tokov odpadnih produktov.

Ključne besede: • fosfor • trajnostna raba • odpadni produkti • fosfatna ruda • mineralna gnojila •

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Challenges in Sustainable Use of Phosphorus

DEAN ČERNEC

Abstract With the increasing world population growth a global demand for food is increasing rapidly. Until recently phosphate rock deposits were not thought of being a finite reserve and extracting phosphorus from this rock seemed to be the ultimate source of phosphorus for the future generations. But on the basis of new findings it has become evident that these reserves cannot last forever. This article summarizes some of these findings and presents some alternative ways of phosphorus recovering from waste streams.

Keywords: • Phosphorus • sustainable use • waste products • Phosphate rock • mineral fertilizer •

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1 Uvod

Najpomembnejši nutrienti, potrebni za rast rastlin, so dušik, kalij in fosfor. Čeprav jih povezuje dejstvo, da brez njih ne uspeva (in tudi ne zraste) nobena rastlina, se njihov izvor in zaloge precej razlikujejo. Medtem ko je dušika na pretek že v atmosferskem zraku (78% delež), lahko sledi kalija in fosforja najdemo povsod, kjer je ali je bilo prisotno življenje. Vendar pa te zaloge še zdaleč ne dosegajo porabe, ki jo terja sodobno poljedelstvo. Pretežni del porabe teh dveh mineralov se zato pokriva z izkopavanjem zalog, ki se nahajajo v kamninah, tleh in sedimentih, pri čemer pa gre za relativno omejene vire. Rezerve kalija so velike, pri fosforju pa se po nekaterih raziskavah že približujemo višku izrabe razpoložljivih zalog (ang. peak phosphorus), ki bi ga lahko dosegli že v nekaj desetletjih. Pri tem velja omeniti, da je navkljub dobri medijski izpostavljenosti nekaterih okoljskih problematik (v povezavi s poljedeljstvom sta v ospredju predvsem poraba in onesnaževanje vode), zavedanje o zmanjševanju zalog fosforja prisotno več ali manj le v akademskih krogih in še ni doseglo širše javnosti.

Kot že omenjeno, se fosfor danes pridobiva predvsem z izkopavanjem fosfatne rude oziroma s fosfatom bogatega minerala apatita, zaloge pa bi po nekaterih ocenah lahko izčrpali že v naslednjih 50 – 100 letih. Pri tem so mišljene zaloge tistih nahajališč, ki so dovolj bogata z vsebnostjo fosforja in je zato pridobivanje ekonomsko upravičeno (fosfor je sicer enajsti najbolj pogost element v zemeljski skorji, a bi bila izraba v mnogih primerih zaradi nizkih koncentracij nesmotrna). Fosfor je v zemeljski skorji prisoten povsod po svetu, obsežnejša in bogata nahajališča apatita pa so predvsem v Maroku, Zahodna Afriki, Kitajski, ZDA in Jordaniji. Omenjene države so tudi največji izvozniki fosfatne rude. Zaloge fosfatne rude v Evropi so siromašne, omembe vredna pa so predvsem nahajališča vulkanskega izvora na Finskem.

2 Kroženje fosforja in mineralna umetna gnojila

V geokemičnem smislu je naravno kroženje fosforja eden najpočasnejših ciklov. Ob tektonskih premikih so s fosforjem bogate kamnine izpostavljene vremenskim vplivom in preperavanju. Erozija tal in kemično preperevanje omogočata nastanek prsti, ki jo reke odnašajo v nižine, jezera in oceane. Del teh fosfatov porabijo rastline, ki jih s pomočjo svojih korenin absorbirajo iz tal in jih vežejo v organske spojine, vezani fosfati pa se nato skozi prehranjevalno verige vračajo v tla na več načinov (z živalskimi in človeškimi iztrebki, odmrlimi rastlinami, odpadlim listjem, živalskimi kadavri,...). Sledi proces sedimentacije oziroma kopičenje fosforja organskega in mineralnega izvora v sedimentih. Cikel se ponovi, ko so na novo nastale sedimentne kamnine z dvigovanjem površja spet izpostavljene mehanizmu preperevanja.

V predindustrijski družbi so bili procesi pridelave, predelave in porabe hrane med seboj tesno povezani in so se odvijali v istem življenskem okolju (tam, kjer se je hrana pridelovala, se je tudi porabljala). Fosfor, ki se je porabil za rast pridelkov na poljedelskih površinah, so nadomeščali z načrtnim kolobarjenjem in z uporabo s fosforjem bogatih naravnih gnojil, svoj delež pa so prispevale tudi redne rečne naplavine. Odpadni produkti (gnoj, gvano, iztrebki, ostanki pridelkov,...) so bili torej glavni dejavnik izboljšanja rodovitnosti obdelovalnih površin.

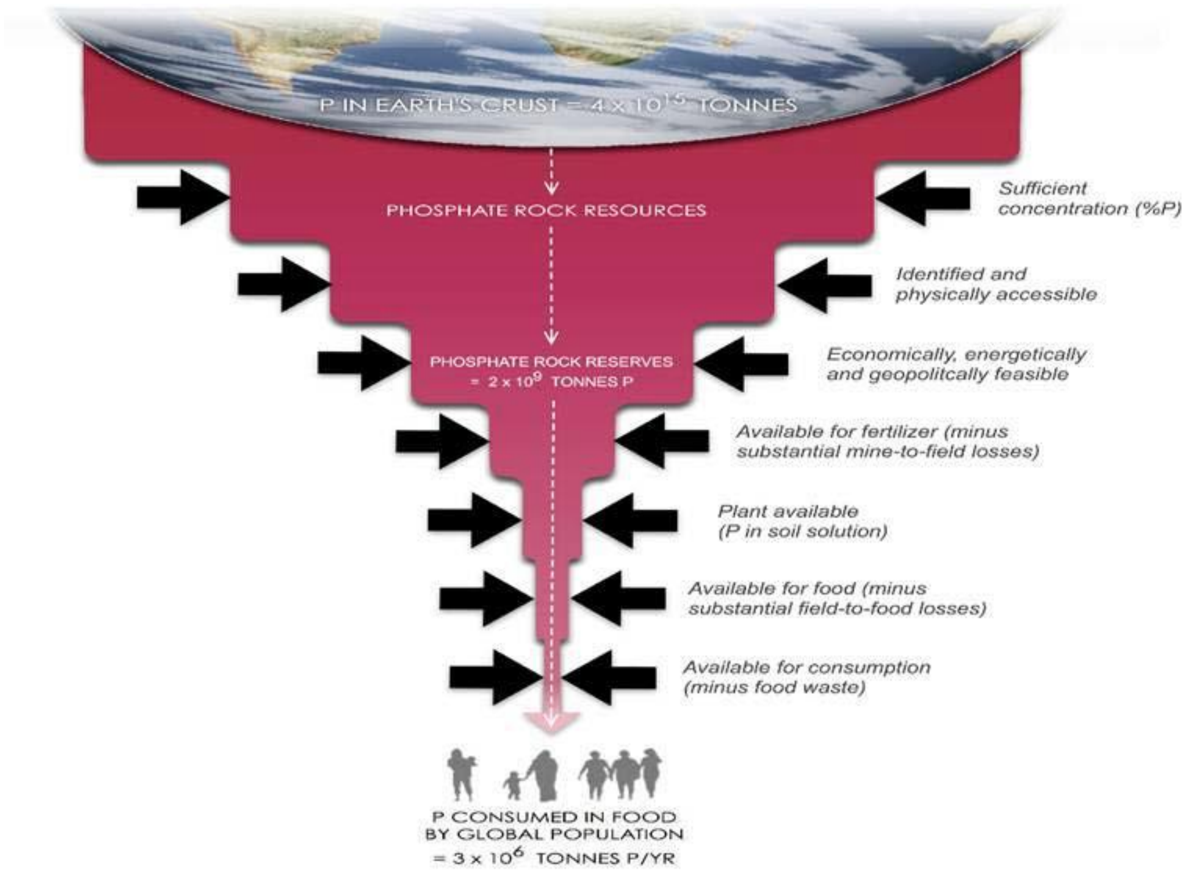
Uvedba umetnih mineralnih gnojil pa je omogočila lažje nadomeščanje fosforja v osiromašenih tleh po spravilu pridelkov. S tem se je, gledano splošno, v precejšnji meri zmanjšala raba naravnih gnojil kmetijskega in komunalnega izvora. Mineralna gnojila so omogočila pridelavo večje količine pridelkov, obenem pa je poljedelstvo začelo postajati dejavnost, ki prostorsko ni bila več nujno povezana z živinorejsko dejavnostjo. To se je še posebej močno odrazilo v razvitem svetu in potreba po mešanem kmetijstvu se je drastično zmanjšala. Ena od posledic je bil nastanek centrov intenzivne živinoreje v bližini gosto naseljenih področij. Uvoz hrane in krmil iz drugih držav je samo še dodatno zmanjšal povezavo med poljedelstvom in živinorejo, kar je rezultiralo v presežnih količinah živalskih iztrebkov in ostalih odpadnih produktov. Količine le-teh so se zaradi intenzivnosti posameznih dejavnosti zvečale do te mere, da jih okoliške obdelovalne površine niso mogle več v celoti absorbirati.

Uporaba umetnih gnojil ni omogočila samo intenzivnejše pridelave in specializacije kmetijskih dejavnosti, temveč je s tem omogočila tudi porast človeške populacije in obilnejše prehranjevalne navade. Žal se je v tem procesu vse manj odpadnih produktov vračalo na obdelovalne površine. Hlevski gnoj, na primer, marsikje sploh ni bil več obravnavan kot dragocen in pomemben vir fosfatov, ki se ga lahko uporabi za obogatitev obdelovalnih površin. Od te točke naprej uporaba naravnih gnojil in mešano kmetijstvo nista bila več nujni pogoj za pridelavo hrane.

Dandanes je pridelava hrane močno odvisna od fosfatnih gnojil, alternativnim virom fosforja pa se še ne posveča dovolj pozornosti. Ta miselnost lahko postane kmalu nevarna, saj so zaloge apatita, ki predstavlja glavni vir fosforja v umetnih gnojilih, kljub vsemu omejene. Prepričanje o samoumevni dostopnosti do hrane, ki je trenutno prisotno v razvitem svetu, bi se z zmanjšanjem zalog fosfatne rude lahko v prihajajočih desetletjih močno omajalo. Če upoštevamo še geopolitično situacijo, ugotovimo, da se glavnina rezerv realno razpoložljive fosfatne rude nahaja le v peščici držav, ki lahko iz takšnih in drugačnih razlogov narekujejo in spreminjajo tržno ceno rude ter njenih derivatov (nazadnje so cene fosfatne rude v letih 2007 in 2008 poskočile v štirinajstih mesecih kar za 700 %). Pri tem velja omeniti tudi to, da ne glede na sorazmerno velike rezerve fosfatne rude le-ta ni povsod enako kvalitetna. V tem pogledu povzroča skrb predvsem vsebnost težkih kovin. Navadno so v fosfatni rudi prisotne sledi kadmija, koncentracija le-tega pa je odvisna od izvora kamnine, ki vsebuje fosfatno rudo. Fosfatna ruda vulkanskega izvora ima na primer zelo nizko vsebnost kadmija, medtem ko je v fosfatni rudi v sedimentnih kamninah ta vrednost precej višja. Z uporabo fosfatnih gnojil se torej lahko povečuje vsebnost kadmija v obdelovalnih površinah, kar povzroča nove težave. Seveda bodo v prihodnosti postale tudi tehnologije za odstranjevanje kadmija ekonomsko sprejemljivejše in bi ta element iz rude lahko odstranili, a to v kontekstu širše problematike in iskanja celostne rešitve v zvezi z uporabo fosfatne rude in mineralnih gnojil ne predstavlja bistvenega napredka. Vsa navedena dejstva namreč kažejo na to, da bi kmetijstvo v prihodnosti moralo postati manj odvisno od uporabe mineralnih fosfatnih gnojil.

3 Razpoložljivost zalog fosfatne rude

Ne glede na pogostnost fosforja v zemeljski skorji, se le majhen delež tega pojavlja v takšnih koncentracijah, ki upravičujejo pridobivanje fosfatne rude za uporabo v mineralnih gnojilih in drugih proizvodih (npr. fosforjeva kislina se uporablja tudi v industriji brezalkoholnih pijač, v proizvodnji pralnih praškov,...). Za nameček so bogata nahajališča fosfatne rude pogosto fizično nedostopna (na dnu oceanov) ali pa vsebnosti težkih kovin v rudi presegajo mejne dovoljene vrednosti. Vse našteto zelo zoži izbor nahajališč, ki omogočajo izkopavanje visoko kvalitetne in lahko dostopne fosfatne rude. Slika 1 prikazuje stopnje izgube fosforja v verigi porabe od ocenjenih zalog v zemeljski skorji do dejanskih razpoložljivih zalog za predelavo ter vse do končnega zaužitja hrane.



Slika 10.1: Izgube fosforja v verigi porabe preden se zaužije s hrano

Iz navedb na Sliki 10.1 je razvidno, da na razpoložljivost fosforja za proizvodnjo mineralnih gnojil in s tem hrane kot končnega produkta, vplivajo mnogi fizikalni, ekonomski, socialni in ekološki dejavniki. Zanimivo je tudi, da apatit oz. fosfatna ruda sodi med bolj pogoste in dobro drobljive primarne minerale, a je fosfor kljub temu od vseh najpomembnejših nutrientov biološko najmanj dostopen. Litosfera (zemeljska skorja) je namreč temeljni vir fosforja v biosferi, fosfati, v obliki kovinskih soli fosforjeve kisline, pa so v vodi slabo topni in jih je zato v vodi, ki jo rastline črpajo iz tal, razmeroma malo. Ker fosfatna ruda ni obnovljiv vir, bodo bogata nahajlišča v prihodnosti vedno redkejša. S tem se odpirajo mnoga vprašanja v zvezi s trajnostno rabo fosforja, ki pa jih je potrebno zastaviti v širšem kontekstu, saj se v verigi izgubljanja fosforja izgubljajo tudi drugi viri. Predvsem so tu pomembne energetske izgube in potrošnja vode pri proizvodnji fosforjeve kisline, obenem pa tudi izgube v kasnejših predelovalnih dejavnostih. Pri tem je potrebno upoštevati tudi obremenjujoče vplive na okolje, še zlasti vnos fosforja v hidrosfero in pojav evtrofikacije.

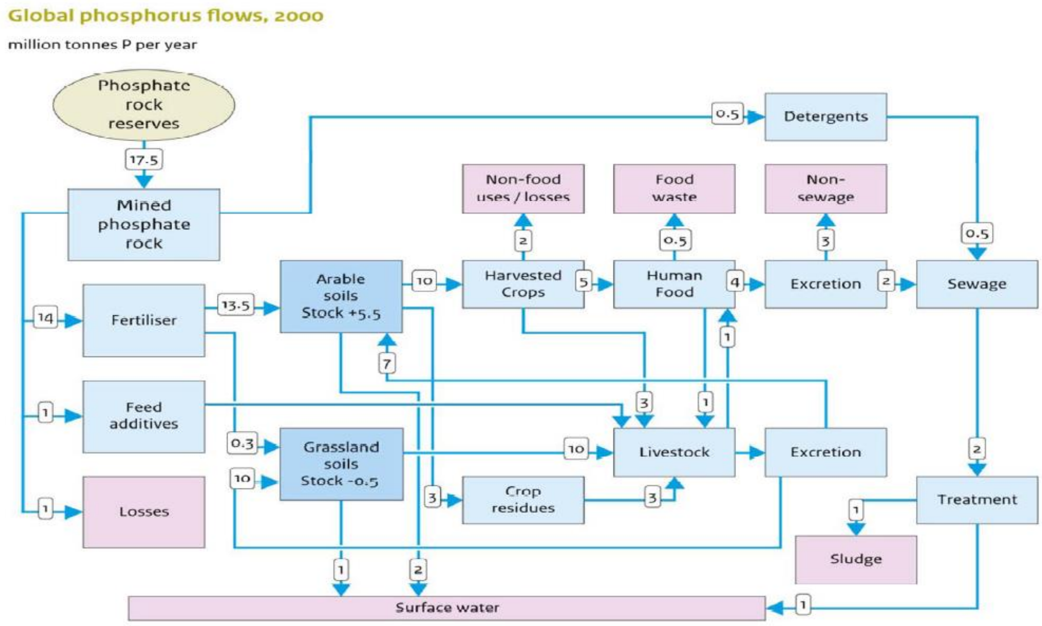
4 Okoljski vplivi izkopavanja fosfatne rude

Izkopavanje fosfatne rude je proces, ki se odvija na velikih površinah, saj gre v glavnem za dnevne kope. Po izkopavanju se iz rude najprej odstranijo nečistoče. Ta proces vključuje različne separacijske metode kot so presejanje, izpiranje, separacija v hidrociklonih, flotacija in magnetna separacija. Tu gre za obsežne faze čiščenja z velikimi kapacitetami, pri katerih se porabi veliko energije in vode, nastajajo pa tudi velike količine stranskih produktov (npr. mulj, ki vsebuje glino, silikati, ki se ločijo pri flotaciji,...). Na lokacijah, kjer je omogočena uporaba cenovno ugodnega zemeljskega plina, se v pečeh izvaja tudi kalcinacija fosfatne rude, da se odstranijo nečistoče organskega izvora. Naslednja faza zajema pretvorbo fosfatne rude v fosforno kislino, pri čemer sta v uporabi dva postopka: kemični in termični. Večina fosforjeve kisline ali superfosfata se proizvaja na prvi način, pri katerem fosfatna ruda reagira z žveplovo kislino. Če namesto žveplove uporabimo dušikovo kislino, dobimo nitrofosfat, v primeru uporabe fosforjeve kisline trojni superfosfat (TSP), z dodajanjem amoniaka pa še monoamonijev fosfat (MAP) in diamonijev fosfat (DAP). TSP, MAP in DAP so mineralna gnojila, ki danes obvladujejo svetovni trg. V procesu pretvorbe fosfatne rude v fosforjevo kislino, se v velikih količinah pojavlja še en stranski produkt – fosforjeva sadra, ki je nizko radioaktivna. Sadra se skladišči v ogromnih skladih ob nahajališčih fosforjeve rude in le majhen odstotek (~ 15%) se je uporabi naknadno v kmetijstvu in gradbeništvu.

Tudi glineni mulj, ki nastaja v fazi čiščenja rude, vsebuje toksične deleže urana in radija in se kot tak ne sme vračati v okolje. Odpadni glineni mulj se zato odvaja v umetna jezera, kjer se delci posedajo in nabirajo na dnu. Negativni vpliv umetnih jezer na okolje se kaže predvsem v prestrezanju določene količine naravnih padavin, saj je s tem oviran proces obnavljanja vodnih zalog v površinskih vodotokih in podtalnici. V primeru, da dno takšnega jezera začne puščati in toksične snovi pridejo v stik z okolico, pa sta lahko resno ogroženi flora in favna v okoliških rekah.

Intenzivno kmetijstvo, ki je daleč največji porabnik proizvodov, katerih osnovna surovina je fosfatna ruda, je poleg kanalizacijskih in določenih industrijskih odplak tudi najpogostejši izvor prekomerne vsebnosti fosfatov v vodnih telesih. Glavni mehanizem prenosa fosforja iz obdelovalnih površin v površinske vode je erozija tal, na območjih, kjer so tla nasičena s fosforjem, pa je za onesnaženje voda dovolj že izpiranje tal. Iz okoljevarstvenega vidika gre tu za dva med seboj povezana problema. Prvi je prekomerna vsebnost fosforja v zemlji, ki sicer ne zavira rasti poljščin, a vpliva na biotsko (ne)raznolikost ekosistema, drugi pa je onesnaženje vodotokov. Povečana koncentracija anorganskih hranil, kot so fosfati in nitrati, je namreč v jezerih, ribnikih in obalnih morjih gonilna sila evtrofikacije (t.j. prekomerne rasti vodnega rastlinja, še posebej alg).

Nevarnost pri uporabi mineralnih gnojil predstavlja tudi vsebnost težkih kovin, predvsem kadmija, ki se ga iz zemlje ne da preprosto odstraniti, ga pa iz zemlje črpajo rastline oziroma poljščine, ki jih gojimo na obdelovalnih površinah. Na »kontaminiranih« področjih lahko tako v sončnicah in oljni repici zaznamo povečano količino kadmija.



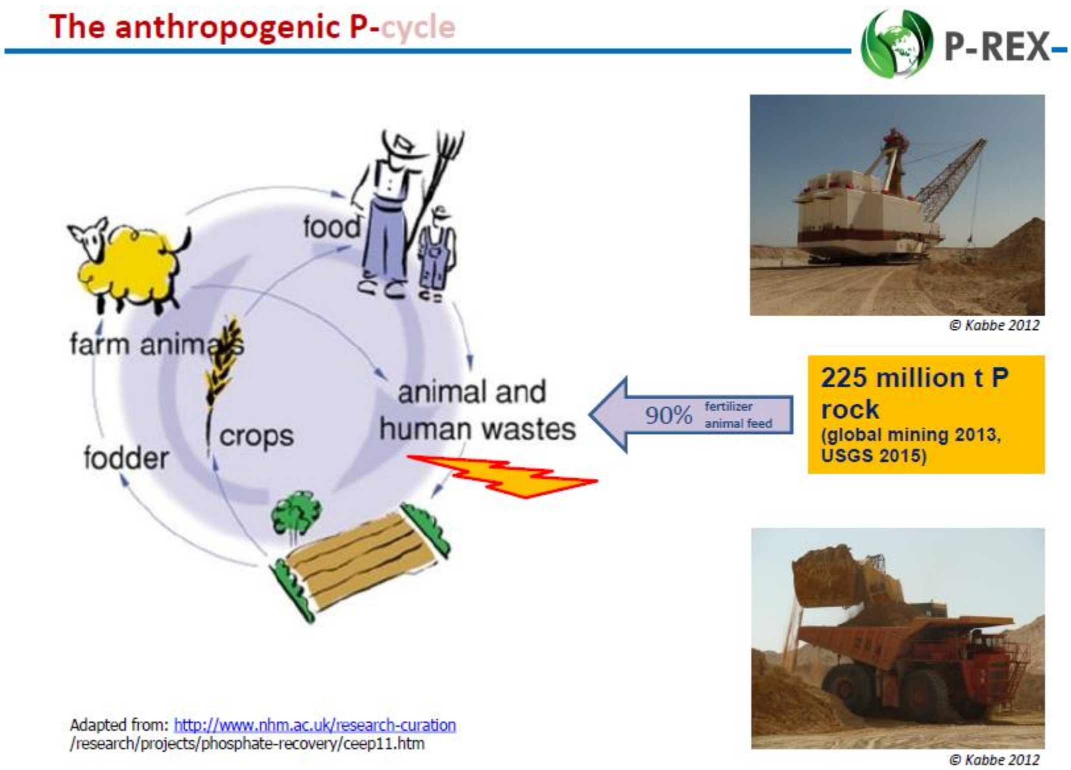
Slika 10.2: Svetovni fosforjevi tokovi v milijonih ton P na leto

Slika 10.2 prikazuje svetovne fosforjeve tokove, pri čemer so upoštevani prehrambena veriga, kmetijska industrija in kanalizacijski sistem.

5 Alternativni viri fosforja

»Peak phosphorus« oziroma višek izkopavanja fosfatne rude, ki ga po nekaterih ocenah napovedujejo že v naslednjih 50 letih (čeprav bi po drugih ocenah lahko nastopil šele čez 300 let) je potrebno razumeti manj kot nevarnost in bolj kot vzpodbudo k raziskovanju in uvajanju novih tehnologij ter načinov ponovne uporabe fosforja. Usihanje najbolj dostopnih virov fosfatne rude sicer predstavlja potencialno nevarnost (zvišanje cen, politični pretresi,...), a to še ne pomeni, da bi človeštvo takoj ostalo brez virov fosforja (z napredovanjem tehnologij v rudarstvu bi na primer že izkopavanje siromašnejše fosfatne rude lahko nadomestilo primanjkljaj na tržišču). Tu gre predvsem za to, da se s povečanjem raznovrstnosti virov fosforja zagotovi enakomernejša svetovna in regionalna porazdelitev tega temeljnega nutrienta. Ker se trenutno približno 90 % vse izkopane fosfatne rude na svetu porabi za krmila in gnojila (Slika 10.3), torej za proizvodnjo hrane, tudi ne moremo iskati možnosti glede zmanjševanja njene porabe (razen, ko gre za potrato; na primer pretirano gnojenje z mineralnimi gnojili ali neskrbno, nemarno ravnanje s hrano). Zaključimo lahko, da je porabo fosfatne rude ob nespremenjeni skupni porabi fosforja možno omejiti in ustaliti edinole z uporabo alternativnih virov fosforja (npr. recikliranje in raba fosforja organskega izvora). S takšnim pristopom, ki ima učinke tako na globalnem kot na regionalnem nivoju, omejimo obseg energetsko zelo potratnega izkopavanja in transporta fosfatne rude, obenem pa v regijah, kjer so zaloge fosfatne rude majhne (npr. EU), zmanjšamo vnos težkih kovin »tujega« izvora v »domača« tla ter zaradi povečane samooskrbe iz alternativnih virov zagotovimo večjo varnost oskrbe s fosforjem, ki je povezana z nestanovitnostjo cen in političnimi razmerami v svetu.

Ker je antropogeno kroženje fosforja, ki zajema pridobivanje osnovne surovine (fosfatne rude), uporabo na poljih in živilski industriji ter porabo hrane z nastankom odpadnih produktov, dandanes zelo neučinkovito, so učinkovitejša raba, recikliranje in zmanjševanje odpadnih produktov postali predmet mnogih raziskav, ki bi v bližnji prihodnosti lahko pripomogle k uvajanju trajnostne rabe fosforja.



Slika 10.3: Antropogeno kroženje fosforja (90 % fosfatne rude se porabi za gnojila in krmila)

Pri trajnostni rabi fosforja iščemo odgovore na široko zastavljena in kompleksna vprašanja, ki jih je potrebno obravnavati celostno in interdisciplinarno. Če želimo v prihodnosti učinkovito zaključiti antropogeni fosforjev cikel, bo v splošnem potrebno ukrepati na treh ravneh: na izvoru (izkopavanje fosfatne rude), pri uporabi (učinkovitejša raba gnojil ter ohranjanje, zadrževanje fosforja na obdelovalnih površinah) ter pri ravnanju z odpadnimi produkti (zmanjšanje količin le-teh in reciklaža).

5.1 Učinkovitejše pridobivanje fosfatne rude

Učinki velikega povečanja cen fosfatne rude v letu 2008 so vidni tudi v pozitivnem smislu. Po ponovni ustalitvi cen so se vlaganja v panogo povečala, to pa je omogočilo povečanje učinkovitosti v nekaterih rudnikih. Uvedle so se številne tehnološke inovacije v povezavi z izgubljanjem osnovne surovine kot tudi pri obdelavi stranskih produktov. Izvedlo se je veliko ukrepov, ki so bili namenjeni zmanjšanju porabe energije in vode. Zaradi zaostrovanja zahtev glede vsebnosti težkih kovin (tu prednjači EU), se je povečala tudi čistost proizvodov. K napredku je prispevalo tudi zavedanje, da zaloge niso omejene in da je optimalnih zalog vedno manj. Tudi preglednost različnih vrst gnojil se je zaradi boljšega označevanja izboljšala. Ukrepi se navezujejo tudi na omejavanje fosfatov in fosforjevih spojin v pralnih sredstvih.

5.2 Učinkovitejša raba in zmanjševanje izgub v kmetijstvu

V poljedelstvu se učinkovitost rabe fosforja navezuje predvsem na njegovo prisotnost v tleh, da ga lahko poljščine črpajo za svojo rast, ter z nezaželjenim odnašanjem in izpiranjem v površinske vode. Pomebno je, da imajo rastline na razpolago dovolj fosforja v vseh fazah rasti, kar pomeni, da mora biti v zemlji na razpolago t.i. kritična raven fosforja, vendar pa ni dobro, če ga je preveč. Današnja raba mineralnih gnojil nosi pečat kmetovalnih praks, ki so se razvile še v času cenovno ugodnih mineralnih gnojil ter slabše okoljevarstvene zavednosti in osveščanja. Stvari se izboljšujejo na podlagi različnih programov in strategij za varstvo tal, vodotokov ter uvajanja sodobnih metod kmetovanja (npr. vbrizgavanje gnoja v tla, uporaba ustrezne količine in vrste gnojila ob primernem času, preverjanje ravni fosforja v obdelovalni zemlji,...), več naporov pa se vlaga tudi v zmanjševanje izgub fosforja zaradi erozije, ki jo povzočata veter in voda. K ohranjanju tal veliko pripomore tudi intenzivnejše kolobarjenje, učinkovitost uporabe gnojil pa se lahko bistveno izboljša tudi v zaprtih sistemih (vrtnarjenje).

Velik napredek je opazen tudi pri živinoreji, kjer se vsebnost fosforja v krmilih prilagaja glede na potrebe rejenih živali v različnih življenskih obdobjih. S takšnim pristopom se celokupno zmanjšuje poraba fosoforja v hrani za živali, hkrati pa se povečuje njena učinkovitost. V zvezi z intenzivno živinorejo se sicer dotaknemo širše problematike, s katero se sooča sodobni človek in pri kateri poraba fosforja ni največja težava. Sodobna živinoreja je namreč kočljiva panoga, ki sproža mnoge polemike na več področjih (razmere v farmah, poraba vode, krčenje gozdov zaradi pridelovanja krme, zdravstveni vidiki,...) in presega okvir tega referata.

5.3 Viri fosforja v odpadnih produktih in ponovna uporaba

Tradicionalne tehnike, ki omogočajo vračanje fosforja v okolje, so na primer kompostiranje, gnojenje zemlje z bolj ali manj predhodno obdelanimi odplakami in gnojenje z živalskim gnojem ter ostanki pridelkov. Te tradicionalne oblike pa v razvitem svetu predstavljajo le majhen delež recikliranega fosforja v sklopu celotnega sistema ravnanja z odpadki. In čeprav v praksi pri ravnanju z odpadnimi produkti še marsikdaj ni vse v okviru regulativ, je napredek v državah, ki so ekološko bolj ozaveščene, občuten. Odpadni produkti, ki vsebujejo fosfor so na primer vsi biorazgradljivi odpadki (npr. kompost, pepel vrtnih rastlin in kuhinjskih odpadkov, pregnito blato,...), fosfor pa vsebujejo tudi ostanki hrane, živalski in človeški iztrebki, urin, kosti,... Kljub velikemu napredku okoljevarstvenih tehnologij v zadnjih desetletjih pa zaključevanje fosforjevega cikla do nedavnega ni bila prednostna naloga in je na tem področju zato še veliko nerešenih vprašanj. Skupne strategije upravljanja številnih tokov odpadkov iz kmetijstva, živinoreje in živilsko predelovalne industrije so šele v začetni fazi razvoja zato se velike količine fosforja nikoli ne prestrežejo. S tem ni mišljeno, da odpadki nekontrolirano končajo v okolju, temveč le, da tehnike obdelave odpadkov še niso prilagojene za reciklažo fosforja. Tako se na primer le majhen delež odpadnega mesa in kostne moke sežge, pepel pa uporabi za proizvodnjo fosforja. Ker se trenutno še vedno preveč biorazgradljivih komunalnih odpadkov odlaga na odlagališčih, kjer se izgubijo precejšne količine fosforja, je pri ravnanju s temi odpadki potrebno sprejeti nove izzive in iskati nove, varne načine ponovne uporabe.

Drugi pomemben alternativni vir fosforja so odpadne vode. Zaradi raznovrstnosti odplak glede na njihov izvor (živinoreja, različne industrijske panoge, komunalne odplake,...) obstaja za obdelavo odpadnih vod na trgu veliko različnih in učinkovitih tehnologij, med katerimi so tudi tehnologije za odstranjevanje fosforja. Pri tem je zanimivo, da so se postopki za izločanje fosforja iz odpadnih vod razvijali prvenstveno zaradi pojava cvetenja alg v stoječih vodah (evtrofikacije) in ne zaradi pridobivanja fosforja. Glavno gonilo razvoja je bila zahteva, da se lahko v vodotoke spuščjo le odplake, ki ne vsebujejo prekomernih količin nutrientov (predvsem fosfatov in nitratov). Uporaba odpadnega blata iz čistilnih naprav v kmetijstvu je bila v tem procesu sekundarnega pomena, pomisleke pa je povzročala (in jih še) tudi vsebnost težkih kovin ter drugih škodljivih snovi v odpadnem blatu. V prihodnosti se bo situacija zelo verjetno obrnila in prioriteta bo postala uporaba odpadnega blata v kmetijstvu, pri čemer pa bodo kriteriji glede vsebnosti škodljivih snovi v blatu še strožji. Podobno kot pri tehnologijah za sežig se tudi pri tehnologijah za obdelavo odpadnih vod pojavlja težava, da so le-te trenutno prilagojene predvsem za odstranjevanje nečistoč in polutantov in ne toliko za njihovo ponovno uporabo, porajajoče tehnologije pa zaenkrat še ne upravičujejo potrebnih finančnih vložkov.

Alternativni viri fosforja so tudi frakcije organskih odpadnih produktov, kamor uvrščamo urin, fekalije, odpadno vodo iz gospodinjstev, živalske iztrebke, mrhovino, odpadke iz klavnic (kosti, kri,...) ter tudi odpadke iz živilske industrije. Pri inovativnih pristopih na tem področju prednjačijo Švedska, Nizozemska, Nemčija in Kanada. Omeniti velja na primer stranišča, kjer se fekalije in urin zbirajo ločeno. Iz frakcije urina z obarjanjem pridobivajo struvit (magnezijev amonijev fosfat), ki se uporablja kot gnojilo s počasnim sproščanjem, fekalije pa skupaj z ostalimi organskimi odpadki posušijo, s čimer močno zmanjšajo volumen odpadnega produkta (odpadno toploto pa izkoristijo za gretje domov). S koncentriranjem fosforja na izvoru tako zmanjšajo prostornino in vsebnost vode odpadnega produkta, s predelavo urina v struvit pa se izognejo oviram pri transportu in znatno zmanjšajo možnost zdravstvene ogroženosti zaradi morebitnih prisotnosti zdravil, hormonov ali bakterij, ki so bile mogoče prisotne v urinu pred predelavo v struvit.

6 Zaključek

Trajnostna raba fosforja bo v prihodnosti le še pridobivala na pomenu, saj se z večanjem števila prebivalstva veča tudi potreba po hrani. Daleč največji delež fosforja, ki ga danes zaužijemo s hrano, je fosfor iz fosfatne rude. Ker se bogata nahajališča fosfatne rude nahajajo le v peščici držav in ker gre za neobnovljiv vir, se zadnje čase tej temi posveča vedno več pozornosti. Glavni namen posvetovanj, izobraževanj in dokumentarnih filmov s to tematiko je, da pride iz okvirov akademskega sveta zavedanje o omejenosti zalog fosfatne rude tudi v širšo javnost. Ob trenutnem izobilju mineralnih gnojil se seveda hitro pojavijo pomisleki glede nujnosti ukrepanja. Takšno prepričanje pa je gotovo zavajujoče, saj se lahko v primeru neukrepanja prihodnji rodovi soočijo s hudim pomanjkanjem hrane. Ker je fosfor eden od temeljnih elementov potrebnih za obstoj življenja in kot tak nenadomestljiv, bo potrebno idejo o trajnostni rabi fosforja, ki zagotavlja vire fosforja tudi v lokalnem okolju, kmalu začeti uvajati v praksi.

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Varstvo osebnih podatkov na področju distribucije električne energije

BOŠTJAN KEŽMAH

Povzetek Varstvo osebnih podatkov trenutno ostaja osrednji normativni mehanizem za splošno zagotavljanje varnosti informacijskih sistemov. Predpisi usmerjajo upravljavce informacijskih sistemov k dobrim praksam upravljanja, vodenja in zagotavljanja varnosti informacijskih sistemov. Pomemben del varnostnih kontrol so revizijske sledi in dosledna identifikacija osebnih podatkov. V prispevku analiziramo definicijo revizijske sledi, njen pomen ter na praktičnih primerih predstavimo identifikacijo osebnih podatkov na področju distribucije električne energije.

Ključne besede: • varstvo osebnih podatkov • distribucija električne energije • informacijski sistem • revizijska sled • identifikacija •

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Personal Data Protection in Electric Energy Distribution

BOŠTJAN KEŽMAH

Abstract Personal data protection remains a central regulatory mechanism for ensuring the overall security of information systems. The regulations guide information systems owners towards best governance, management and information security practices. An important part of security controls are audit trails and systematic identification of personal data. In this paper, we analyse the definition of the audit trail, its importance and practical examples to present identification of personal data in the area of electricity distribution.

Keywords: • personal data protection • electric energy distribution • information system • audit trail • identification •

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1 Uvod

Varstvo osebnih podatkov postaja vse pomembnejši vidik zagotavljanja varnosti informacijskih sistemov. Pri tem se velikokrat postavlja vprašanje kaj je osebni podatek, čeprav je v zakonu jasno opredeljen kot katerikoli podatek, ki se nanaša na posameznika, ne glede na obliko, v kateri je izražen [1]. Kadar je podatek osebni podatek, morata upravljavec in morebitni pogodbeni obdelovalec osebnih podatkov zagotoviti, da se ti podatki obdelujejo skladno s predpisi.

Zakon o varstvu osebnih podatkov (v nadaljevanju ZVOP-1) v 5. odst. 24. čl. določa, da zavarovanje osebnih podatkov obsega tudi ukrepe, ki omogočajo poznejše ugotavljanje kdaj so bili posamezni osebni podatki vneseni v zbirko osebnih podatkov, uporabljeni ali drugače obdelani in kdo je to storil. Veliko upravljavcev in pogodbenih obdelovalcev osebnih podatkov po naših izkušnjah dojema to določbo kot izrazito pretirano, nesorazmerno in nepotrebno. Pa je res tako?

2 Dnevniki informacijskega sistema

Velika večina sodobne programske opreme pri svojem delovanju ustvarja t.i. dnevniške zapise. Cilji beleženja dnevniških zapisov so različni, od beleženja dogodkov z namenom odkrivanja napak v delovanju operacijskega sistema, programske in druge opreme, do beleženja aktivnosti uporabnikov z namenom vrednotenja uporabniške izkušnje in beleženja aktivnosti uporabnikov z namenom kasnejšega ugotavljanja kdo, kdaj in katere funkcije v informacijskem sistemu je uporabljal.

Izrazit primer predstavlja operacijski sistem Windows, ki privzeto beleži pomembnejše dogodke, kot je npr. namestitev nove programske opreme, prijava uporabnika v operacijski sistem, izklop operacijskega sistema ipd. Le redki lastniki informacijskih sistemov pa se tega zavedajo in se odločijo, da bodo privzete nastavitve spremenili. Med pomembnejšimi nastavitvami so število dogodkov, ki naj jih operacijski sistem ohrani.

V sklopu revizij informacijskega sistema pogosto ugotavljamo, da upravljavci informacijskega sistema ne poznajo odgovora na vprašanje za koliko časa lahko zagotovijo dnevniške zapise operacijskega sistema. Ko namreč število zabeleženih dogodkov prekorači vnaprej nastavljeno vrednost, najstarejše dogodke operacijski sistem samodejno izbriše.

Nekoliko višja stopnja zrelosti je značilna za procese, kjer so dnevniki pomembni pri operativnem delu. Primer takih procesov so podpora uporabnikom, odprava napak v delovanju programske in mrežne opreme. V teh okoliščinah so dnevniki nepogrešljiv pripomoček za natančnejšo identifikacijo in odpravo napake in imajo praviloma uporabniki teh dnevnikov interes, da skrbijo za njihovo obstojnost in ustrezno vsebino.

Pri izvajanju nadzornih funkcij, kot je npr. revizija informacijskega sistema, so v dnevnikih ključni podatki za izvedbo analize stanja delovanja notranjih kontrol. Predstavljajo pomembne vhodne podatke, na podlagi katerih lahko revizor informacijskih sistemov s pomočjo statističnih in drugih metod odkriva vzorce, nepravilnosti in sumljive dogodke v množici dnevnikov in na ta način bolj uspešno pripravi oceno tveganja, ki je osnova za pripravo revizijskega načrta. Dnevniki so pomemben vir podatkov tudi kasneje, pri testiranju delovanja notranjih kontrol.

Ker naj bi nadzor temeljil na objektivnih, preverljivih in avtentičnih podatkih, se predvsem v zvezi z avtentičnostjo pri podrobni obravnavi posameznih zapisov odpirajo dodatna vprašanja. V primeru, ko v sklopu nadzora ugotovimo pomembne nepravilnosti ali celo goljufije, je namreč bistveno, da je mogoče te ugotovitve povezati s točno določenim uporabnikom. Za potrebe dokazovanja na sodišču je lahko tudi to premalo, saj je treba tudi računalniško identiteto uporabnika povezati s točno določeno osebo.

3 Revizijske sledi

Dnevnik, ki ga želimo uporabiti kot zanesljiv dokaz, mora torej imeti dodatne značilnosti. Te značilnosti praviloma bistveno presegajo obseg tehnične rešitve (kot je shranjevanje podatkov v datoteko), ampak predstavljajo skupek organizacijskih, tehničnih in logično-tehničnih postopkov in ukrepov, ki zagotavljajo avtentičnost in celovitost dnevniškega zapisa.

Pri tem avtentičnost pomeni, da je zapis nastal kot posledica dejansko izvedene aktivnosti uporabnika in da je zapis izdelala prav programska oprema, ki je navedena v dnevniku oz. upravlja predmetni dnevnik, celovitost pa nakazuje, da lahko zaupamo podatkom dnevnika v smislu, da se podatki niso spremenili ter da dnevnik ne vsebuje umetno dodanih ali drugače zavajajočih podatkov ter da posamezni podatki niso bili izbrisani.

Kadar so izpolnjeni ti pogoji, ne govorimo več o dnevniškem zapisu, temveč o revizijski sledi. Po definiciji stroke revizije informacijskih sistemov je revizijska sled od izvirnega dogodka ločen zapis ali več zapisov, ki se nanašajo na izvirni dogodek v informacijskem sistemu, z navedbo vseh ključnih podatkov za enolično prepoznavo okoliščin nastanka dogodka, kot tudi njegovih posledic. Revizijska sled mora biti nedvoumna, neizpodbitna, celovita, nespremenljiva in trajna [2]. Uspešnost beleženja revizijske sledi je neločljivo povezana s splošnimi notranjimi kontrolami informacijskega sistema .

Tudi kontrolni okvir upravljanja in vodenja informacijskih sistemov COBIT 5 v vodstveni praksi DSS05.04 določa, da mora upravljavec informacijskega sistema vzdrževati revizijsko sled dostopa do informacij, ki so bile klasificirane kot visoko občutljive (DSS05-04.8) [3].
Razen tega mora biti upravljavec informacijskega sistema sposoben določiti vse aktivnosti obdelave podatkov posameznega uporabnika (DSS05.04-7) [3].

Podobne zahteve izhajajo tudi iz skupine standardov na področju varovanja informacij, ISO 27000.

Vodenje revizijskih sledi obdelave osebnih podatkov torej sploh ni izum ZVOP-1, temveč so revizijske sledi eno temeljnih načel upravljanja in vodenja informacijskih sistemov, vgrajene v temeljne aktivnosti in strokovne dobre prakse.

Dobro urejeni informacijski sistemi torej sploh ne bi smeli imeti posebnih težav z zagotavljanjem skladnosti z ZVOP-1.

Ne glede na to je treba izpostaviti, da vpeljava ustrezne rešitve za vodenje revizijske sledi ni enostavna. Če se osredotočimo samo na možnost, da bi administrator informacijskega sistema lahko sam, neopaženo spreminjal podatke revizijske sledi, kmalu ugotovimo, da vodenje revizijskih sledi zahteva dobro zasnovan načrt celovite verige notranjih kontrol, kadar je le mogoče samodejnih, ki so zasnovane tako, da ne puščajo prav nobenega dvoma v nedvoumnost, neizpodbitnost, celovitost ter nespremenljivost revizijske sledi.

Ločimo horizontalno in vertikalno vodenje revizijske sledi. Pri horizontalnem se v revizijski sledi zapisujejo vsi podatki zapisa pred spremembo. Ta način je primeren za beleženje izbrisanih zapisov, vendar je prostorsko najbolj zahteven. Pri vertikalnem vodenju revizijske sledi se zapišejo samo podatki, ki so se spremenili . V nekaterih primerih podatkov, ki se navezujejo na obdelavo, ki jo beleži revizijska sled, ne zapisujemo. Zavedati se je treba, da v primeru, ko v revizijsko sled zapisujemo osebne podatke, tudi sama revizijska sled vsebuje kopijo podatkov, kar bo imelo posledice tako pri zagotavljanju varnosti revizijske sledi, beleženju dostopov do revizijske sledi kot tudi morebitnem izbrisu podatkov iz revizijske sledi, ki se nanašajo na posameznika.

S padanjem cene kapacitet za hrambo podatkov obseg beleženja podatkov tako ni več problem ekonomike, temveč iskanje ravnotežja med zadostnim in prekomernim beleženjem podatkov v revizijski sledi.

3.1 Posledice neustreznega zagotavljanja revizijskih sledi

Kljub metodološko doslednemu testiranju in vgrajeni varnosti informacijskih sistemov zaradi velikega števila vejitev, ki so sestavni del sodobne programske kode, v vsaki rešitvi pomemben del vejitev ni testiran pred predajo v uporabo. To pomeni, da je upravičeno pričakovati, da tekom delovanja informacijskega sistema odkrivamo dodatne pomanjkljivosti in ranljivosti informacijskega sistema.

Eden novejših primerov je nepooblaščeno razkritje podatkov Univerzitetnega kliničnega centra Ljubljana (v nadaljevanju UKC Ljubljana).

Neznanec je vdrl v spletno stran UKC Ljubljana, prek katere pacienti rezervirajo termin obiska pri zdravniku z napotnico. Dostopni so bili občutljivi in osebni podatki pacientov, vključno z njihovimi napotnicami, ter osebni podatki zaposlenih [4]. Informacijski sistem je sicer izrekel globo tako zdravstveni ustanovi (4.170 EUR) in odgovorni osebi (830 EUR) [5], vendar globa ne odpravi posledice, to je, da so bili občutljivi osebni podatki, med katere spadajo podatki o zdravstvenem stanju posameznika, že razkriti.

Bistven problem incidenta ni v tem, da je ranljivost obstajala, temveč v tem, da varnostne kontrole, ki bi morale zaznati, omejiti ali vsaj zabeležiti neupravičen dostop do osebnih podatkov, niso delovale. Čeprav postopek nadzora Informacijskega pooblaščenca še ni končan, prve informacije nakazujejo, da UKC Ljubljana nima podatkov o tem kateri podatki in kdaj so bili neupravičeno razkriti. To pa pomeni, da niti če bi želel o incidentu obvestiti posameznike, tega ne more, ker nima dovolj podatkov.

Če bi bila programska oprema ustrezno izdelana, potem bi morala ne glede na to, da je napadalec zlorabil predvideno delovanje programske opreme, v revizijsko sled zabeležiti dostop do podatkov. Na podlagi tega bi moralo biti mogoče ločiti upravičene dostope od neupravičenih in na ta način določiti podatke, ki so bili nepooblaščeno razkriti tretji osebi.
Podoben primer izhaja iz preiskave opr. št. I Kpd 21345/2010, ki je temeljila na sumu storitve kaznivega dejanja, v sklopu katerega je uslužbenec policije nepooblaščeno proti plačilu spreminjal vrsto prometnega prekrška na že vpisanih plačilnih nalogih, z namenom, da voznik ne bi prekoračil predpisanega števila kazenskih točk.

V sklopu preiskave se je izkazalo, da je imela policija leto in pol izključeno revizijsko sled zaradi nadgradnje informacijskega sistema, kar je bistveno otežilo preiskavo. Nazadnje je bilo mogoče identificirati storilca na podlagi spremljajočih aplikativnih podatkov. Za vsak zapis plačilnega naloga je programska oprema zapisovala tudi uporabnika in čas zadnje spremembe. Pri ročnem pregledu plačilnih nalogov in primerjavo s stanjem v podatkovni bazi smo ugotovili, da je vse plačilne naloge, ki se v elektronski obliki niso ujemali z nalogom v papirni obliki, nazadnje spremenil isti uporabnik.

3.2 Prednosti zagotavljanja revizijskih sledi

Z doslednim vodenjem revizijske sledi se izognemo vprašanju avtentičnosti in zanesljivosti aplikativnih podatkov in hkrati zagotovimo tudi skladnost s predpisi.

Revizijske sledi ne predstavljajo nujno samo pasivne zbirke zgodovinskih podatkov. Predvsem največji upravljavci osebnih podatkov, kot so Google, Facebook ipd., se jasno zavedajo vrednosti zbranih podatkov. V Sloveniji je prepoznavanje vrednosti velike količine podatkov (t.i. velepodatkov – angl. »Big Data«) še v povojih. V veliko podjetjih v sklopu revizije informacijskih sistemov npr. opažamo, da brez tehtnega preudarka in načrta upravljavci informacijskih sistemov preprosto brišejo dnevnike spletnih strežnikov in da so te aktivnosti in presoja koristnosti podatkov prepuščena operativi, kot so npr. administratorji informacijskega sistema.

Vse to vodi v nenadomestljivo izgubo podatkov. Ti podatki pa imajo razen uporabne vrednosti pri analizi vedenja uporabnikov in iskanju zakonitosti, povezanih z razumevanjem navad uporabnikov, visoko uporabno vrednost tudi v nadzornih procesih.

Pravzaprav kmalu ugotovimo, da je v revizijskih sledeh shranjena bistveno večja količina podatkov, kot je poslovnih transakcij samih, zato so prav revizijske sledi odličen vir velepodatkov.

Analitika si je šele začela utirati pot v nadzorne procese, kot je npr. revizija informacijskih sistemov. S povečevanjem števila virov zanesljivih podatkov postajajo vse bolj izvedljivi revizijski postopki, ki prvenstveno temeljijo na velepodatkih, zbranih v informacijskem sistemu. To zahteva miselni preskok, predvsem pa spremembo v načinu dela in prenovo procesov revidiranja, saj analitike nad velepodatki zaradi velike količine podatkov ni smiselno izvajati na samostojnih delovnih postajah, s katerimi delajo člani revizijske skupine. Zahteva celovit pristop in celovito rešitev za analitiko podatkov [6].

3.3 Kriptografsko varne verige zapisov

Tisti, ki jih tudi uporaba velepodatkov ne prepriča v nujnost beleženja revizijskih sledi v naprednih informacijskih sistemih zaradi vložkov, ki so potrebni pri zagotavljanju spremljajočih organizacijskih in drugih ukrepov, da revizijska sled sploh nastane, lahko posežejo po tehnično naprednih metodah, ki se šele uveljavljajo.

Kriptovalute kot so Bitcoin niso koristne samo zato, ker iz transakcije verige izločajo banko in s tem znižujejo stroške prenosa sredstev, temveč predstavljajo tehnično osnovo za inovacije na področju zagotavljanja verodostojnosti revizijskih sledi.

Pojavljajo se že prvi inovativni poskusi uporabe kriptografsko varnih verig za zanesljivo ugotavljanje izvora in nespremenljivosti dejstev, shranjenih v takšni verigi [7, 8].

Izdelava rešitev za vodenje revizijskih sledi, ki temelji na kriptografski varnostni verigi je nova priložnost za ponudnike rešitev, hkrati pa pomembna priložnost za zniževanje stroškov in zapletenosti zagotavljanja revizijskih sledi v informacijskih sistemih, ki jih vodijo.

4 Osebni podatki v distribuciji električne energije

Površen pregled podatkov, ki se uporabljajo pri distribuciji električne energije, bi lahko dal napačen vtis, da informacijski sistem uporablja zelo malo osebnih podatkov, kot npr. ime in naslov uporabnika električnega priključka.

Ob izhodišču, da je tudi IP naslov računalnika osebni podatek, kot izhaja iz mnenj Informacijskega pooblaščenca, pa izhaja, da je treba osebni podatek razumeti veliko širše. IP naslov se v skladu z ZVOP-1 šteje za osebni podatek (dinamični IP naslovi skupaj s podatkom o času dodelitve oziroma vključenosti v omrežje ali statični IP naslovi – ker je na njihovi podlagi posameznik določljiv oziroma določen) [9]. To ne velja samo za statične IP naslove, temveč tudi za dinamične, torej takšne, ki se s časom spreminjajo [10].

Osebni podatek je torej vsak podatek, ki je povezan s posameznikom oziroma določa posameznika, ne glede na to, ali ta informacija izhaja že iz podatka samega. V primeru IP naslovov lahko praviloma posameznika identificira šele ponudnik dostopa do interneta, pa je kljub temu osebni podatek.

Primeri osebnih podatkov v distribuciji električne energije, ne glede na to, da podatki sami po sebi še ne razkrivajo identitete posameznika, so tako npr. številka merilnega mesta in številka električnega števca. Oba podatka lahko distributer ali celo dobavitelj električne energije poveže s posameznikom, zato sta to osebna podatka.

Ob splošno znanem vzdušju uporabnikov interneta, da jih zasebnost ne skrbi, »ker nimajo česa skrivati«, je vendar treba izpostaviti varnostne implikacije razkritja identificiranih osebnih podatkov oziroma dodatnih podatkov, ki so s temi podatki povezani.

Če bi napadalec iz informacijskega sistema distributerja električne energije lahko ugotovil kakšna je poraba električne energije posameznika, bi lahko iz teh podatkov ugotovil kdaj je njegovo stanovanje prazno in temu prilagodil fizični vdor.

Če podatki o električnem števcu ne bi bili osebni podatek, potem tudi z njim povezana poraba električne energije ne bi predstavljala osebnega podatka, kar pomeni, da bi lahko policija te podatke pridobila in tudi analizirala. To pomeni, da bi lahko na podlagi primerjave s povprečno porabo električne energije in značilne porabe za nedovoljene dejavnosti identificirala potencialne porabnike električne energije, pri katerih obstaja utemeljeni sum, da gojijo nedovoljene rastline (npr. marihuano). To pa že vodi v samodejni nadzor države nad državljani.

5 Sklep

Kljub temu, da državljani »ničesar ne skrivamo«, ima varstvo osebnih podatkov pomembno nalogo pri zagotavljanju zasebnosti državljanov. Pomembno vlogo pri tem imajo tudi revizijske sledi, ki pa niso samo posledica varstva osebnih podatkov, temveč predstavljajo enega od temeljnih načel zagotavljanja varnosti informacijskih sistemov.

Na področju distribucije električne energije je ključno, da ne spregledamo podatkov, ki predstavljajo osebne podatke, kot so npr. identifikacijske oznake števcev električne energije za namene samodejnega pošiljanja stanja števcev, saj morebitna povezava teh enoličnih identifikatorjev s posameznikom bistveno povečuje njegova varnostna tveganja.

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Slovensko-Japonski raziskovalno-razvojni demonstracijski projekt

BOGOMIL JELENC

Povzetek Spoznavnost in vodljivost sta končni cilj vsakega sistemskega operaterja. Večanje števila razpršenih virov v distribucijskem omrežju in trendi po širokem razmahu e- mobilnosti postavljajo koncept distribucijskega omrežja, kot smo ga poznali v povsem novo luč. Pretoki energije se ne bodo samo povečali (enako velja za konične moči) ampak zelo verjetno tudi obrnili. Krepitev omrežja kot odgovor na te izzive je sicer realna vendar draga rešitev, pogosto tudi izvedbeno zamaknjena v prihodnja leta. Večja vodljivost pa prinese zmožnost nadzora nad pretoki moči, kar omogoča nižanje konične obremenitve, vzdrževanje napetosti znotraj predpisanih mej in zmanjševanju izgub v omrežju.

Ključne besede: • slovensko-japonski projekt • spoznavnost • vodljivost • razpršeni vir • distribucijsko omrežje •

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Slovenian-Japanese Research and Development Demonstration Project

BOGOMIL JELENC

Abstract In control theory, observability is a measure for how well internal states of a system can be inferred by knowledge of its external outputs. The observability and controllability of a system are mathematical duals. Both of them are also final goal of every System operator.The development of the Smart Grid concept is the pathway for assuring flexible, reliable and efficient distribution networks while integrating high shares od Distributed Energy Resources. Within smart grid paradigm the highly flexible and controllable Low Voltage Network is able to decentralize the distribution management and control system while providing additional controllability, observability and improves the security and reliability of the system.

Keywords: • Slovenian-Japanese project • observability • controllability • distributed energy source • distribution network •

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1 Zgodovina sodelovanja

Slovensko-japonsko sodelovanje na področju pametnih skupnosti in pametnih omrežij sega v leto 2012, ko je Slovenska tehnološka agencija (sedaj Javna agencija RS za spodbujanje podjetništva, internacionalizacije, tujih investicij in tehnologije – SPIRIT Slovenija) podpisala sporazum o sodelovanju z japonsko agencijo za nove energetske in industrijske projekte – NEDO. Namen sporazuma je krepitev povezovanja in tehnološkega sodelovanja med slovenskimi in japonskimi podjetji na področju naprednih energetskih in industrijskih tehnologij.

Sklenitev sodelovanja pri izvedbi demonstracijskega projekta oziroma več demonstracijskih projektov na izbranih tehnoloških področjih je bila sprejeta z izborom treh tem potencialnega skupnega demonstracijskega projekta.

Demonstracijski projekt pametne skupnosti in pametna omrežja zajema tri področja, in sicer:
razvoj in prikaz delovanja (demonstracija) integriranega sistema upravljanja distribucijskih omrežij (Distribution Management System, DMS) za skupno uporabo v slovenskih distribucijskih podjetjih, ki bo hkrati interoperabilen v sklopu različnih tehnoloških sistemov v uporabi;

razvoj in prikaz delovanja (demonstracija) integriranih rešitev na področju upravljanja s porabo (Demand Side Management / Demand Response, DR), s katerimi bo omogočeno učinkovito prilagajanje odjema distribucijskih omrežij glede na predvideno povečevanje porabe električne energije in proizvodnje iz razpršenih virov, čemur lahko sledi nameščanje pametnih števcev in prikaz delovanja (demonstracija) ustreznega uravnavanja odjema v okviru različnih storitev, ki jih izvajajo distribucijska podjetja;

uvedba in prikaz delovanja (demonstracija) sistema celostnega upravljanja z energijo (Energy Management System ‒EMS), ki bo omogočal nadzor in vodenje celostne preskrbe z energijo v urbanih območjih.

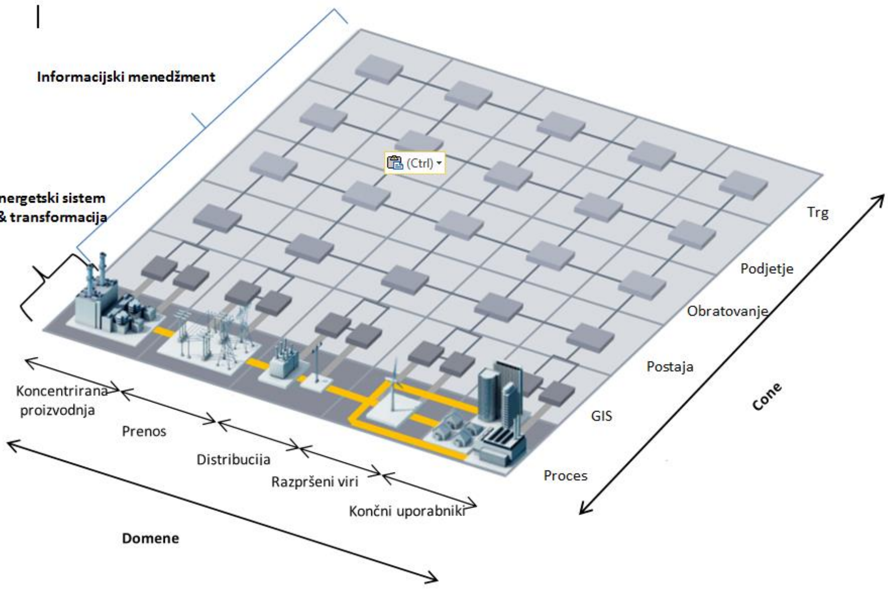
V dogovore za izvedbo demonstracijskega projekta pametnih omrežij in pametnih skupnosti se je konec leta 2015 vključil sistemski operater prenosnega elektroenergetskega omrežja ELES, ki od SPIRIT Slovenija prevzema koordinacijo projekta in sodelovanje z NEDO. ELES je 3. februarja 2016 podpisal pismo o nameri sodelovanja z japonsko agencijo NEDO. ELES je z japonsko stranjo pripravil končni vsebinski obseg partnerstva, izvedbeni načrt in izbor izvajalcev.

ELES tako s svojim delovanjem podpira uporabo Študije izvedljivosti za identifikacijo in izvedbo skupnega slovensko-japonskega demonstracijskega projekta na področju pametnih skupnosti in pametnih omrežij v Sloveniji [1], ki jo je na podlagi javnega naročila ter izsledkov terenskih analiz, ki so jih v preteklih letih izvajali japonski partnerji, izdelala Fakulteta za elektrotehniko Univerze v Ljubljani. Na podlagi ugotovitev teh aktivnosti je bila natančno določena oblika partnerstva in sklenjen je bil sporazum o sodelovanju med slovenskimi in japonskimi predstavniki.

Japonsko-slovensko sodelovanje ima tudi cilj spodbujanja novih pristopov za zagotavljanje sistemskih storitev v elektroenergetskem sistemu, uporabo izdelkov v sistemskih aplikacijah, ki še niso na tržišču, ustrezno uporabo prostorskih in demografskih značilnosti Slovenije ter omogočanje dolgoročnih strateških partnerstev med slovenskimi in japonskimi podjetji.

2 Cilji in izzivi projekta NEDO

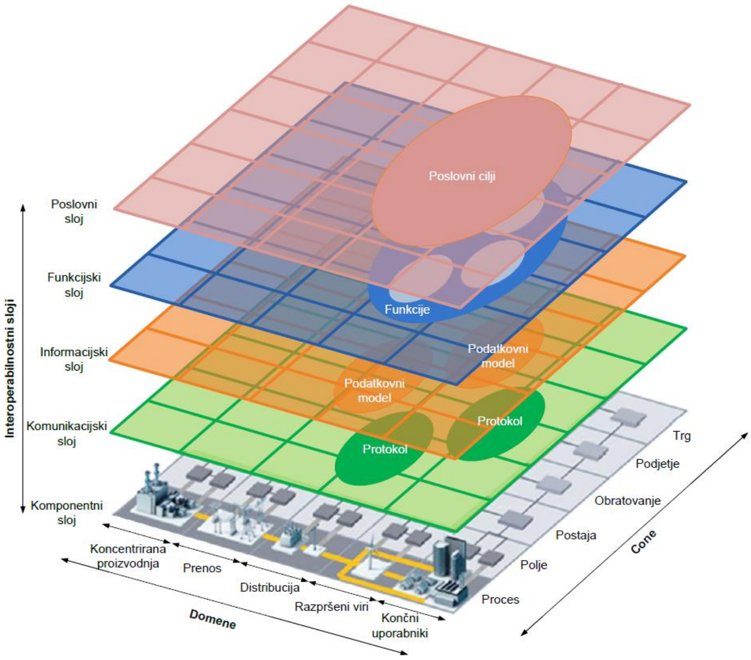
Projekt NEDO zajema praktično vse domene arhitekturnega modela evropskih pametnih omrežij CEN-CENELC-ETSI [2].



Slika 12.1Arhitekturni model evropskih pametnih omrežij

Cilji Informacije iz omrežja in stanje topologije uporabiti v realnem času za izboljšanje kvalitete napajanja	DMS-rešitve FDIR Lociranje okvare in ponovna vzpostavitev napajanja	Avtomatska ponovna vzpostavitev napajanja po lociranju in izolaciji mesta okvare z daljinsko vodenimi progovnimi stikali
Optimizacija omrežja za vključevanje in obratovanje razpršenih obnovljivih virov	VVO Optimizacija napetostni in jalove moči	Napredno vodenje in optimizacija omrežja za maksimalno penetracijo obnovljivih virov
Optimizacija konične moči	EMS+ z vključitvijo AEMS	Z vključitvijo AEMS doseči naslednje cilje: • področna (bilančna) optimizacija W_{el} • strateško planiranje • krmiljenje bremen (tudi kot poslovna priložnost)ŁŁ

Podroben pregled DMS-rešitev pokaže večplastno interoperabilnostno povezovanje različnih slojev arhitekturnega modela evropskih pametnih omrežij.



Slika 12.2 Interoperabilnostno povezovanje različnih slojev arhitekturnega modela evropskih pametnih omrežij

3 Spoznavnost in vodljivost

Z večanjem deleža razpršenih virov (RV) se razmere v omrežju spreminjajo do te mere, da so v določenih primerih obratovalna stanja zelo blizu predpisanih mejnih vrednosti ali jih celo presežejo. Omrežje je namreč bilo načrtovano in grajeno za prenos električne energije iz VN-nivoja v SN- in NN-omrežje. Za obratovanje omrežij z visokim deležem razpršenih virov znotraj predpisanih standardov je tako potrebno poznavanje spremenljivk stanja omrežja (fazne napetosti vozlišč in fazni toki vej), ki so temeljni pogoj za analizo sistema. To imenujemo spoznavnost (observabilnost) sistema in brez tega ni mogoče zagotoviti vodljivosti (kontrolabilnosti) sistema, ki je končni cilj vsakega sistemskega operaterja. Večji nadzor nad elementi omrežja ne omogoča zgolj usklajeno delovanja le-teh, ampak tudi boljšo izrabo infrastrukture in s tem tehnično in ekonomsko optimalno obratovanje omrežja. V splošnem večja vodljivost prinese zmožnost nadzora nad pretoki moči, kar omogoča nižanje konične obremenitve, vzdrževanje napetosti znotraj predpisanih mej in zmanjševanje izgub v omrežju. Z ustreznim merilnim sistemom in primarno opremo (odklopniki) je mogoče izvesti tudi sistem za določanje mesta okvare v omrežju in ponovno vzpostavitev napajanja po okvari, kar lahko pomembno zmanjša čas trajanja prekinitve napajanja porabnikov.

Aktivnosti, ki so osnova za spoznavnost, tako obsegajo:

- vzpostavitev naprednega merilnega sistema za trajno spremljanje stanja SN- in NN-omrežja,
- ocenjevalnik stanja (state estimator) za oceno stanja omrežja v točkah, kjer meritve niso na voljo,
- vzpostavitev naprednega merilnega sistema za trajno spremljanje kakovosti električne energije v SN- in NN-omrežjih,
- napredna vizualizacija napetostnih profilov in obremenitev,
- določanje lokacije mesta okvar.

Ena izmed prvih težav, ki se pojavljajo z večanjem deleža RV v omrežjih, so prav gotovo neustrezne napetostne razmere. Rešitev tega problema je sicer mogoča s krepitvijo (ojačanjem) omrežja, vendar pa to zahteva visoke investicije v omrežje, praviloma pa tudi podaljšan čas do izvedbe. Druga možna rešitev je uporaba sodobnih pristopov vodenja omrežja, ki temeljijo predvsem na uporabi informacijsko-komunikacijskih tehnologij, vključevanju virov in porabnikov v vodenje omrežja ter na sodobnih algoritmih za regulacijo napetosti. To pa so aktivnosti s področja vodljivosti:

regulacija napetosti s pomočjo VN/SN in SN/NN regulacijskih transformatorjev ter vodenje razpršenih virov,

vodenje omrežja ob visokem deležu razpršenih virov, ki vključuje tudi optimizacijo delovanja omrežja in kompenzacijske naprave.

Posledično je glavni cilj spoznavnosti in vodljivosti povečanje spoznavnosti, ki je osnova za izvedbo ustrezne vodljivosti. Izvedba naprednih sistemov regulacije napetosti v distribucijskem omrežju z zagotovitvijo dovolj meritev napetosti v različnih točkah omrežja in ustrezne primarne opreme (odklopnikov) je tako jedro projekta NEDO.

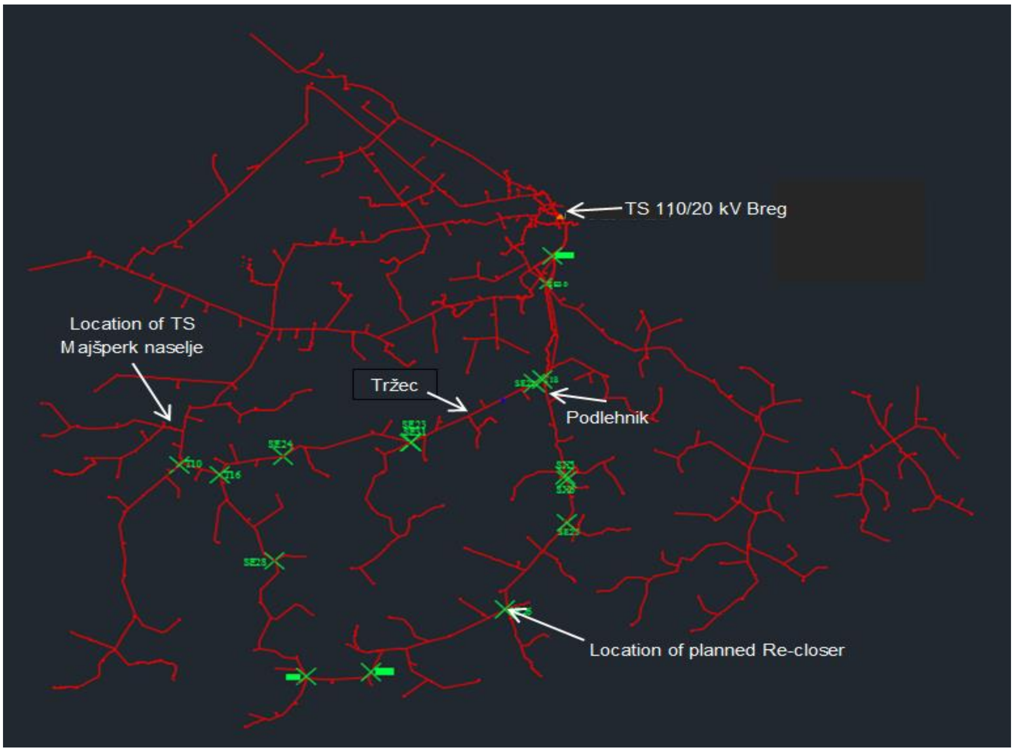
Implementacija v realnem omrežju bo prinesla nujne izkušnje, potrebne za optimizacijo delovanja in razvoja omrežja. Podredni cilj pa je prikaz funkcionalnosti FDIR (lociranje in izolacija okvare ter ponovna vzpostavitev napajanja), ki lahko znatno poveča neprekinjenost oskrbe z električno energijo. Vse omenjeno je združeno v del projekta NEDO pod kratico DMS. Projekt NEDO pa se s tem še ne konča. Za optimizacijo konične moči (tudi kot novo poslovno priložnost) projekt NEDO vključuje tudi segment aktivnega vključevanja bremen oziroma izravnavo konic oziroma prilagajanje odjema (Demand Response). [1]

Širši cilj v okviru segmenta aktivnega vključevanja odjema je vzpostaviti platformo za fleksibilen odjem, ki bo omogočala pregledno in nediskriminatorno aktivno vključevanje odjemalcev v sistem. Platforma bo povezana z ostalimi distribucijskimi sistemi (merilni center, DMS itd.) in s prenosnimi sistemi (napoved porabe, SCADA, EMS), s čimer se bo zagotovilo, da si posamezni ukrepi v omrežju ne bodo nasprotujoči in ne bodo imeli medsebojnih kolizij. Celotno platformo za aktivno vključevanje odjema sestavlja vrsta sistemov, ki so medsebojno povezani s standardiziranimi protokoli izmenjave podatkov. Pilotni projekt, v okviru katerega se bo preizkusil mehanizem kritične konične tarife, pokriva eno izmed možnosti vključevanja aktivnega odjema, ki je osredotočena na distribucijsko omrežje. Ključna je sinergija z ostalimi sistemi vključevanja aktivnega odjema, ki bodo vzpostavljeni v okviru projekta NEDO s ciljem optimizacije stroškov vključevanja aktivnega odjema v delovanje elektroenergetskega sistema.

4 DMS –avtomatsko lociranje in izolacija okvare in ponovna vzpostavitev napajanja

Kot je že bilo omenjeno, FDIR pomeni avtomatsko lociranje okvare, njeno izolacijo in vzpostavitev napajanja neokvarjenih delov (sektorjev) omrežja.

Na območju Elektra Maribor bo v okviru segmenta DMS nameščenih 16 daljinsko vodenih stikal na trasi dveh 20 kV daljnovodov, ki imata stično točko. S takšno konfiguracijo bo na obeh daljnovodih ustvarjenih 17 sektorjev, ki se jih bo lahko v primeru okvare osamilo (izoliralo). Tako bo hkrati omogočena izvedba ponovnega napajanja vseh neokvarjenih sektorjev.



Slika 12.3 Geografski prikaz lokacij daljinsko vodenih stikal

Vsako stikalo bo imelo meritev napetosti na obeh straneh, standardni nabor zaščit in avtomatski ponovni vklop. V povezavi s programskim orodjem DMS bo tako omogočena izvedba in testiranje funkcionalnosti Lociranja okvare in ponovne vzpostavitve napajanja (FDIR), ki samodejno določi sektor, na katerem je okvara. V nadaljevanju ta sektor izolira in nato samodejno izvede stikalne manipulacije za ponovno vzpostavitev napajanja ostalih sektorjev.

5 DMS – koordinirana regulacija napetosti

Po vsem svetu skokovito narašča število inštaliranih razpršenih proizvodnih virov (RV). Priključujejo se tako v srednje napetostno (SN) kot nizko napetostno (NN) omrežje. V Evropi in Sloveniji je ta skokovit narast povezan tudi s podpornimi shemami in subvencijami za t. i. zeleno energijo ozir. obnovljive vire kot je npr. fotovoltaični sistem.

Nizko napetostno omrežje v splošnem ni (bilo) grajeno za masovno vključevanje razpršenih virov. V veliki večini primerov je bilo le to projektirano in grajeno za distribucijo energije do končnih uporabnikov. Omenjeno pomeni, da je maksimalen padec napetosti v vseh priključnih točkah uporabnikov izračunan in predviden v naprej kar posledično pomeni, da je najvišji v najbolj oddaljenih točkah omrežja. Z vključitvijo razpršenih virov se vse to lahko spremeni in v skrajnih primerih privede do zrcalne slike napetostnih razmer v omrežju brez inštaliranega razpršenega vira torej, da napetost narašča od začetka izvoda proti koncu (RV). Razpršeni vir z injektiranje delovne moči v omrežje namreč dviguje napetost v točki priklopa.

Kvaliteto električne napetosti predpisuje standard EN 50160. Če se omejimo zgolj na amplitudo napetosti mora le ta biti v pasu +/- 10% nazivne napetosti, ki znaša 400 V medfazno in 230 V med fazo in nevtralno točko. [6]

Porabniki v omrežju za svoje delovanje potrebujejo delovno energijo, nekateri pa za delovanje potrebujejo tudi jalovo energijo. Električna energija za porabnike se generira in prenaša preko visokonapetostnega in srednje napetostnega omrežja, generira pa se tudi v nizkonapetostnem omrežju samem. Pretok energije teče preko različnih elementov elektro energetskega omrežja. Daljša kot je ta pot več elementov je v tem toku, posledično so višje izgube. Idealno bi bilo, če se električna generira kar najbližje porabnika. To je torej glavni vzrok, da so razpršeni viri zaželeni v NN omrežju.

Pri obratovanju razpršenih virov pa se pojavlja problem upravljanja jalove energije razpršenih virov. Razpršeni vir namreč lahko proizvaja ravno dovolj delovne energije za bremena v NN omrežju vendar pri svojem obratovanju zase potrebuje jalovo energijo, ki se pretaka k njemu iz višjih napetostnih nivojev. Lahko tudi proizvaja dovolj delovne energije za bremena, jalove pa ne proizvaja in se posledično le ta do bremen prenaša iz višjih napetostnih nivojev. Lahko pa proizvaja ravno dovolj delovne in jalove energije za bremena v NN omrežju, kar je iz vidika izgub idealno stanje. Z upoštevanjem dejstva, da so izgube zaradi pretoka delovne energije v NN omrežju za faktor cca. 2 višje kot v SN omrežju po drugi strani pa so izgube zaradi pretoka jalove energije v SN omrežju za faktor cca.15 višje kot v NN omrežju je logičen zaključek, da bi se morala jalova energija generirati v NN omrežju. Omenjena razmerja so posledica razmerja X/R, ki je v SN omrežju mnogo višji kot v NN omrežju. [5]

Proizvodnja jalove energije razpršenih virov v NN omrežju (poleg delovne), v NN omrežju tudi zmanjša izgube zaradi pretoka delovne moči in posledično povzroči dvig napetosti v omrežju. Pri previsoki proizvodnji jalove energije pa bi lahko napetost v NN omrežju narasla izven dovoljenih mej.

V Evropski uniji je edini standard (EN 507438), ki predpisuje priključevanje mikro generatorjev (do 16 A po fazi) v NN omrežje, ki dovoljuje obratovanje v območju faktorja moči generatorja med 0,95 (prevzbujan) in 0,95 (podvzbujan, tudi -0,95). Za vire, ki so močnejši skupnega predpisa ni. Različni nacionalni predpisi kot npr.: Navodila za priključevanje in obratovanje elektrarn inštalirane električne moči do 10 MW", SODO d.o.o., 2010; [7] standardu v različni meri sledijo, pri čemer pa že predpisujejo proizvodnjo jalove energije tudi za najmanjše enote.

Omenjeno privede do zaključka, da je dobro razpršenim virom "dovoliti" poleg proizvodnje delovne energije v NN omrežje injektirati tudi nekaj jalove energije. Omenjeno namreč močno zniža izgube, zaradi prevladujočega ohmskega značaja NN omrežja (R>>X) pa je vpliv na dvig napetosti relativno majhen. Edina omejitev je število takšnih naprav. Zaradi tega se v nekaterih evropskih državah že pojavljajo težnje, da bi razpršeni vir pri polni proizvodnji delovne energije porabil še več jalove energije in s tem omogočil vključitev večjega števila razpršenih virov.

Koordinirana regulacija napetosti se bo v projektu Nedo testirala v distribucijskem omrežju, napajanem iz ene RTP. V omrežje se bo vgradilo dodatne aktivne elemente – SN/NN regulacijske transformatorje. Cilj je izboljšati regulacijo napetosti na NN-nivoju z upoštevanjem prispevka SN/NN regulacijskega transformatorja. Pomemben cilj projekta je tudi oceniti potencialne težave pri interakciji med VN/SN regulacijskim transformatorjem in SN/NN regulacijskim transformatorjem.

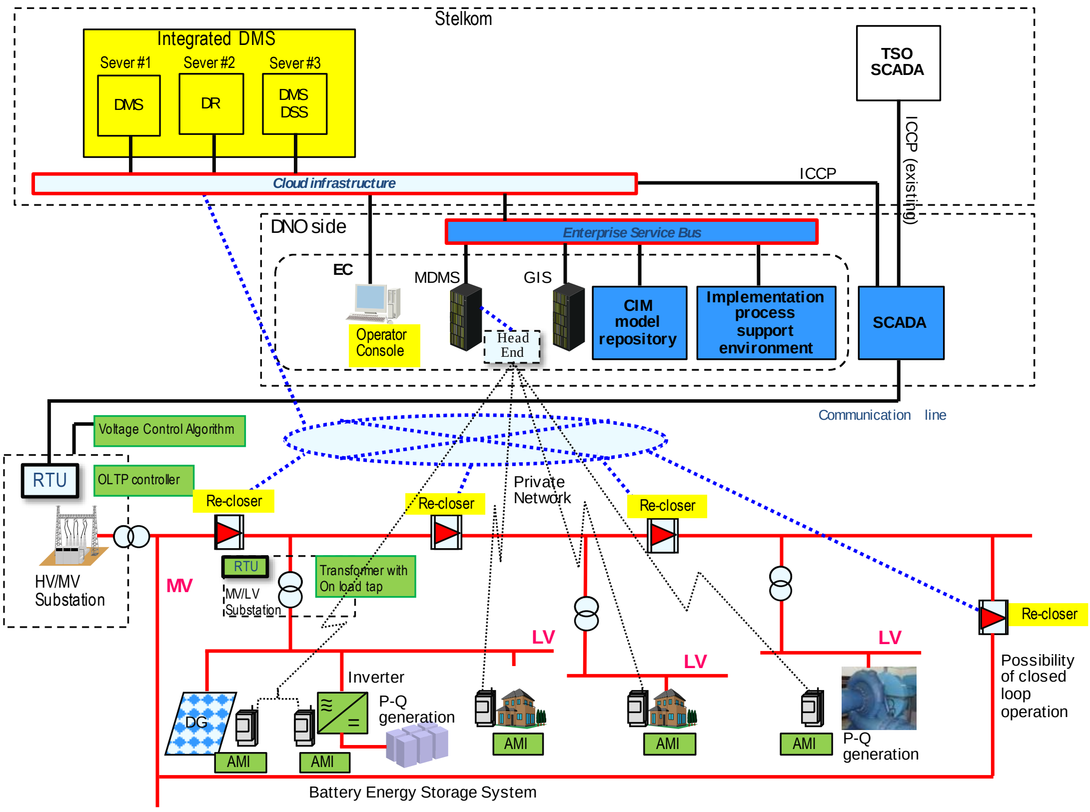
V okviru aktivnosti se bo analiziralo in primerjalo naslednje principe regulacije napetosti:

- Klasičen pristop: regulacija napetosti s pomočjo VN/SN regulacijskega transformatorja (meritve napetosti v eni točki).

- Regulacija napetosti v NN-omrežju s pomočjo SN/NN regulacijskega transformatorja: regulacija napetosti v NN-omrežju s pomočjo regulacijskega transformatorja (več merjenih točk v omrežju).
- Koordinirana regulacija napetosti: koordinirano vodenje VN/SN regulacijskega transformatorja in SN/NN regulacijskih transformatorjev.

Sistem regulacije napetosti bo implementiran na dveh nivojih:

- Hitachijev sistem Integrated DMS ponuja pregled nad celotnim distribucijskim omrežjem in omogoča optimizacijo delovanja omrežja.
- Lokalni sistem regulacije napetosti na SN-nivoju se uporablja v razmerah, ko je prekinjena komunikacija z integriranim DMS-sistemom.
- Za potrebe meritev napetosti bo v SN- in NN-omrežju na različnih točkah nameščenih 70 meritev napetosti, ki se bodo prenašale v DMS.



Slika 12.4 Shema projekta NEDO

6 Glavni izziv projekta

Glavni izziv projekta bo dodatno predvsem integrirati različne informacijske sisteme v skladu z arhitekturnim modelom evropskih pametnih omrežij.

Razviti in raziskati bo treba napredne pristope sistemske integracije in semantičnih mrež, ki bodo omogočale integracijo obstoječih (MDMS, SCADA, CIM) z v projektu vpeljanimi (integriran DMS, DRCS) z uporabo oblačne storitve, kot je nakazano na zgornji sliki. S takšnimi pristopi pa so podani temelji in stične točke tudi za ostale storitve kot npr. EMS (Energy management system), Peak Shaving (upravljanje konic), DR (aktivno vodenje bremen) in aktivno vključevanje ter vodenje proizvodnje iz obnovljivih virov.

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Univerzitetna založba
Univerze v Mariboru

“AKKU 4 LIFE” – Eksperimentalna diagnostika stanja rabljenih litij-ionskih baterij

STEPHAN THALER, CHRISTOPH URAN & MARTIN PECNIK

Povzetek Z namenom omogočiti ponovno uporabo rabljenih baterij je potrebna zanesljiva ocena njihovega stanja. Za predselekcijo v procesu recikliranja je potrebna hitra in smiselna analiza stanja. Ta predselekcija mora potekati preko elektronskih sistemov za analizo, pa naj bo govora o popolnem uničenju, spremembi, obnovi ali je potrebno ponovno polnjenje in »osvežitev«. Osnova za vključitev merilnega sistema bo v tem projektu potekala pod naslovom »Dinamični Analizator Baterij«.

Ključne besede: • diagnostika • rabljene baterije • litij-ion • merilni sistem • analiza baterij •

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"AKKU 4 LIFE" - An Experimental Health Condition Diagnosis of Second-Life Lithium-Ion Batteries

STEPHAN THALER, CHRISTOPH URAN & MARTIN PECNIK

Abstract In order to enable the reuse of a second hand battery a reliable assessment of their health status is necessary. For preselection in the recycling route very quick and meaningful status analyzes are required. This preselection whether total loss, alteration, rebuilding or reloading and "Refreshing" is necessary, and is to take place via electronic analysis systems. The basis for this measurement system integration is to take place under the Device title "Dynamic Battery Analyzer DBA" in this project.

Keywords: • diagnosis • second hand batteries • Lithium-Ion • measurement system • battery analyzer •

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Available at: http://press.um.si.

1 Introduction

Secondary battery cells, that do not fulfill their function anymore will be deposited or discarded nowadays. Recycling the resources gained from these batteries is the method of choice today. But with the rising amount of mobile devices and electric cars on the market also a higher amount of batteries is discarded although they are still in a condition where they could be used in so called Second Life Applications (e.g. storage stacks at photovoltaic systems). Before these cells can be used in other applications a state diagnosis has to be done to guarantee a defined state of the battery. For this interpretation the State of Health (SOH) is used. The SOH in this case is defined by the quotient of the actual battery capacity divided by the nominal capacity. The nominal capacity can be found

in the specific datasheet of the battery tested [Panasonic 2012]. Since the background of the project, the experimental classification method, is not only a scientific but also economic, other parameters have to be taken into account as well. Therefore, the goal is to analyze just the first ten seconds of the discharging behavior of a fully charged battery. To perform this measurement, special electronics as well as statistical methods are needed to calculate a representative result to the user of

the system. Only a fast as well as precise algorithm will allow the usage of this system in an industrial environment. In the following sections, the different sub-systems as well as the algorithm needed to perform this result will be described.

2 Approach

As already mentioned in the introduction, the goal is to develop a method to classify secondary lithium-ion batteries. This method is then planned to be implemented on a measurement device that will allow a user to perform a cell classification without having any special knowledge about measurement techniques. To be able to fulfill this goal a general system structure was established at the beginning of the development phase. This structure consists out of three main parts to be developed that can be seen in figure 13.1.

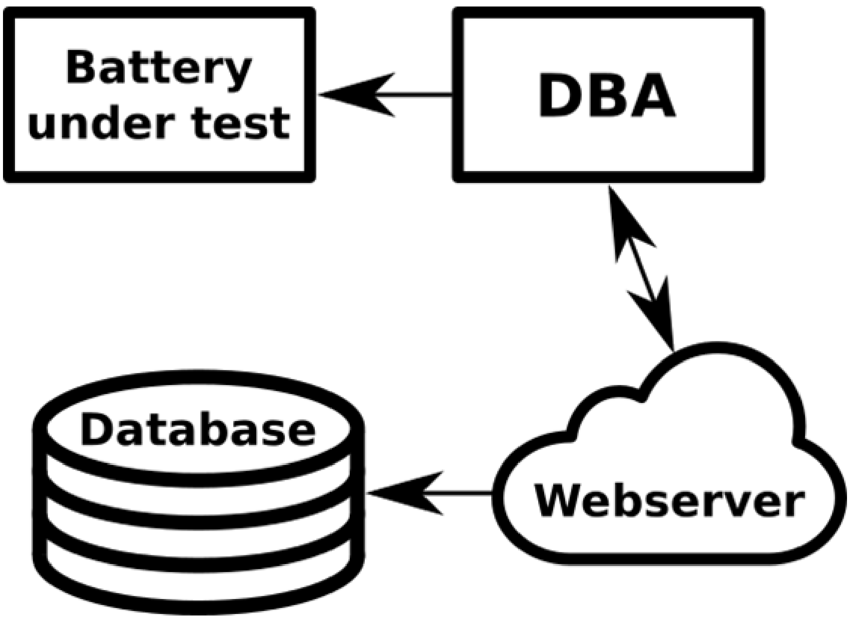

Fig. 13.1. Overall system structure

The Dynamic Battery Analyzer (DBA) is the connection between the user and the measurement system. A battery to be analyzed (which is the battery under test in figure 1) is plugged into the device and when the user presses the start button the measurement is done automatically. The cell characterization itself does not take place on the DBA to save resources. Instead, it is executed on the web-server. The communication between the DBA and the server takes place over the Internet, to which the DBA is connected via a pre-defined WiFi network. This web-server then compares the measured values with reference values which are stored in a database. This modular system structure is more complex to develop because of the different platforms to develop on but will also allow a maximum amount of flexibility and performance for more complex algorithms. The classification method is a curve comparison algorithm between reference data and measured data. The former will be stored in a database on the web-server while the latter is coming from the DBA. To gain the reference data, precharacterization measurements are performed in a laboratory environment. These measurements are executed on a special test stand that allows to charge and discharge batteries with defined C-rates and temperatures. These measurements allow us to analyze the capacity decrease of a secondary battery and therefore its voltage behavior when a load is applied. Since the discharge behavior varies depending on temperature, load, SOH of the cell and other factors, three distinctive temperatures as well as one discharge load was chosen for every supported battery type.

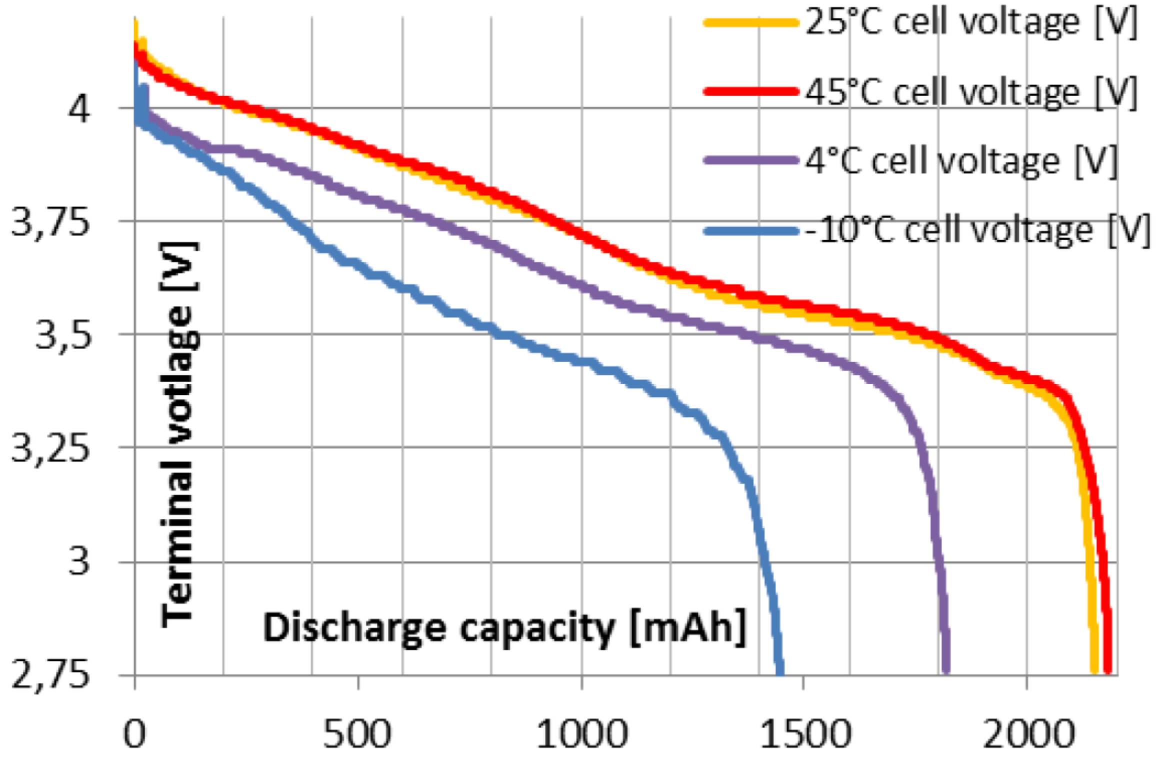

Fig. 13.2. Capacity variation through different temperatures [Elbe 2014]

3 Methodology

This section gives a more detailed description of the subcategories mentioned in the previous section.

3.1 Battery Aging

The battery aging is performed on special test bench which was developed within the project Akku4Future at the Carinthia University of Applied Sciences [Elbe 2014]. One of the outcomes of this project was that there are certain temperatures were batteries have highly different discharge behavior though the same load is applied (see figure 13.2).

Therefore, three significant temperatures were chosen for the battery aging process: 0_C, 25_C and 45_C. The batteries to be analyzed are from Panasonic [Panasonic 2012], Samsung and Sony [BMZ 2011]. For batteries used in the industry, most of the times there is no charge and discharge history available which provides information about the condition of the battery. Therefore, the load applied on the batteries under test is assumed to be the maximum load specified in the datasheet. Only batteries that are in an overall good condition, which means that they can be reused, allow such high load without a too high initial voltage drop or even breakdown.

3.2 Data Analysis and Preparation

Before saving the data from the test bench in the database the different curves have to be standardized to later guarantee the usage of one mathematical function for all different battery types realized. The results from the test bench are voltage curves that describe the charge and discharge behavior. Using the discharging currents over the time it is possible to recalculate how much capacity is drawn out of a battery. This discharge cycle will describe the battery’s SOH as described in the following equation.

$$SOH = \frac{C_{meas}}{C_{nom}} \tag{1}$$

Cmeas in this case describes the calculated capacity through the measured current over time relation and Cnom is the nominal capacity that can be found in the datasheet of a battery. With the help of this discharge data a classification can be done. For this purpose, curves with SOH steps of 5% were used to later on represent a certain discharge behavior depending on the SOH of a battery.

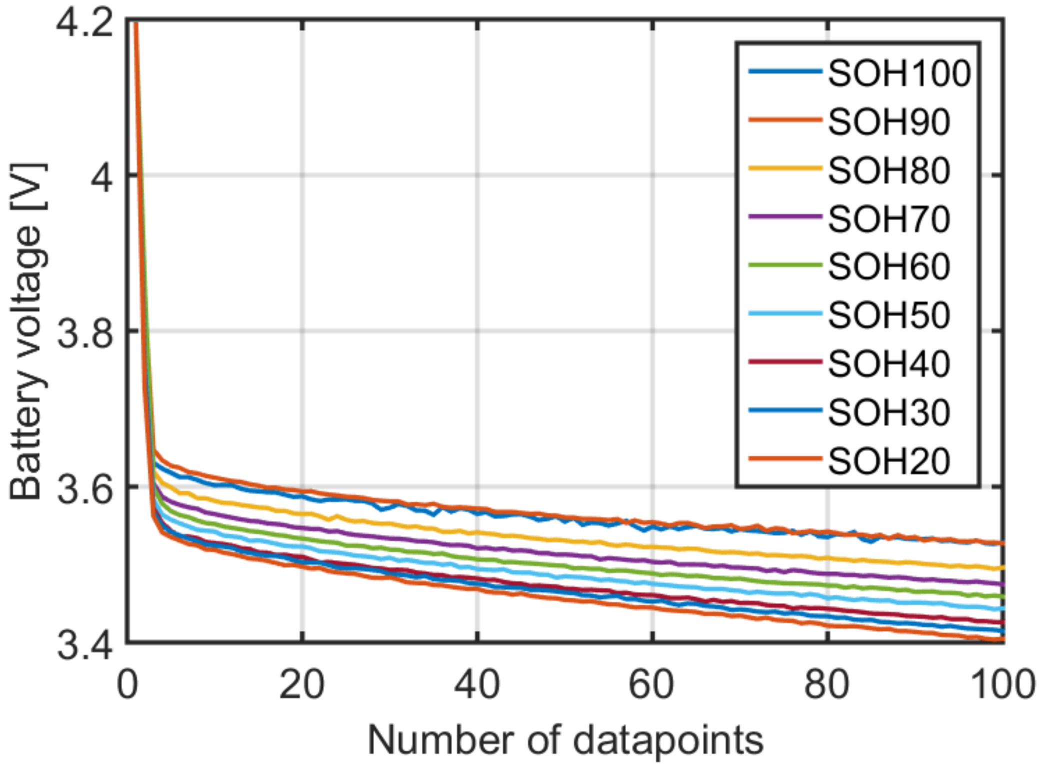

Fig. 13.3. Classification curves representing different SOH values

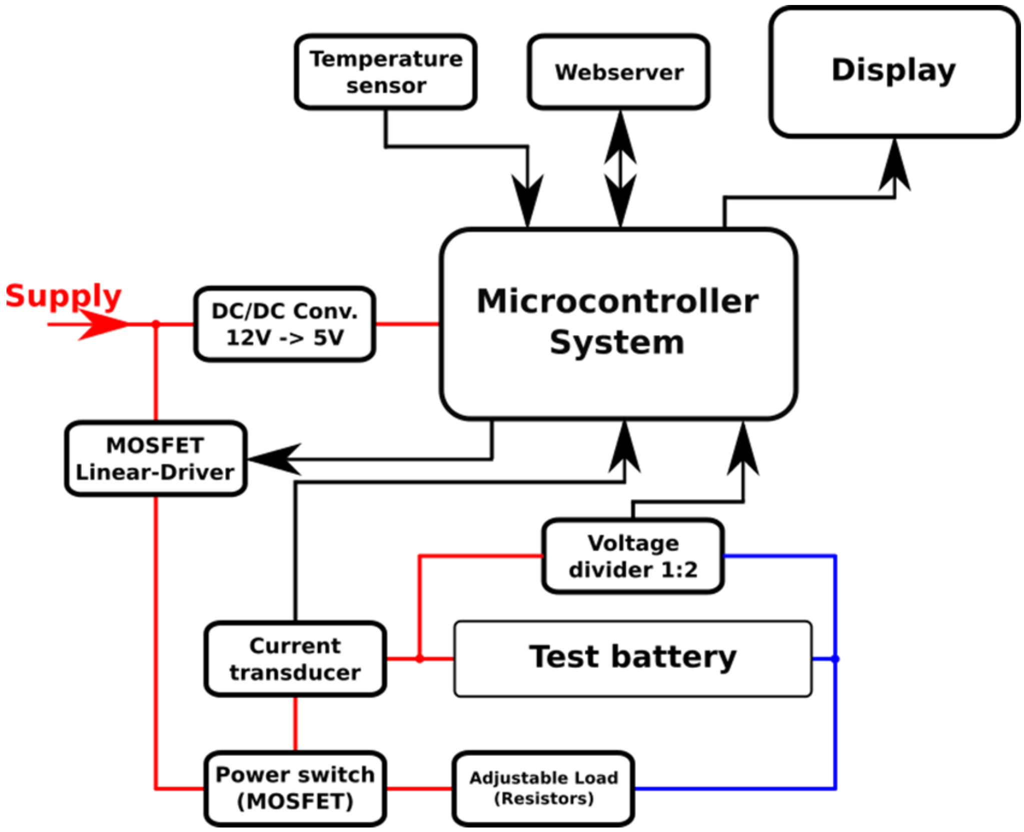

Fig. 13.4. Systematic structure of the Dynamic Battery Analyzer

After the classification and labeling of the discharge curves they can finally be prepared for the database. Since it was already mentioned in the introduction the goal is to charac-terize the unknown battery cells with a ten second maximum current discharge. Also the labeled reference dataset, that show the complete discharge of the cell, have to be prepared for this purpose. To minimize the storage needed for the database only the first 1000 values from the discharge curves are stored. They were measured at a frequency of 100Hz and therefore represent the first ten seconds of discharge. Finally, 20 reference curves (similar to the ones seen in figure 13.3) will be stored in the database to later on represent a certain SOH. The method that will be used for this comparison will be described in the section IV.

3.3 Dynamic Battery Analyzer

The DBA is a device that helps to indicate the SOH of an unknown battery cell using a newly developed experimental classification method. In this case, unknown battery means that neither the charging or discharging history of the cell nor the temperatures the battery was used at are known. The task of the DBA is to provide a user interface, where a user is able to select the type of battery to be measured, enter a battery identification number and start the characterization after inserting a fully charged battery into the device. The system structure of the DBA can be seen in figure 4. The complete system will be supplied by a 230VAC to 12VDC ACDC converter. The 12VDC level was chosen to provide an amplitude that is high enough to drive elements like operational amplifiers without having any additional boost converters. For the supply of the micro-controller system a linear voltage regulator is used that will provide 5VDC at the output. The micro-controller system itself consists of a Raspberry Pi1 communicating via I2C2 with an Arduino Uno3. The Raspberry Pi in this case works as the main controller, displays the user interface, allows the input via a touch display, coordinates the I2C data transmission to the Arduino Uno and finally also performs the communication with the web-server via WiFi. The Arduino Uno was chosen for the measurement task because it is an inexpensive platform that is well documented on the web. The task of the Arduino is to discharge the battery under test with a constant current, measure the terminal voltage and later on send these voltage values back to the Raspberry Pi via I2C. Since the I2C bus only allows to send values of size 'Byte' and the voltage is stored as millivolts, the only way to send one voltage value is to split it up to four single characters on the Arduino and send them to the Raspberry Pi sequentially, where they are pieced back together after the transmission has finished. Since this procedure takes a lot of time, the complete measurement is first performed on the Arduino, where all the voltage values are stored in an array. After finishing the measurement the complete array is sent to the Raspberry Pi at once with the method described before. Also the temperature is of high importance as it was already mentioned in section 3.1. Therefore an ambient temperature measurement is performed before the actual battery discharge to later on decide, which SOH reference curves have to be used. The battery discharge circuit consists of four main elements. The first is the battery itself that will only close the circuit if inserted into the battery tray. For the discharging process itself, a MOSFET is used, where the gate is not controlled via a PWM signal coming from a MOSFET driver, but an analogue voltage provided by an operational amplifier circuit. This has the big advantage that the current signal seen by the current transducer is also an analogue signal and can directly be used without using any average calculations. The current transducer was chosen to work on Hall effect because of the high discharge currents of up to 30A. The disadvantage of this MOSFET control method is that there is a lot of heatloss since the drain-source path is not opened completely. Therefore a high-ohmic load resistor has been used between the MOSFET and the battery to lower the voltage drop across the MOSFET and consequently also decrease the losses produced. To support the heat conduction, a separate heat sink is attached to the MOSFET. The most important information is the voltage behavior of the battery that will directly be measured via a voltage divider based on resistors. The voltage divider is only used for protection since the maximum input voltage for the analogue input of the Arduino Uno is 5VDC. The measurement frequency for the voltage will be 100Hz. The current has to be controlled with a much higher frequency since the quality of the measurement is depending on how exact the discharge current can be held depending on the specification from the dataheet. The currents for every single battery type will not be saved on the Arduino but initially sent via I2C from the Raspberry Pi. Therefore the only logic functions working on the Arduino are the current measurement and the data logging. The voltage data is then transferred to the Raspberry Pi and afterwards sent to the web server via WiFi as described in the next section.

3.4 Server and Database

As already mentioned in the previous sections, the data produced by the DBA is sent to the server via the Internet. However, the communication mechanism has not yet been explained. Basically, it works via a RESTful web service [Richardson/Ruby 2008] provided by the server. The reason for using the REST (Representational State Transfer) paradigm is that the provided and requested data is stateless, i.e. immediately successive measurements by a single DBA are not related in any way. Furthermore, using REST has the advantage that one can use simple and well-defined HTTP (Hyper Text Transfer Protocol) requests such as GET (retrieving information), POST (sending information), PUT (updating information) and DELETE (deleting information) as defined in RFC 2616 [Berners-Lee et al. 1999]. Also status codes of the responses are defined in the RFC, e.g. status code 200 for OK or 201 for Created. All of this makes the communication much more standardized and easier to handle on both the DBA and the server. For transmitting the desired data, we use JSON (JavaScript Object Notation). This enables us to remain very flexible in terms of how the transmitted data is structured. The server in its current form provides two so-called REST endpoints:

Check: This endpoint checks if the connection to the server can be established by the DBA. After a GET request is received by this endpoint, it either returns a response with the status code 204 (for No Content) if the server is reachable and can be used or a response with the status code 500 (for Internal Server Error) if the server encountered problems.

Soh: This endpoint has two purposes. The first purpose is to return the SOH according to the given measurement values. When receiving a POST request with a correctly formatted JSON string it returns a response with the status code 200 (for OK) and the calculated SOH for the given measurement values. Furthermore, it stores the request for later analysis. If the server encounters a problem, it returns a response with the status code 500. The second purpose is to display the last measurements in human readable form. When receiving a GET request on this endpoint the server returns a response with the status code 200 and an HTML (Hyper Text Markup Language) representation of the last measurements in a table. The following listing shows an example for a JSON formatted request onto the soh endpoint to get the SOH according to the given measurement values.

```
{"deviceId": "123abc",
"type": "Battery1",
"temp": 25.2,
"voltages": [3.5, 3.4, 3.2, ...]}
```


For finding the set of reference values that best matches the measured values we have chosen to use the NRMSE (Normalized Root Means Squared Error), which is shown in equation 2. All of the logic explained above has been implemented in Java and Apache Jersey4 has been used as a REST framework. In addition to the server software also an efficient database structure was needed. The created structure can be seen in figure 13.5. Due to the table reference type the system is very modular in terms of which kind of measurement data can be processed. If at any point it is desired to measure the amperage or the wattage instead of or in addition to the voltage, this can be easily achieved with this structure. Furthermore it is possible to handle any amount of battery types and measurement temperatures as well as any resolution for the SOH.

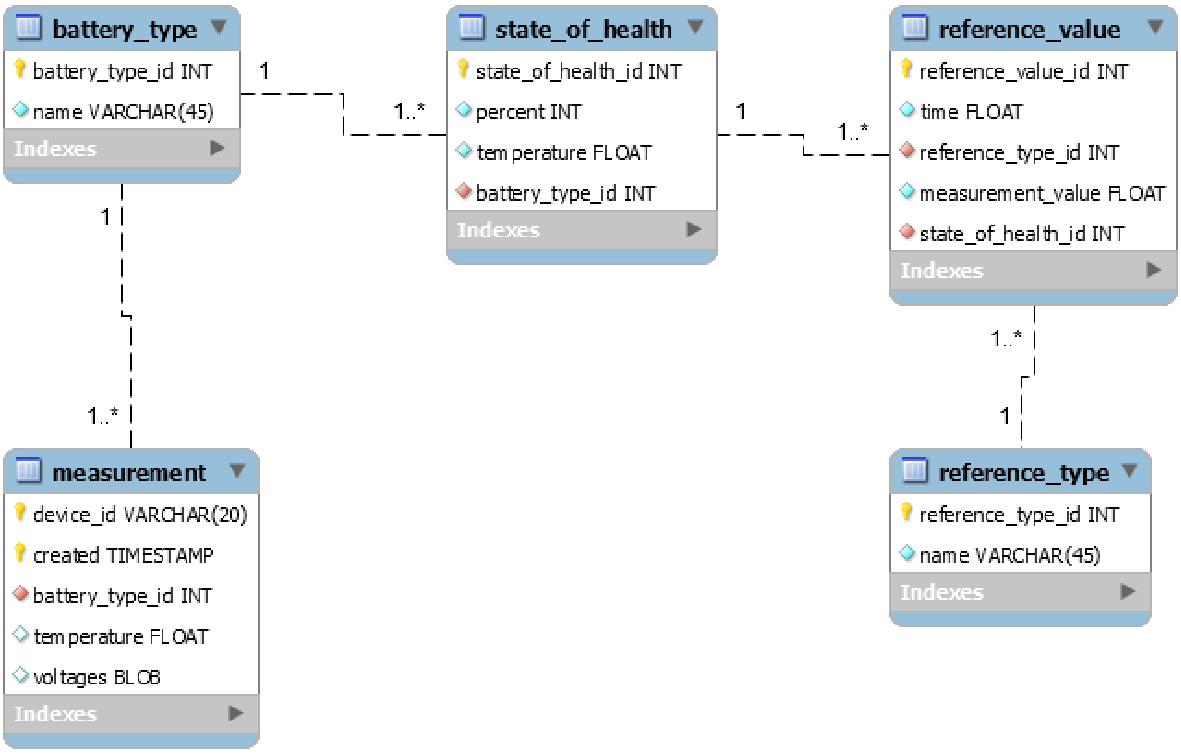

Fig. 13.5. Structure of the database for measurement and reference data

4 Results

In this section, the results of the comparison algorithm using measured data coming from the test bench can be seen. For this purpose a statistical method based on the chi-squared test goodness of fit method was used [Peck/Devore 2012]. This function was then normalized to gain a result as it can be seen in equation 2. It can also be found in the Matlab 'goodnessoffit' function 5 in a similar way. The implementation will lead to a slightly different result since the Matlab function will use 1 as a perfect fit and the equation 2 will directly show the error, so 0 would indicate no error.

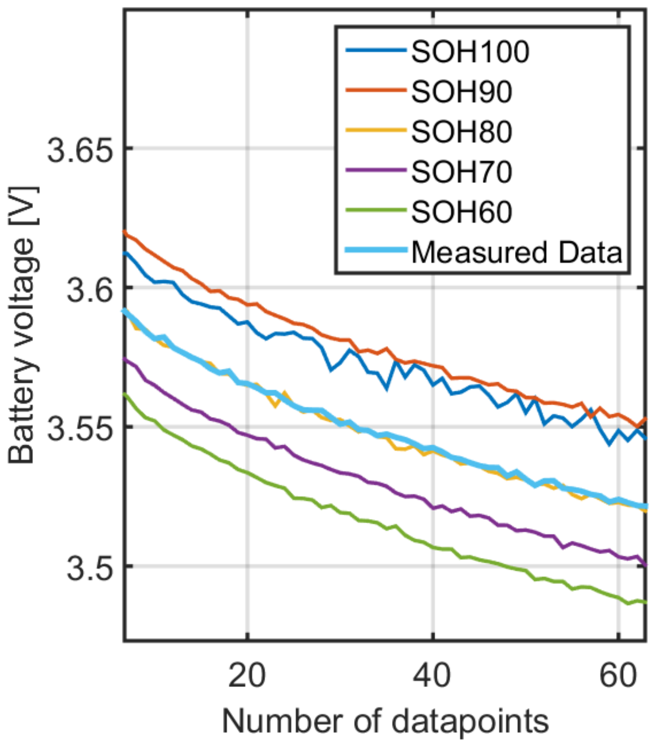

Fig. 13.6. Comparison of measured and reference data

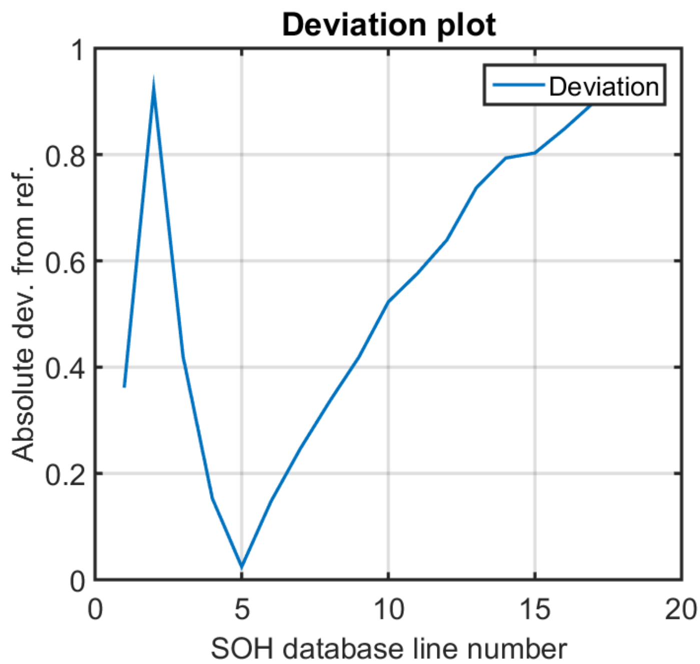

Fig. 13.7. Deviation between measured and reference data

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i}-X_{model,i})^2}{n}}}{X_{obs,max}-X_{obs,min}} \qquad (2)$$

Since the algorithms running on the server do not have a direct graphical user interface, the reference data from the database and measured data from the test bench were used in a Matlab script with to visualize the results. Equation 2 was used in Matlab to make the comparison between measured and reference data. For the measured values, data from the controlled battery aging process were used because they are already characterized and therefore will also show if the method used for comparison is whether right or wrong. The data used for the comparison can already be seen in figure 13.3. When zoomed in, the a more clear result can be seen as shown in figure 13.6. For this test a measured curve very similar to the reference curve was chosen because it shall show that there are huge differences in the deviation compared to other reference curves (see figure 13.7). This deviation, the result of the NRMSE algorithm, will be stored in an array. Finally the array entry with the lowest deviation will show the SOH of the battery tested. In the server, this value will then be passed on to the Raspberry Pi to be shown to the user.

5 Conclusion

The aim of this project is to develop a method to classify secondary lithium-ion batteries. This was achieved with a measurement device which includes the user interface, the battery measuring point, and the connection to the web server where the comparison of the measured values with the stored values takes place. As one will directly notice, the results published in this paper are from an ongoing project and document its state at the end of February 2016. The section "Results" shows that the methods used for the indication are plausible and will work as long as the measured data coming from the DBA is accurate enough that there will not be too high ripples. The server and database system implemented work fine in combination with the Raspberry Pi and using I2C bus for the communication between Raspberry Pi and Arduino also shows good results when sending single characters. The future goal of this project will be the implementation and test of all sub-functions within in one system. Since all single systems can already run nonindependent the most important work will have to be invested in the improvement of the current measurement at the DBA and the NRMSE method running on the web-server.

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Pomen poznavanja dejanskega stanja hidravličnega olja kot osnova za strateška odločanja

DARKO LOVREC & VITO TIČ

Povzetek Običajna hidravlična olja na mineralni osnovi in turbinska olja, katera se uporabljajo na strojih in napravah imajo različno dolgo uporabno dobo. Ta je odvisna od vrste različnih faktorjev: od pravilnega vzdrževanja in uporabljen vrste nadzora in aktivnosti in od skrbne izbire vrste olja. Mehanizmi staranja hidravličnih olj in pa vzroki, zakaj jih je potrebno zamenjati so sicer zelo dobro znani uporabnikom, manj poznano pa je dejstvo, da so med posameznimi vrstami olj velike razlike glede njihove vzdržljivosti, ko so le ta izpostavljena delovnim pogojem stroja.

Vsako podaljšanje uporabne dobe hidravličnega ali turbinskega olja ponuja tako finančne kot okoljske prednosti, a predpostavlja poznavanje dejanskega stanja olja. Za namene ocene preostale uporabne dobe olja, je v prispevku predstavljena nova metoda za primerna za on-line nadzor stanja in za testiranje vzdržljivosti oz. oksidacijske odpornosti različnih hidravličnih olj. Rezultati takšnega testiranja uporabniku nudijo možnost strateškega odločanja pri postopku nabave najprimernejšega olja z dolgo uporabno dobo.

Ključne besede: • hidravlično olje • staranje • on-line nadzor • testiranje • strateško odločanje •

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The Importance of Hydraulic Oil Real-Condition Identification as a Basis for Strategical Desicion-Making

DARKO LOVREC & VITO TIČ

Abstract Conventional mineral-based hydraulic oils and turbine oils used within energy plants and machines have different long service-lives. This depends on variety of different factors: by proper maintenance, monitoring activities and strategies, and by careful selection of oil-type. Aging mechanism of hydraulic oils and the fact why they need to be replaced are well-known to the user, but lesser-known is the fact that there are great differences in the durability of hydraulic oils when exposed to machine-operating conditions.

Any extensions in the service-lifetimes of hydraulic or turbine oils can deliver both, cost savings and environmental benefits, but requires the knowledge of real oil-condition. In order to evaluate the service-life of oil, this paper proposes a novel method appropriate for on-line condition monitoring and testing the durability and oxidation stabilities of different hydraulic oils. The test results can be used for selecting the more adequate oil with a long service-lifetime.

Keywords: • hydraulic oil • aging • on-line monitoring • testing • strategical decision-making •

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1 Introduction

Increasing investment costs of machines incorporating fluid power combined with increased demands on mean time between failures put pressures on manufacturers to incorporate condition monitoring function into their systems [1].

Different energy plants, e.g. water, nuclear, thermal power plants or off shore wind energy regeneration plants, are operated in 24/7 cycle and in some cases far off any maintenance departments and stuffy, and with the expectation that they generate electricity all year round. The same applies to some production machines in complex production environments where reliability has to increase, while downtime and unscheduled breakdowns have to be kept at an absolute minimum. All these systems are using hydraulic drive technology with increasingly complex components that need to be monitored, as well as the hydraulic oil condition in the hydraulic system. Hydraulic oil can be changed when necessary and not at predetermined time intervals. Thus cost for the purchase, disposal and storage decreases with reduced consumption and sustainability of regrowing sources increases and natural resources last longer.

Typical characteristics of wear and failure rate, which applies to all technical components, are shown in Figure 14.1.

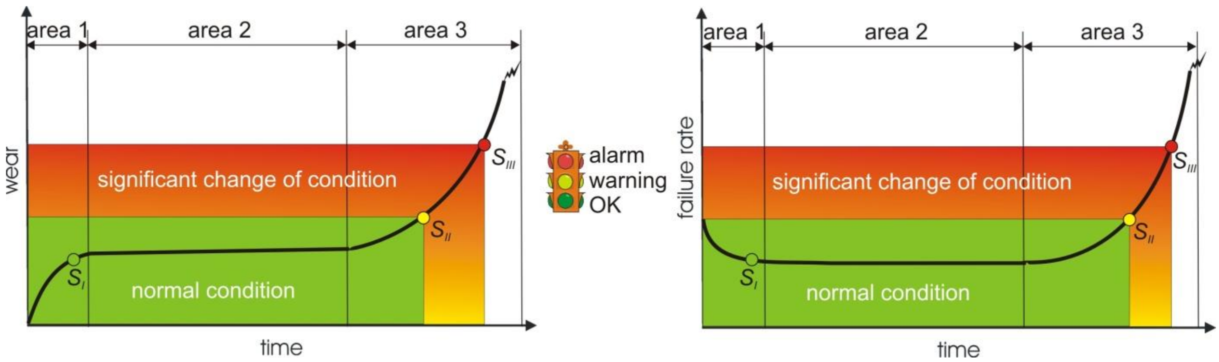
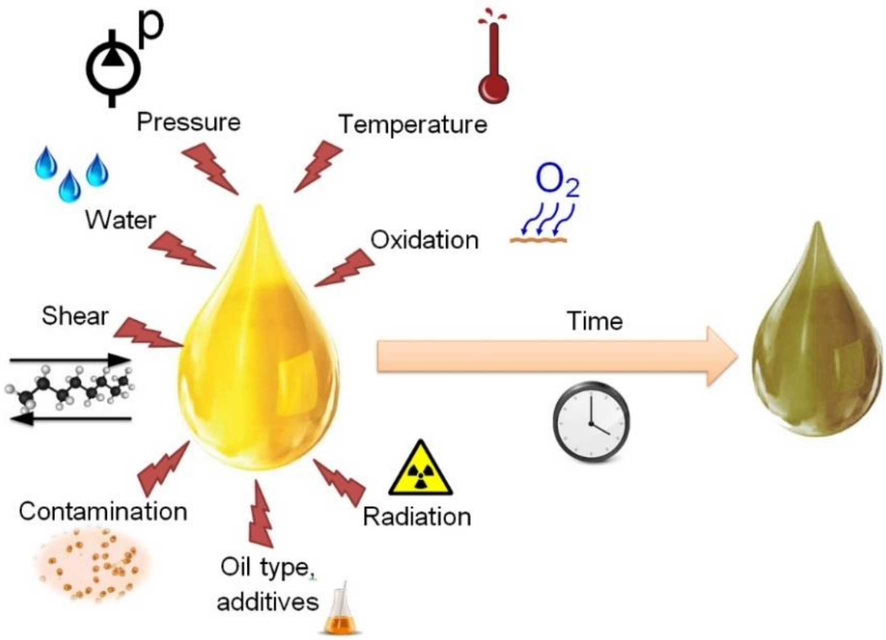


Figure 14.1: Typical characteristics of wear and failure rate [1]

Area 1 stand for increased wear or even early failures due to faults in material, poor tolerances, assembly errors, brought-in dirt or the use of incompatible fluids. A good quality control management system should take care of these early failures and prevent them from occurring. Area 2 comprehends the real system lifetime without much wear and any failures. It is followed by area 3 with gradual wear and failures and then self-enhanced demolition of a system failure. Here it becomes important for a condition monitoring system to recognize the failure and visualize counter measures for action items by the user.

The same course of changes also applies to hydraulic fluids - eg. the most commonly used mineral based hydraulic oils. But in this case the profile course concerns the changes relate to changes in physical and chemical properties of hydraulic fluid. In order to satisfy all requirements regarding the long service-lifetime, the different physical and chemical properties of the hydraulic fluid must remain within certain limits. Unfortunately, throughout its life-cycle the hydraulic fluid is subject to several physical and chemical operational effects [2], e.g. high pressures and temperatures, oxidation, mechanical and/or fluid contamination and others, as shown in Fig. 2. Consequently, over time the hydraulic fluid loses its abilities for performing the key functions and therefore must be changed.



Nowadays the lifetimes of the hydraulic fluids are still mainly determined by the machines' manufacturers, i.e. at certain fixed time intervals or number of hours [2]. In most cases these are empirically estimated time intervals with certain degrees of safety factors. The actual quality of a fluid is rarely taken into account, or the operating conditions of the machine. Therefore the quality of a fluid may be better than estimated and the fluid may be changed much earlier than actually needed.

All the above-mentioned depend of the type and "quality" of used hydraulic oil. Therefore it is very important to know what the durability of the used hydraulic oil is (under normal operational conditions). Different test methods are used to obtain this information.

2 Oil Degradation and ageing test

When properly maintained, mineral based hydraulic oils have relatively long service-lives from 5 to 10 years and in the case of hydraulic turbine oils even more than 20 years. Therefore it is reasonable to obtain data regarding physical and chemical changes using an accelerated-ageing test.

Due to the diversity of the base-oils, and the diversity of additives present within the oil, it is impossible to provide a precise and unique statement regarding the general mechanisms of oil ageing and on-going chemical processes. Hydraulic oils oxidise during "the performing their work" which is reflected in significant increases in friction and wear that affects the performance of the machine and consequently its reliability. The main effect of oxidation is a gradual rise in the viscosity and acidity of the oil.

As already mentioned mineral oils oxidise during their service-lifetimes and this causes significant increases in friction and wear that affects the performance of the machine. The main effect of oxidation is a gradual rise in the viscosity and acidity of the oil, as well as the formation of deposits, in form of sludge and warmish, which can cause the blocking the oil pathways inside the components.

The oxidation rates can be affected by temperature, metals in contact with the oil, and the amount of water and oxygen present within the oil. The temperature especially has a profound effect on oxidation rates, which can be doubled or even tripled by a temperature rise of 10 °C [3], [4]. This is why accelerated oil-ageing tests usually involve high temperatures, high pressures and the additions of different catalysts, and water.

The commonly used accelerated oil-ageing tests can be divided into two main groups: the mechanical ones and the thermal or chemical ones. The mechanically accelerated oil-ageing tests performed on specially built test rigs are otherwise closer to real conditions but they have very long testing times. Therefore these kinds of tests are performed using real hydraulic components under harsh, tougher usages: higher temperatures and pressures, smaller oil quantities, bigger pump-sizes, higher contamination with solid particles, higher water content or moisture, etc.

By using the so-called thermal oil ageing tests we obtain quicker information regarding the oil durability. There are several standardised accelerated-ageing tests available, mainly developed for the evaluation of oxidation stabilities regarding fresh and in-service hydraulic oils, e.g. [5], [6]. They are based on exposing the hydraulic fluid to high temperatures, air or oxygen, different contaminants such as water, copper, iron, that act as catalysts. A brief overview of the common tests and their operational conditions can be found in Table 14.1.

Table 14.1: Overview of standardised thermal oxidations tests

Test (ASTM)	Gas	Pressure	Temp	Catalyst
PDSC (D6186)	O_2	34.5 bar	180 °C	Fe
RPVOT (D2272)	O_2	6.2 bar	150 °C	Cu/Fe
UOT (D6514)	Air	Atmospheric	155 °C	Cu/Fe
UOT (D5846)	Air	Atmospheric	135 °C	Cu/Fe
TOST (D943)	O_2	Atmospheric	95 °C	Cu/Fe/H_2O

The listed tests are not suitable for further extensive research related to the determinations and identifications of variations in the physical and chemical properties of the tested oils, as they are tested on smaller quantities of oil, eg. RPVOT: 50 g and TOST: 300 mL. Therefore we were forced to develop our own thermal test for accelerated oil-ageing using a larger sample volume of 1,500 mL, which would suffice for all subsequent laboratory analyses (so-called the thermal dry LaOH test). Our own novel test is based on the more established and more frequently used standardised RPVOT and TOST tests. During our test, the oil is heated using a magnetic mixer to 160 ±0.1 °C whilst 3 ±0.1 L/min of air is being constantly induced. The test also includes a catalyst in the form of a 1.5 mm^2 copper wire of which 15 m is bent into a spiral.

The test is carried out under atmospheric pressure within a sealed chamber with a dedicated system oil extraction of oil vapour. As shown in Figure 14.3, the chamber allows for the testing of both single and multiple samples at the same time.

Figure 14.3: Thermal durability LaOH test for hydraulic oils

The used test does not have specific end-times because its main goal is to record the process of accelerated oil-ageing over its service-life. Thus multiple tests over various durations are carried out on one type of oil in order to achieve different degrees of oil-ageing and oxidation rates. So we obtain several different degraded samples on which we can carry out further laboratory analyses. After the test, all the samples are first measured using several on-line sensors and then sent to a laboratory for further in-depth chemical analysis.

Figure 14.4: Hydraulic mineral oil samples after the different testing hours; different degrees of ageing and oxidation; sludge formation on copper wire

The tests and laboratory analyses conducted (Figure 14.5) revealed, that the oil-ageing and oxidation processes can best be monitored and evaluated using the following parameters:

- colour (ASTM D 1500),
- viscosity (ASTM D 445),
- neutralisation number (ASTM D 974),
- FT-IR oxidation (ASTM E 2412),

shown as a function in regard to achieved test time.

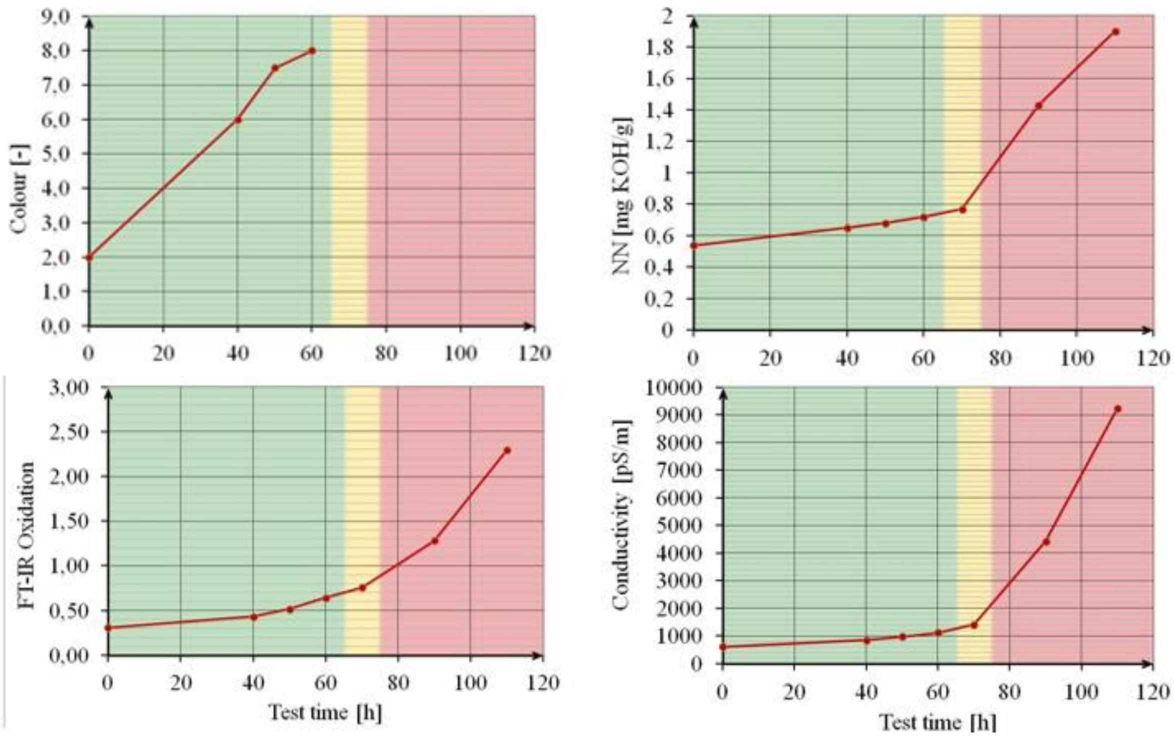


Figure 14.5: Accelerated oil-ageing test results

On the basis of the described test and after the detailed laboratory analysis of the more important physical and chemical parameters of the oil, comparative testing of three different turbine oils was carried out.

3 Determinatio of different turbine oil's lifetimes

In regard to testing the useful lifetimes or durability of hydraulic turbine oils three different turbine hydraulic oils types have been used: mineral turbine oil (TO1), pre-treated mineral turbine oil (TO2), and saturated synthetic ester as a turbine oil (TO3). All three types of turbine oils were tested according to the described procedure - the durability dry thermal test.
The tests and laboratory analysis conducted revealed that:

- Certain oils resist the oxidation and ageing processes much better than others and may have double or even several multiple extended service lifetimes.
- The results can be used for carefully selecting more appropriate high quality oils with high oxidation stabilities, which would have extended service -lives.

After the completion of a more detailed analysis using laboratory results for the physical and chemical parameters of the tested oils, the results revealed that oil-ageing can best be monitored and evaluated beside by colour, viscosity, neutralisation number and FT-IR oxidation with an electrical conductivity. The electrical conductivity as a physical-chemical parameter and as an oil-ageing degree indicator is especially appropriate for an on-line Condition Monitoring system.

A direct comparison between the results on the same graph certainly provides better insight into the changing of individual parameters during the testing times, using the same time-scale – Figure 14.6.

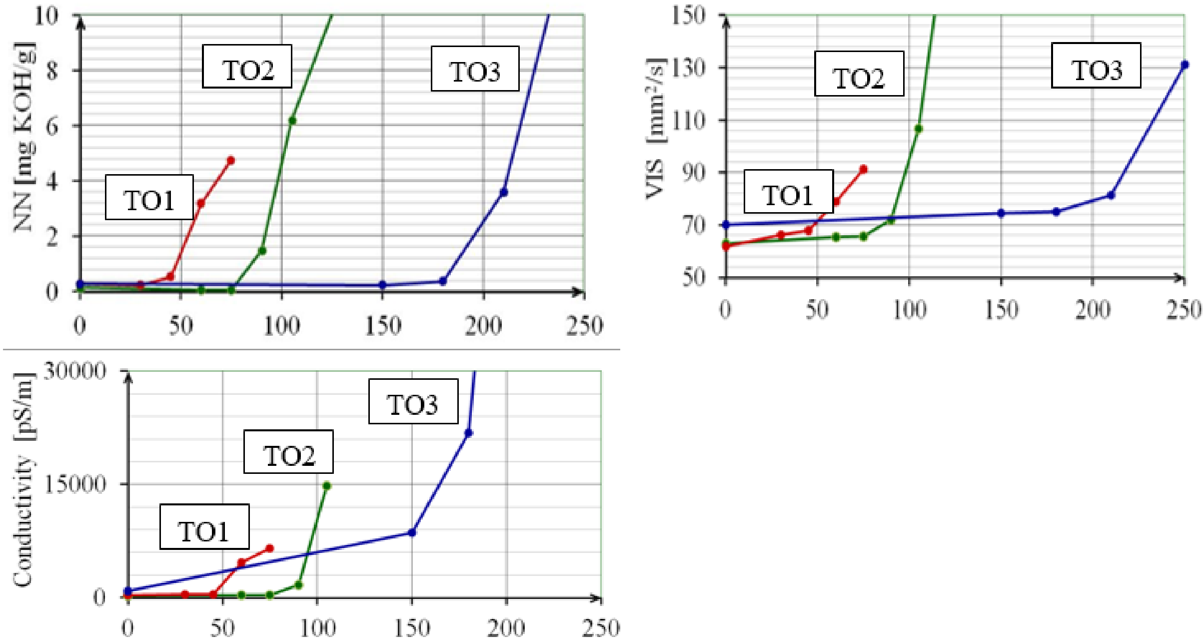


Figure 14.6: Different parameters of three turbine oils in direct comparison

If we take a closer look at the graphs shown in Figure 14.6, we can make comparisons between three different turbine oils' performances during the test. We can see the poor performance of mineral turbine oil TO1 (red) in every aspect. It lasted the least time until the values started to increase exponentially. A much better performance was achieved by the turbine oil TO2 (green line), which lasted almost twice as long as the TO1. The interesting thing is that they basically have the same price. Turbine oil TO3, which is a synthetic, saturated ester had the best performance but it‘s price is also higher than those of TO1 and TO3.

The neutralisation number (NN) and electrical conductivity are two very important or revealing parameters regarding the state of oil degradation were recalculated to 'real time' and 'real operating' conditions - at operating oil temperatures of 60 °C, as shown in Figure 14.7.

As known from the literature, at temperatures higher than 70°C for every 10°C the status changes by a factor of 2, and the same condition increases the time by a factor of 2. This should be at a temperature of 80 °C instead of 70 °C, and thus the lifetime of a mineral oil is halved. This can be written in the equation below:

$$f = 2^{\frac{T - T_{ref}}{10}} \qquad (1)$$

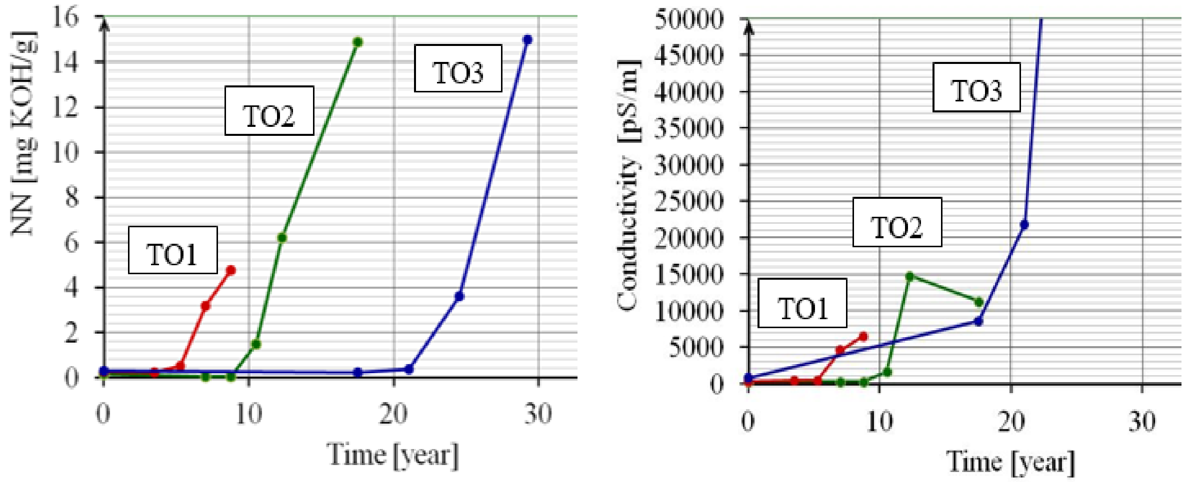


Figure 14.7: Results of measurements converted to real-time and real operating conditions

Both Figure 14.6 and Figure 14.7 show the differences between the various turbine oils' resistances to ageing and are very significant, even more than 4 times. The reason is, that saturated esters (TO3) do not readily react with oxygen and are, therefore, significantly more stable than non-saturated ester products. This is also a major factor in their 'lifetime fulfilling' characteristics.

4 Conclusion

The extensions of service-lives regarding hydraulic fluids is gaining prominence due to several considerations including environmental pollution, conservation of natural resources and the economic benefits associated with extended service-life. By using the enhanced fluid management techniques and hydraulic oil with the highest durability, several economic and environmental benefits can be obtained over a longer period of time.

The presented novel method for testing the durability and oxidation stabilities of hydraulic fluids can be simultaneously used in two ways. Firstly for comparing different hydraulic oils and for selecting more adequate oils with higher oxidation stabilities and longer service-lifetimes and secondly for the development of a prognostic model for an accurate prediction of an oil's condition and its remaining useful lifetime, which could help to extend the service life of the oil without concerns about damaging the equipment

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Izzivi oddaljenega spremljanja stanja hidravličnih olj

VITO TIČ & DARKO LOVREC

Povzetek Zagotavljanje ustrezne kakovosti hidravličnega olja ter ustrezno predvidevanje menjave polnitve je ključnega pomena za stabilno in nemoteno obratovanje mnogih industrijskih naprav. Pri tem nam največjo mero zanesljivosti vsekakor ponuja stalno spremljanje stanja hidravličnih olj, ki se običajno vrši oddaljeno s pomočjo sodobnih senzorjev.

Kljub temu pa razvoj in implementacija takšnega sistema predstavlja svojevrstni izziv, saj je merjenje stanja olja veliko bolj zapleteno, kot merjenje običajnih obratovalnih parametrov, kot sta na primer tlak ali temperatura.

Ključne besede: • hidravlično olje • kakovost • oddaljeno spremljanje • menjava olja • sodobni senzorji •

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1 Uvod

Zaradi vedno večje dostopnosti on-line senzorjev za merjenje lastnosti maziv, so naše zadnje razvojne aktivnosti usmerjene v on-line nadzor stanja maziv ter posredno strojev, kjer so vgrajena. Sistemi za nadzor stanja maziv na daljavo imajo mnogo prednosti pred konvencionalnimi rešitvami. Ker gre za nenehni nadzor stanja maziva v realnem času, lahko sistem zazna tudi nenadna poslabšanja stanja in sproži alarmno obvestilo, še preden pride do nastanka katastrofalnih posledic. Vgradnja sodobnega on-line sistema za nadzor stanja maziva uporabniku zagotavlja najvišjo stopnjo zanesljivosti obratovanja ter mu omogoča zmanjševanje okvar na stroju, podaljševanje vzdrževalnih ciklov in intervalov menjav maziv.

Kot smo že omenili, je največja prednost on-line analiz, v primerjavi s klasičnimi laboratorijskimi analizami, njihova kontinuirana meritev in zanesljivo odkrivanje nenadnih oz. nepredvidljivih dogodkov, saj je napaka odkrita tako rekoč v realnem času. Naslednja prednost je beleženje trenda meritev, saj se običajno pri izvajanju on-line analiz za zajemanje podatkov uporabljajo avtomatizirani sistemi, ki hranijo tudi zgodovino rezultatov meritev [1].

On-line spremljanje stanja ima seveda tudi svoje omejitve, med katerimi je potrebno izpostaviti predvsem omejeno število senzorjev oz. veličin, ki jih lahko spremljamo. Prav tako se parametri, ki jih merimo z on-line senzorji, običajno razlikujejo od parametrov, ki jih določamo z laboratorijskimi analizami, zato neposredna primerjava med njimi ni mogoča. Nenazadnje, pa je za interpretacijo meritev običajno potrebno izvesti kalibracijo senzorjev, ki je veljavna le za posamezno vrsto hidravlične tekočine [1].

Zaradi omenjenih omejitev je on-line spremljanje stanja hidravličnih tekočin, za razliko od meritev tlaka ali temperature, veliko bolj kompleksno. Stanje olja namreč ni odvisno le od posameznega parametra, temveč od večih hkrati. V odvisnosti od obremenitve, vrste olja in drugih mejnih pogojev se stanje olja tudi spreminja [2].

Pri načrtovanju in izvajanju oddaljenega nadzora stanja hidravličnih naprav je za dosego kvalitetnih merilnih podatkov ključnega pomena več dejavnikov, kot npr:

- izbira ustreznih senzorjev,
- ustrezna vgradnja senzorjev,
- ustrezno mesto zajemanja vzorca iz hidravličnega sistema (reprezentativnost vzorca),
- ustrezna povezava senzor – enota za zajemanje in obdelavo podatkov,
- dodatni ukrepi za izboljšanje natančnosti in verodostojnosti meritev.

Z ozirom na zgoraj navedene točke se prispevek v nadaljevanju osredotoča na predstavitev konceptov in ukrepov za doseganje ustrezne kvalitete merilnih podatkov ter izboljšanje natančnosti on-line meritev.

2 Online senzorji

V sklopu on-line spremljanja stanja hidravličnih tekočin so se do danes najbolj uveljavile meritve:

- temperature,
- relativne vlažnosti,
- viskoznosti,

- dielektrične konstante,
- električne prevodnosti,
- ter stopnje čistosti.

Omenjene metode ter pripadajoče senzorje smo že večkrat podrobneje predstavili v različni literaturi [3–5], v glavnem pa jih delimo na dve skupini, in sicer na senzorje za zaznavanje fizikalno-kemijskih parametrov tekočine ter na števce delcev.

Pred izvedbo ukrepov za izboljšanje meritev vsekakor velja posebno pozornost posvetiti vgradnji oz. povezavi senzorskega sistema v nadzorovani hidravlični sistem, saj lahko sámo mesto vgradnje senzorjev oz. mesto odvzema hidravlične tekočine močno vpliva na točnost meritev.

3 Načini vgradnje senzorjev

On-line senzorje za spremljanje stanja maziv lahko v osnovi namestimo na štiri različne načine oz. mesta, in sicer:

- v rezervoar,
- na povratni vod,
- na tlačni vod,
- ter v obtočni sistem.

3.1 Namestitev senzorjev v rezervoar

S stališča vgradnje senzorjev je največja razlika med senzorji fizikalno-kemijskih lastnosti tekočine ter med števci delcev ta, da števci delcev za svoje delovanje oz. merjenje potrebujejo določen pretok tekočine skozi senzorski element, ki običajno znaša med 30 in 300 ml/min. Zato v primeru namestitve senzorjev v rezervoar ne moremo vgraditi števca delcev. V kolikor pa sistem on-line nadzora stanja ne predvideva uporabe števca delcev, pa se priporoča vgradnja senzorjev v bližino sesalnega voda. V tem predelu rezervoarja je namreč hidravlična tekočina običajno že umirjena, ohlajena ter vsebuje minimalno količino kontaminantov (npr. zrak, trdni kontaminanti), ki lahko popačijo merilne rezultate [6].

Ostale tri opcije namestitve nam zagotavljajo pretok hidravlične tekočine skozi senzorski sistem in s tem omogočajo tudi namestitev števca delcev.

3.2 Namestitev senzorjev na povratni vod

Zajemanje tekočine na povratnem vodu se sprva zdi najbolj primerno, saj običajno zajemamo tekočino pred filtrskim elementom in s tem merimo stanje tekočine, ki je ravno prepotovala sistem in vsebuje največ kontaminantov oz. informacij o stanju sistema. Pri tem načinu namestitve se običajno izkoristi tlačna razlika na povratnem filtrskem elementu

(2 – 5 bar), ki zagotavlja pretok skozi obtočni senzorski sistem. V primeru uporabe števca delcev, pa ta majhna tlačna razlika komaj zadostuje za minimalni pretok tekočine skozi števec. Poleg tega je ta pretok nizko-tlačni ter spremenljiv glede na viskoznost in temperaturo olja ter glede na zamašenost filtrskega elementa. Ker so izvedena testiranja pokazala, da so on-line števci delcev mnogo bolj natančni pri višjih pretokih (vsaj 100 ml/min) ter višjih tlakih (nad 30 bar), montažo števca delcev na ta način odsvetujemo.

3.3 Namestitev senzorjev na tlačni vod

Pri zajemanju tekočine iz tlačnega voda potrebujemo za senzorskim blokom dodaten regulator pretoka, ki skrbi za konstanten pretok skozi senzorski sistem, ne glede na tlak, viskoznost in temperaturo olja v primarnem hidravličnem vodu. Števec delcev običajno namestimo pred regulator, s čemer je tekočina v števcu izpostavljena visokemu tlaku, ki stisne morebitne prisotne zračne mehurčke in s tem izboljša merilno natančnost in stabilnost meritev. Ker ostali senzorji fizikalno-kemijskih lastnosti običajno ne dopuščajo visokih tlakov, jih namestimo za regulator pretoka, kjer je prisoten le nizek tlak tekočine (povratni vod v rezervoar).

3.4 Namestitev senzorjev v obtočni sistem

Olje lahko zajemamo iz rezervoarja tudi s posebno črpalko in s tem ustvarimo obtočni sistem. Čeprav je takšna izvedba običajno najdražja, nam zagotavlja najboljše oz. najbolj konstantne pretočne razmere skozi senzorski sistem, kar je zlasti pomembno pri uporabi on-line števcev delcev.

Pri tem načinu namestitve se pri večjih rezervoarjih pojavlja nevarnost, da tekočino zajemamo iz »mrtvega« področja rezervoarja (kjer tekočina ne kroži, ampak miruje), kar lahko povzroči večje napake v meritvah [7]..

4 Ukrepi za izboljšanje natančnosti in ponovljivosti meritev

Poleg dobrega poznavanja pretočnih razmer, tako v primarnem hidravličnem vodu, kakor tudi v senzorskem sistemu, je za doseganje kvalitetnih rezultatov on-line meritev pomembno tudi razumevanje delovanja senzorjev, skupaj z ovrednotenjem njihovih rezultatov. Z namenom razumevanja delovanja senzorjev in izboljšanja njihove merilne natančnosti smo izvedli več manjših raziskav, ki so predstavljene v nadaljevanju.

4.1 Meritev relativne vlažnosti

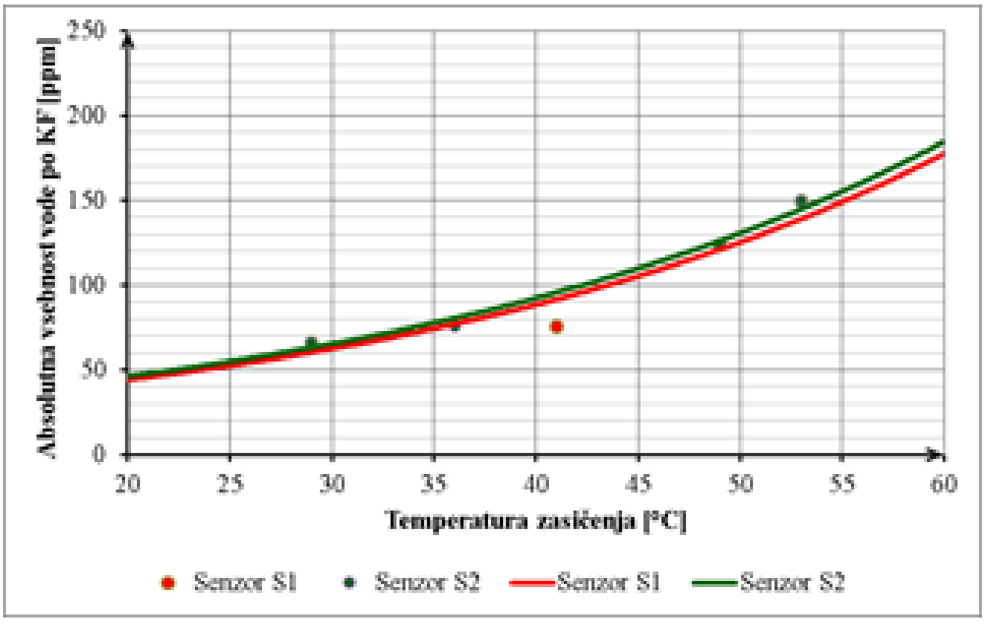
On-line senzorji zaznavajo relativno vsebnost vode v mineralnem olju, in jo podajajo v odstotkih. Olje je 100 % nasičeno tedaj, kadar vsebuje maksimalno količino vode pri določeni temperaturi in tlaku – meja zasičenja. V nasprotju pa pri klasičnih kemijskih laboratorijskih analizah olja merimo absolutno vsebnost vode po metodi Karl-Fischer, ki nam poda količino vode v utežnih odstotkih ali ppm.

Meja zasičenja lahko občutno variira glede na vrsto merjene hidravlične tekočine oz. glede na različna bazna olja in različne formulacije paketov aditivov mineralnih hidravličnih olj. Zato je smiselno opraviti testiranja, s katerimi določimo mejo zasičenosti določenega tipa olja, saj le-ta predstavlja mejo, nad katero postane vsebnost vode v hidravličnem olju škodljiva.

Določanje meje zasičenja z on-line senzorji in po Karl-Fischer metodi smo izvedli po naslednjem postopku. Enemu litru hidravličnega olja smo dodali različne količine vode. Nato smo posamezne vzorce ob segrevanju najprej pomerili z on-line senzorjema in odčitali temperature, pri katerih je posamezni senzor dosegel mejno zasičenost olja z vodo (tj., ko je senzor pokazal relativno vlažnost olja 100 %). Na omenjenih vzorcih smo nato opravili še primerjalne laboratorijske analize absolutne vsebnosti vode po Karl Fischer postopku. Rezultati meritev so prikazani v tabeli 15.1 ter na sliki 15.1.

Tabela 15.1: Rezultati meritev meje zasičenja z on-line senzorji in Karl-Fischer metodo

Vzorec	**Abs. vsebnost vode po KF**	**Temperatura zasičenja (°C)**	
		Senzor S1	**Senzor S2**
1	65,9	29	29
2	76,1	41	36
3	123,7	49	49
4	149,7	53	53

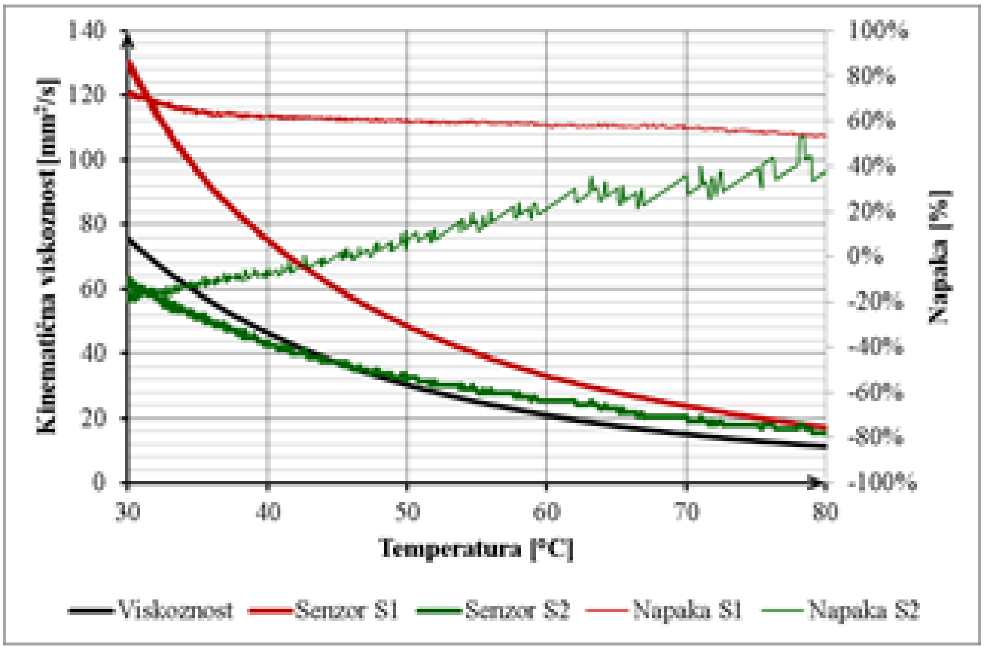


Slika 15.1: Meja zasičenja obravnavanega mineralnega hidravličnega olja z vodo

Na podlagi podatkov v tabeli 15.1 smo lahko poiskali krivuljo, ki podaja mejo zasičenja obravnavanega mineralnega hidravličnega olja z vodo (slika 15.1). Iz poteka krivulje je razvidno, da leži meja zasičenja obravnavanega olja pri delovni temperaturi od 40 do 60 °C med 90 in 180 ppm, kar je dosti nižje od še dopustne meje, ki jo običajno podajajo proizvajalci maziv (500 ppm).

4.2 Meritev viskoznosti

Viskoznost hidravlične tekočine je ena izmed njenih najpomembnejših lastnosti, ki jih je potrebno stalno nadzirati. Analizo natančnosti dveh on-line senzorjev za meritev viskoznosti olja smo opravili z mineralnim hidravličnim oljem ISO VG 46 v območju med 30 in 80 °C.



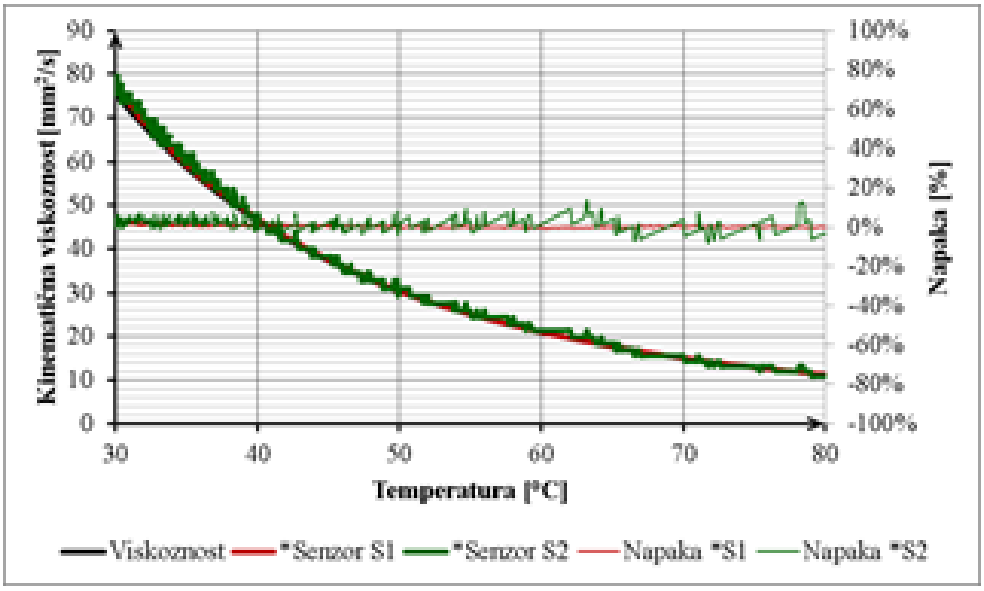
Slika 15.2: Rezultati meritev dveh on-line senzorjev viskoznosti olja

Rezultate prikazuje slika 15.2, na kateri črna črta predstavlja »dejansko« viskoznost olja, ki smo jo izmerili v kemijskem laboratoriju po postopku ASTM D 445 pri dveh karakterističnih temperaturah, tj. pri 40 in 100 °C. Kinematično viskoznost na celotnem razponu smo nato izračunali s pomočjo poenostavljene Walther enačbe, ki izvira iz standarda ASTM D341 [8]. Odebeljeni črti (rdeča in zelena) pa predstavljata izmerjene rezultate dveh on-line senzorjev.

Rezultati meritve prikazujejo močno odstopanje izmerjenih vrednosti kinematične viskoznosti senzorja S1 in senzorja S2 v primerjavi z dejansko kinematično viskoznostjo. Odstopanje je na sliki 15.2 ponazorjeno tudi v obliki relativne napake meritve (tanjši barvni črti), ki znaša pri senzorju S1 od 50 do 70 % ter pri senzorju S2 od -20 do 40 %.

Prikazano odstopanje je vsekakor preveliko in meritve s takšnima senzorjema bi bile popolnoma neuporabne. Predvidevamo, da takšna odstopanja nastanejo, ker so senzorji tovarniško kalibrirani le z določenim tipom tekočine. Natančnost meritev pa lahko močno izboljšamo, če opravimo umeritev določenega senzorja na določen tip hidravlične tekočine.

V primerjavi z dejanskimi izhodnimi vrednostmi senzorjev, ki so prikazane na sliki 15.2, so na sliki 15.3 predstavljeni rezultati meritev z upoštevanimi umerjevalnimi krivuljami. Iz slike je razvidno, da smo z umerjevalnima krivuljama, ki sta bili namensko določeni za uporabljen on-line senzor in uporabljeno hidravlično tekočino, močno izboljšali natančnost on-line meritev viskoznosti.



Slika 15.3: Rezultati meritev dveh on-line senzorjev viskoznosti olja z upoštevano umerjevalno krivuljo za določen tip olja in senzorja

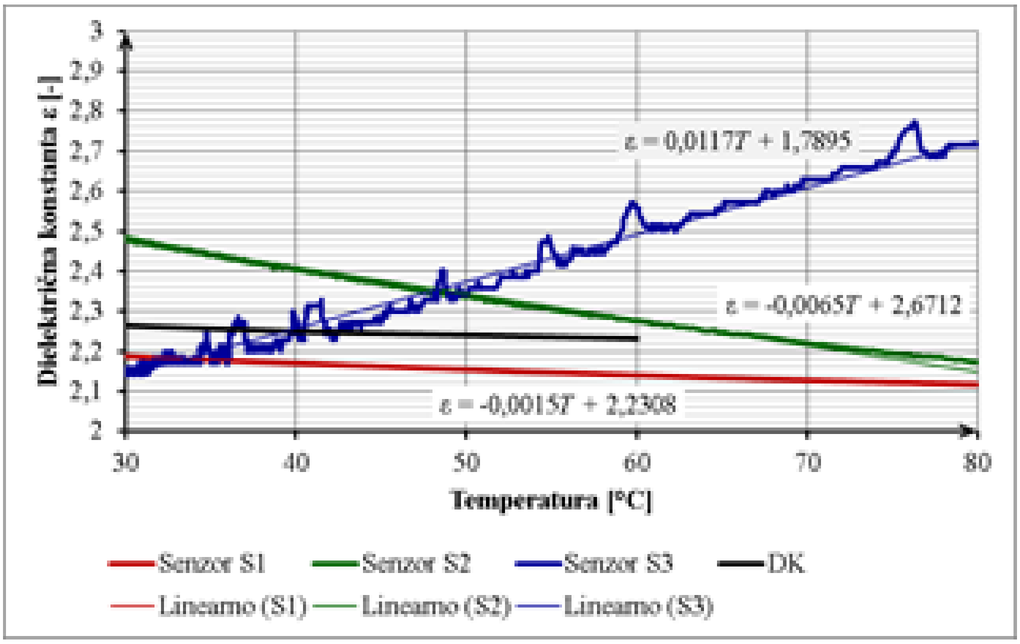
Po implementaciji umerjevalne krivulje, se relativna napaka senzorja S1 v celotnem območju giblje v območju ± 5%, medtem ko je relativna napaka senzorja S2 v predelu nižjih viskoznosti nekoliko večja zaradi zelo nizkih vrednosti izhodnih signalov in nenatančnosti uporabljene A/D kartice za zajem signala.

Poleg implementacije namenske umerjevalne krivulje za določen tip olja in določen senzor, lahko viskoznost natančneje spremljamo, če izmerjeno kinematično viskoznost pri temperaturi meritve preračunamo na viskoznost pri karakteristični temperaturi 40 °C. Za omenjen preračun smo zasnovali namenski program, ki temelji na standardih ASTM D341 in D2270, ter na iskanju rešitve z bisekcijo. Ta na osnovi vhodnih parametrov (kinematična viskoznost pri podani temperaturi, temperatura ter indeks viskoznosti) izračuna kinematično viskoznost hidravlične tekočine pri 40 in 100 °C. Na ta način lahko veliko bolje spremljamo trend sprememb viskoznosti hidravlične tekočine pri 40 °C, kljub nihanjem temperature v on-line sistemu.

4.3 Meritev dielektrične konstante

Dielektrično konstanto obravnavanega mineralnega hidravličnega olja smo v sklopu raziskav merili s tremi on-line senzorji. Rezultati meritev dielektrične konstante teh on-line senzorjev v primerjavi z natančno laboratorijsko meritvijo (Biotehniška fakulteta Ljubljana) so prikazani na sliki 15.4, iz katere je razvidno, da vrednosti dielektrične konstante, izmerjene z on-line senzorji, močno odstopajo od dejanske dielektrične konstante olja. Na tem mestu bi lahko, podobno kot pri on-line meritvi viskoznosti, poiskali umerjevalno krivuljo za določen tip hidravlične tekočine in za vsak senzor posebej. Ker bi morali za vsak tip hidravlične tekočine posebej meritev natančne dielektrične konstante ponovno zaupati zunanjemu izvajalcu, smo se zaradi ekonomskih razlogov odločili, da bomo zanemarili absolutno vrednost dielektrične konstante. Namreč, pri on-line spremljanju stanja hidravličnih tekočin nam največ pove relativna sprememba dielektrične konstante in ne njena absolutna vrednost.

Iz slike 15.4 je razvidno, da se dielektrične konstante spreminjajo linearno s temperaturo, zato moramo poiskati njihov ustrezen temperaturni gradient, s pomočjo katerega lahko pri izvajanju on-line meritev vrednosti DK preračunavamo na referenčno vrednost pri 40 °C.



Slika 15.4: Meritev dielektrične konstante s tremi on-line senzorji

4.4 Meritev stopnje čistosti

Kot pri vsaki meritvi, je tudi pri merjenju stopnje čistosti najpomembnejša verodostojnost izmerjenih vrednosti. Natančnost on-line števcev delcev smo določili s primerjalnim testom različnih on-line senzorjev stopnje čistosti (SSČ), izmerjene rezultate pa primerjali z natančnim laboratorijskim instrumentom Internormen

CCS 2. Opravljena primerjalna analiza je zajemala štiri on-line senzorje stopnje čistosti. Merilni sistem je bil osnovan na obtočnem principu, kjer je pretok skozi senzorje zagotavljala manjša obtočna črpalka, ki je tlačila hidravlično tekočino skozi zaporedno vezane senzorje. S tem so bile zagotovljene enake pretočne razmere skozi vse on-line senzorje.

Tabela 15.2: Rezultati raziskave natančnosti on-line senzorjev stopnje čistosti

Povprečno odstopanje	**ISO 4**	**ISO 6**	**ISO 14**
Senzor stopnje čistosti	0,3	0,7	-0,15
Senzor stopnje čistosti	-1,15	-1,2	-0,85
Senzor stopnje čistosti	-1,1	-0,55	0,25
Senzor stopnje čistosti	-1,4	-0,85	-1,25

Tabela 15.2 prikazuje odstopanja posameznega senzorja v ISO razredu (standard ISO 4406), glede na laboratorijski instrument CCS 2, umerjen na ± 0,1 ISO razred, ki je bil v hidravlični sistem vezan vzporedno. Med izvajanjem meritve smo naredili vsaj 4 odčitke oz. več, predstavljeni rezultati pa so prikazani kot povprečje teh odčitkov.

Podana natančnost (s strani proizvajalcev) on-line števcev delcev je ± 0,5 ISO razreda za meritve v območju od 13/11/10 do 23/21/18. Iz rezultatov opravljenih testiranj je razvidno, da on-line senzorji te natančnosti žal ne dosegajo. Testiranja so pokazala, da števci običajno delujejo z natančnostjo ± 1 ISO razred, pri čemer prihaja tudi do razlik med samimi senzorji. Lahko pa povzamemo, da on-line števci delcev običajno izmerijo 1 ISO razred manj, torej za 1 ISO razred čistejšo tekočino, kar predstavlja »nevarnejši« rezultat za uporabnika.

Ugotovljeno je bilo, da se pojavljajo tudi težave pri on-line merjenju stopnje čistosti olj v hidravličnih agregatih ob njihovem delovanju. Zato smo izvedli tudi testiranja, s katerimi smo želeli preveriti odziv senzorjev na določene pojave, kot je npr. vpliv zračnih mehurčkov. Namreč, zračni mehurčki ali vodne kapljice v hidravlični tekočini tudi uklonijo svetlobo, kar senzor zazna kot delec.

Rezultati meritev stanja olja brez in ob prisotnosti zračnih mehurčkov ter pripadajoča razlika, so povzeti v tabeli 15.3. Iz preglednice je razvidno, da zračni mehurčki najbolj vplivajo na meritev ISO 14 in ISO 21 razreda, zato lahko tudi sklepamo, da ima večina zračnih mehurčkov premer večji od 21 μm.

Tabela 15.3: Rezultati raziskave vpliva zračnih mehurčkov na on-line senzorje stopnje čistosti

	Brez zračnih mehurčkov			**Prisotnost zračnih mehurčkov**			**Povp. razlika**
	SSČ1	**SSČ2**	**SSČ3**	**SSČ1**	**SSČ2**	**SSČ3**	
ISO 4	17,9	17,0	17,4	18,9	18	18,5	1,0
ISO 6	16,0	16,0	16,1	17,6	16,9	17,1	1,2
ISO 14	11,9	11,0	11,2	16,2	13,7	14,7	3,5
ISO 21	10,2	8,7	9,1	16,5	12,9	13,8	5,1

Zato moramo poskrbeti, da pred meritvijo iz tekočine odstranimo morebitne zračne mehurčke in vodne kapljice, ki bi sicer povzročili prikaz lažnih rezultatov (oz. uporabimo druge ukrepe za minimiranje vpliva mehurčka, kot je npr. dvig tlaka hidravlične tekočine pri pretoku skozi števec nad 30 bar, pri čemer se zračni mehurčki stisnejo do te mere, da ne povzročajo popačenja meritev).

5 Sklep

On-line sistemi spremljanja stanja maziv nam ponujajo najvišjo stopnjo zaščite našega sistema, saj stanje maziva (ter tudi sistema) spremljamo neprekinjeno 24 ur na dan. V predstavljenem prispevku smo se želeli osredotočiti na pravilno namestitev on-line senzorjev, njihovo natančnost ter ukrepe za izboljšanje meritev, kar je ključnega pomena za uspešno delovanje on-line sistema in pravilno interpretacijo meritev. Namreč, v praksi lahko marsikje zasledimo nameščene on-line senzorje, ki služijo le lepotnemu namenu in ne opravljajo svoje primarne naloge.

Poleg omenjenih postopkov namestitve in ukrepov za izboljšanje meritev, ki jih predstavlja prispevek, je nadvse pomembno tudi kvalitetno beleženje in prikazovanje merilnih rezultatov. Za ogled merilnih podatkov smo razvili poseben vmesnik, ki je dostopen preko spletne strani z običajnim internetnim brskalnikom. Na ta način lahko naša tehnična služba, kot tudi posamezni partner, praktično kadarkoli in kjerkoli dostopajo do informacij o stanju nadzorovanega maziva. Spletni vmesnik omogoča vpogled v zgodovino meritev na osnovi poljubno prilagodljivih več-osnih histogramov ter poleg izpisa trenutnih vrednosti ponuja tudi funkcijo alarmiranja v primeru preseženih maksimalnih oz. minimalnih vrednosti.

Naši sistemi so se že izkazali tudi v praksi. Pri enem izmed partnerjev smo uspeli podaljšati interval zamenjave hidravlične tekočine za 4-krat, medtem ko smo pri drugem partnerju zaznali nenaden vdor vode v hidravlični sistem, ter ga z opozorilom obvarovali pred nastankom večje škode.

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Challenges of on-Line Condition Monitoring of Hydraulic Oils

VITO TIČ & DARKO LOVREC

Abstract Ensuring adequate quality of hydraulic oil and planning its change is crucial for a stable and smooth operation of many industrial machines. The best reliability can certainly be provided by using continuous monitoring of hydraulic oils, which is usually carried out remotely by means of modern online sensors.

Nevertheless, the development and implementation of such a system represents a unique challenge, since the measurement of the oil condition is much more complicated than measuring usual operating parameters, such as pressure or temperature.

Keywords: • hydraulic oil • quality • on-line monitoring • oil change • modern sensors •

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1 Introduction

Due to the increasing availability of on-line sensors for oil condition monitoring, our latest research and development activities have focused on on-line condition monitoring and also indirectly the machinery to which they are fitted. Remote on-line condition monitoring systems have many advantages over conventional monitoring systems and chemical analyses. Thanks to constant monitoring of lubricants in real-time, the system can also detect sudden deteriorations of lubricants' conditions and trigger alarm notification, before catastrophic consequences might occur. Fitting a modern on-line condition monitoring system provides the user with the highest level of operational reliability and allows him/her to reduce machines' down-times and extend lubricant maintenance intervals.

As already mentioned, the greatest advantage when on-line condition monitoring of lubricants, in comparison with conventional laboratory analyses, is their continuous measuring and reliable detection of sudden and unforeseeable events, when the fault is detected, so to speak, in real-time. Another advantage is the trend recording, considering the data from on-line sensors are usually acquired by automated systems that can store the history of the measurement results [1].

On the other hand, on-line monitoring has its own limitations. The most significant of them is the limited number of sensors and parameters that can be monitored. Also the parameters, measured by on-line sensors, tend to differ from the parameters, as determined by laboratory analysis. Thus, a direct comparison between them is impossible. Last but not least, calibration of the sensors is complicated and often valid for only one fluid type [1].

Due to these specific features, the on-line monitoring of lubricants is much more complex than the monitoring of single physical parameters, such as pressure or temperature. The oil condition cannot be determined by a single parameter but rather by several parameters measured at the same time. Additionally, the properties of oil change depending on the system load, type of oil, and other boundary conditions [2].

In order to achieve adequate quality of results from an on-line monitoring system, there are several key factors to consider whilst designing and implementing the system:

- selection of suitable on-line sensors,
- proper installations of the sensors,
- determination of appropriate mounting locations for the sensors (representation of the sample must be ensured),
- adequate data acquisition unit for gathering and processing data from the sensors,
- additional measures and procedures for improving the accuracy and credibility of the measurements.

With regard to the points given above, this paper presents some of the concepts and measures that can be used to enhance accuracy and quality of on-line sensors' measurements.

2 Online sensors

Most of the common parameters measured by today's on-line monitoring systems for lubricants are:

- temperature,
- relative humidity,
- viscosity,
- dielectric constant,
- electrical conductivity,
- lubricant cleanliness class.

We have already presented these methods and sensors in detail in various literature [3-5]. The sensors can be divided into two main groups: sensors that detect the physical-chemical properties of the lubricant and sensors that measure the cleanliness class of the lubricant – particle counters.

Before taking actions for improving sensor measurements, special attention should be paid to the installations and locations of the sensors, as the sensors' locations alone (the locations where the lubricants are measured) can have significant influences on the measurements' results.

3 Mounting locations of on-line sensor systems uvod

On-line sensors for oil condition monitoring can be mounted at four main locations:

- on a hydraulic tank,
- on the main hydraulic return line,
- on the main hydraulic pressurised line and
- on a hydraulic bypass line.

3.1 Mounting sensor system in a hydraulic tank

When it comes to the mounting locations of the sensors, the biggest difference between sensors of physical-chemical properties of oil and particle counters is that the particle counters need a certain oil flow through the sensor element that usually stands between 30 and 300 ml/min. Therefore, particle counters cannot be used if the sensor system is mounted in the tank because the sensors are only immersed in oil.

In those cases where there are no particle counter predictions during the monitoring system, it is recommended that the sensors are installed near the pump intake lines. The oil flow in this region of the tank is usually the calmest and more stable with the least amount of contaminants (e.g. air, soiled-contaminants), that might distort the measurements' results [6].

If the sensor system includes particle counters, it is necessary for them to be mounted on hydraulic piping and in this case, there are three main options, as presented in the continuation.

3.2 Mounting sensor system on main return line

Mounting the sensor system on the main hydraulic return line seems more appropriate, as the fluid is measured before the filter element. Thus, the fluid is measured that has just passed the whole hydraulic system and contains the most contaminants (information about the condition of the hydraulic system). This method of mounting usually takes advantage of pressure difference on the filter element (2 – 5 bar), which is used to power the fluid flow through the sensor system. If a particle counter is being used, this small pressure difference almost satisfies the flow needs of a counter. Moreover, this flow is low-pressurised and is also variable, as it depends on the fluid's viscosity and temperature. As our tests have revealed that the accuracies of on-line particle counters are much better at higher flows and pressures, we do not recommend the installations of a particle counter in such way.

3.3 Mounting sensor system on main pressurised line

When mounting a sensor system on the main hydraulic pressurised line, an additional flow valve is needed, which regulates the oil flow rate through the sensor system, regardless of oil pressure, viscosity, and temperature. The particle counter is usually installed at the front of the valve, so that oil flowing through the counter is under high pressure, which then compresses any air bubbles (if present) and thus improves the accuracy and stability of the cleanliness class measurement. As the sensors regarding the physical-chemical properties of oil must not usually be exposed to high pressures, they are placed after the valve, where only low pressure is present (return line to the tank).

3.4 Mounting sensor system on bypass line

By using an additional (small) pump, which powers the fluid through the sensor system, a bypass hydraulic system can be designed for condition monitoring. Although such a design is the more expensive one, it provides the best and most constant flow conditions for on-line sensors, which is especially important when an on-line particle counter is being used.

Suction and return line locations within the hydraulic tank must be placed carefully when designing a condition monitoring bypass system. Pumping and measuring oil from "dead-zones" of a hydraulic tank (where fluid does not circulate) could lead to substantial errors during condition monitoring [7].

4 Measures to improve the accuracies and credibilities of measurements

In order to obtain high quality results with on-line monitoring systems, knowing well the flow conditions in the system is insufficient, it is also crucial to understand the operating principles of the on-line sensors and how their data is evaluated.

4.1 Measurement of relative humidity

On-line sensors detect relative water content in the oil and express it as a percentage. The oil is 100 % saturated if it contains a maximum amount of water at a certain temperature and pressure (saturation limit). Whilst as, in conventional chemical laboratory analysis, the absolute water content is measured by the Karl-Fischer method, which reports the volume of water in weight percent or ppm.

The saturation limit can vary significantly, depending on the type of hydraulic oil (different base oils and various additive packages used). Therefore it is sensible to determine the saturation limit of a particular oil, as it represents the threshold above which water becomes extremely harmful to a hydraulic system (free water is present).

The saturation limit was determined using two on-line sensors and the Karl-Fischer method according to the following procedure. Various amounts of water were added to one litre of hydraulic oil. Then each sample was measured using on-line relative humidity sensors over a temperature range. The temperature was recorded when the sensor had reached 100 % relative humidity (saturation limit). The same samples were then passed for comparative laboratory analysis of the absolute water content using Karl Fischer procedure. The measurement results are shown in Table 16.1 and in Figure 16.1.

Based on the data in Table 16.1 we then determined a plot of the saturation limit for the mineral hydraulic oil (ISO VG 46). Figure 16.1 clearly shows that the saturation limits at operating temperatures of 40 – 60°C lay at between 90 and 180 ppm, which is much lower than the permissible limits provided by lubricant producers (500 ppm).

Table 16.1. Results of saturation limit measurement

Sample	**Karl Fischer (ppm)**	**Saturation temperature(°C)**	
		Sensor S1	**Sensor S2**
1	65,9	29	29
2	76,1	41	36
3	123,7	49	49
4	149,7	53	53

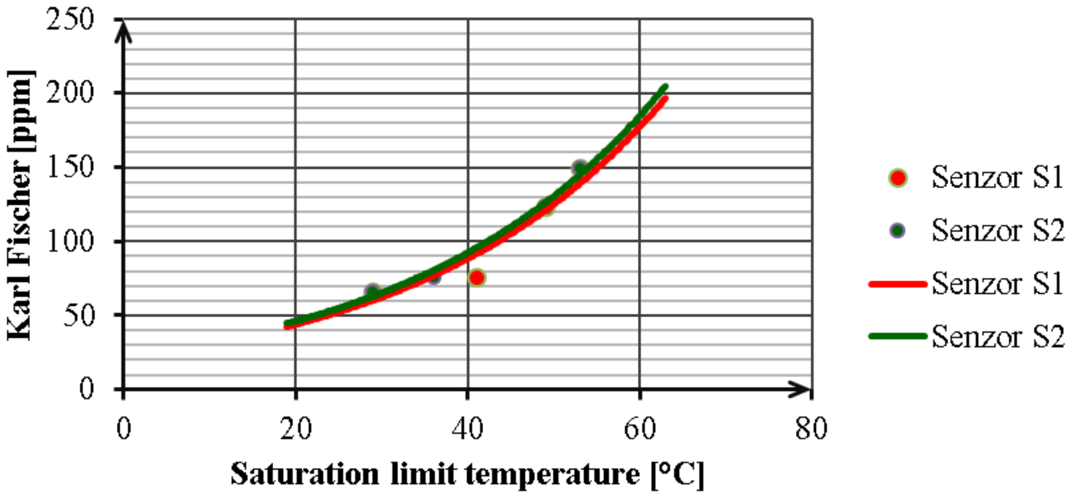

Figure 16.1. Saturation limit of mineral hydraulic oil (ISO VG 46)

4.2 Measurement of viscosity

The viscosity of a hydraulic fluid is one of its more important properties that must be constantly monitored. The accuracies of two on-line viscosity sensors were tested on mineral hydraulic oil ISO VG 46 within a temperature range from 30 to 80 °C.

The results are presented in Figure 16.2 (chart above), where the black line represent the "actual viscosity" of the oil, and was determined in a chemical laboratory according to the ASTM D445 at two characteristic temperatures (40 and 100 °C). The kinematic viscosity over the entire temperature range was then calculated using a simplified Walther equation derived at from the ASTM D341 standard [8]. However, the bold lines (red and green) represent the viscosity measurements' results from two on-line sensors.

The results show a strong deviation of on-line measured viscosity compared to the actual kinematic viscosity. The measuring errors of the on-line viscosity sensors are also presented in the form of relative errors (thinner lines), which reached up to 70 % for both sensors S1 and S2. The presented inaccuracies were definitely too great and monitoring with such sensors would only be a waste of time and money. We assumed that such deviations occurred because the sensors are factory calibrated only by a certain type of fluid. Nevertheless, the accuracy could be greatly improved if a particular sensor were to be additionally calibrated to a specific type of hydraulic fluid.

In comparison to Figure 16.2 (chart above), Figure 16.2 (chart below) shows the on-line viscosity measurement results after the sensors had been additionally calibrated. It can be clearly seen from the figure, that calibration of a specific sensor to a specific hydraulic fluid significantly improves the accuracies of on-live viscosity measurements.

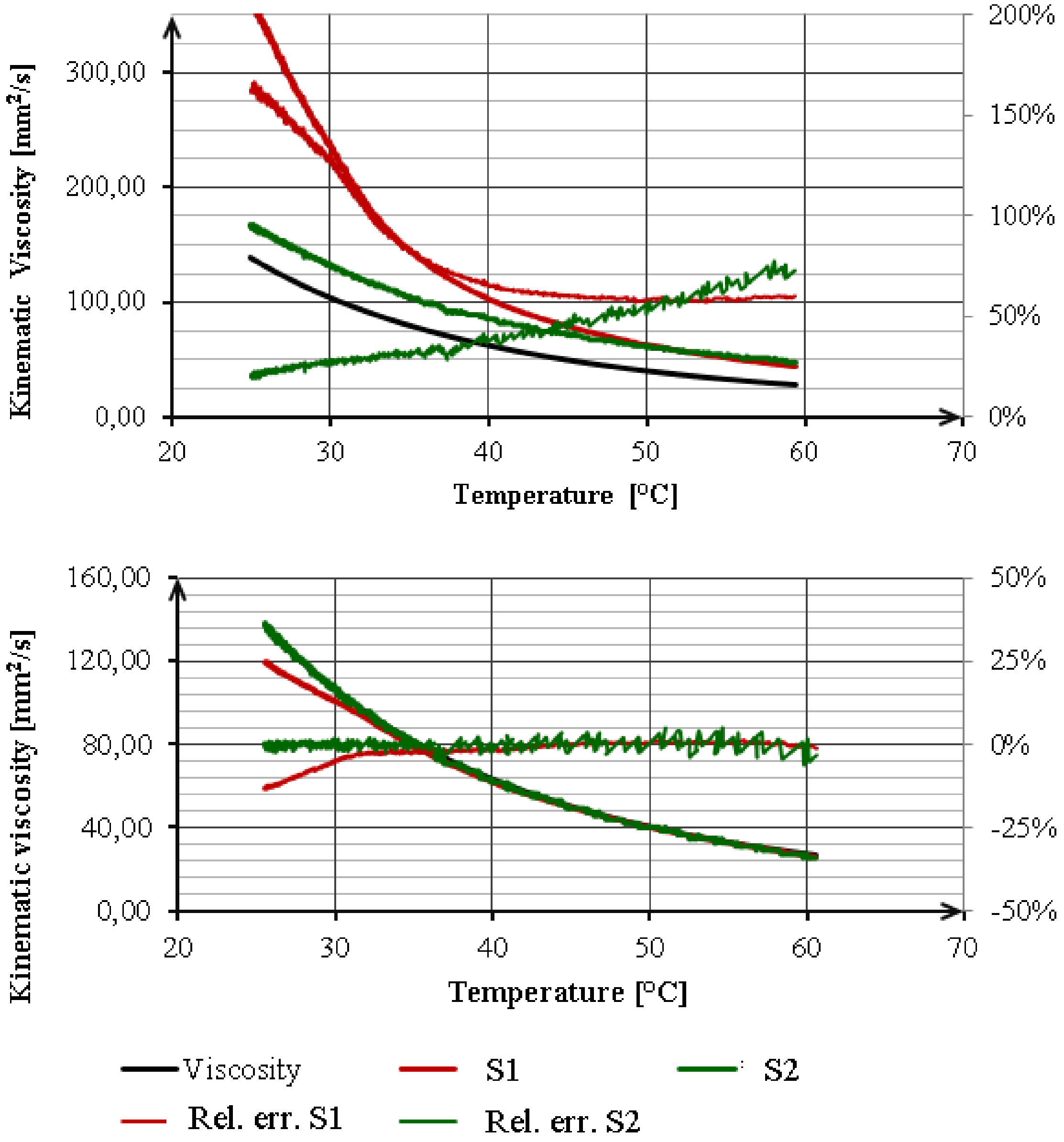

Figure 16.2. On-line viscosity measurements vs. actual viscosity

above: raw sensors readings; below: after the implementation of calibration curve

After implementation of the calibration curve, the relative errors of sensor S1 were reduced to 5 %, whilst the relative errors of sensor S2 were slightly higher due to very low output signals and the inaccuracy of the used A/D data acquisition card.

In addition to the implementation of a dedicated calibration curve, valid only for a specific oil and sensor combination, the viscosity can only be monitored if the kinematic viscosity at the operating (measuring) temperature is calculated to viscosity at 40 °C. Thus, we have developed a special program based on ASTM D341 and D2270 standards, which transforms the viscosity at a measured temperature to viscosity at 40 °C. In this way, the trend of viscosity change can be monitored over a longer period of time, despite the temperature fluctuations within the hydraulic system.

4.3 Measurement of dielectric constant

Within our research, the dielectric constant of the mineral hydraulic oil was measured by three different on-line sensors. Figure 16.3 presents the results, which have been compared to a precise laboratory measurement of the dielectric constant, made by the Biotechnical Faculty of Ljubljana. The figure shows that the dielectric constants measured by on-line sensors significantly differed from the actual values. At this point we could implement a calibration curve, similar to that we did for the viscosity measurement. As this procedure should be done for each combination of oil type and sensor, we decided (due to economic reasons) to ignore the absolute value of the dielectric constant. As we only monitor and track relative changes in the dielectric constant of oil, the accuracy of its actual value is rather unimportant.

Figure 16.3 also shows the temperature dependency of the dielectric constant. As the dielectric constant changes linearly with temperature, we need to find corresponding temperature gradients for each sensor, which then allows us to transform each measuring result (at a given operating temperature) to its reference value at 40 °C – trend tracking.

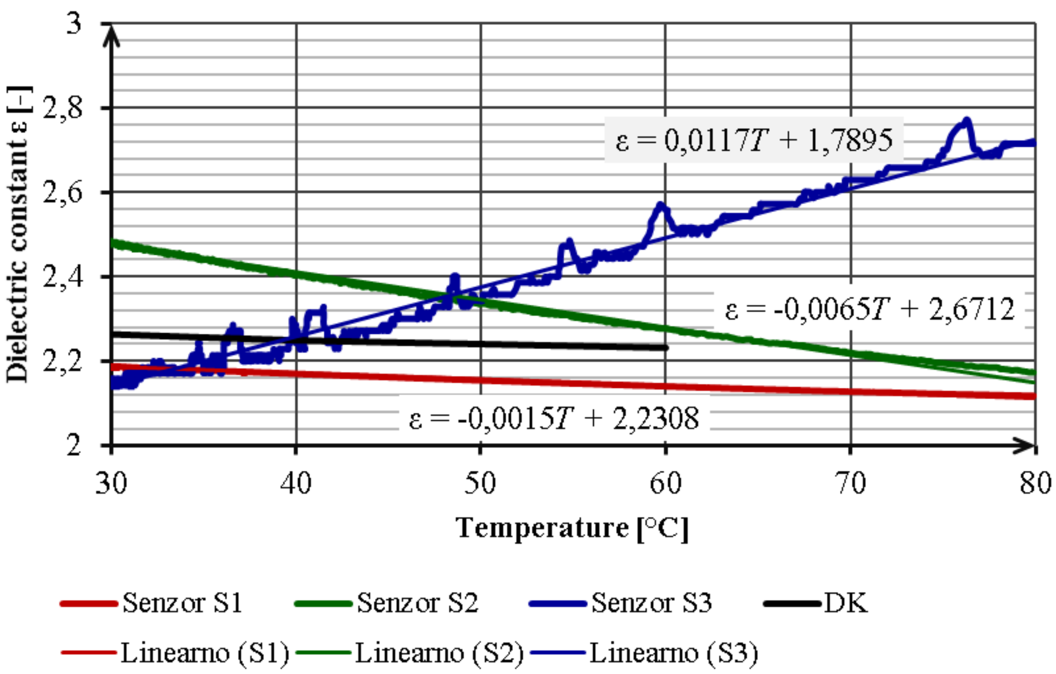

Figure 16.3. On-line measurements of dielectric constant with three sensors

4.4 Measurement of cleanliness class

As during any measurement procedure, the credibility of the measured values for the cleanliness class is the key factor. The practical accuracies of on-line particle counters were determined by a comparative test, in which several on-line particle counters were compared to a precise and calibrated laboratory instrument – particle counter Internormen CCS2. Four on-line sensors were connected in series to guarantee the same flow conditions throughout each one, followed by the precise laboratory particle counter.

Table 16.2 shows the deviations of each particle counter in the ISO 4406 class with respect to precise instrument calibration to ± 0.1 ISO class. During the test, at least 4 readings were taken for each test point and the results report the average of these readings.

Table 16.2. Results of comparative test on the accuracy of on-line particle counters

Average deviation	**ISO 4**	**ISO 6**	**ISO 14**
Particle counter PC-1	0,3	0,7	-0,15
Particle counter PC-2	-1,15	-1,2	-0,85
Particle counter PC-3	-1,1	-0,55	0,25
Particle counter PC-4	-1,4	-0,85	-1,25

The accuracy of on-line particle counters is provided by the producers and is usually ± 0.5 ISO class for measurements within the range from 13/11/10 to 23/21/18. The conducted tests revealed that on-line particle counters did not achieve this accuracy, but rather they operated within an accuracy of ± 1 ISO class. There were also differences amongst the sensors. However, we can sum up that particle counters typically measure 1 ISO class less (1 ISO class cleaner fluid), which represent dangerous results for the user.

We also noticed that the particle counters experienced some difficulties whilst measuring the cleanliness of the oil whilst the hydraulic system was operating. Therefore, we performed several tests to investigate the responses of the particle counters to certain interferences, such as the presence of air bubbles. As air bubbles (and also water droplets) in oil also deflect the light passing through the oil, they are also detected as particles.

Oil with air bubbles and without them was measured and the results are summarised in

Table 16.3, which indicates that air bubbles mostly affect the measurements of the ISO 14 and ISO 21 classes. Thus, it can be assumed that the majority of air bubbles have diameters of 21 μm or more.

Table 16.3. Results of test on air bubbles' presence in hydraulic oil that affect particle counters

	Without air bubbles			**With air bubbles**			**Average error**
	PC-1	**PC-2**	**PC-3**	**PC-1**	**PC-2**	**PC-3**	
ISO 4	17,9	17,0	17,4	18,9	18	18,5	1,0
ISO 6	16,0	16,0	16,1	17,6	16,9	17,1	1,2
ISO 14	11,9	11,0	11,2	16,2	13,7	14,7	3,5
ISO 21	10,2	8,7	9,1	16,5	12,9	13,8	5,1

Therefore, we must ensure that any air bubbles and water droplets are removed from the oil prior to entering the particle counters otherwise the measurements will lead to false results. Another option is to minimise the impact of the presented air bubbles by raising the pressure of the hydraulic fluid passing the measuring cell in the particle counter to at least 30 bar or more, whereby the air bubbles are squeezed to a minimum and thus do not cause distortions of the measurements.

5 Conclusion

On-line monitoring systems for lubricants offer us the highest level of protection for our systems because the lubricants (and the systems) are monitored constantly 24 hours a day. In this paper we have tried to focus on the proper installations of on-line sensors and tried to provide insights into some measures and procedures that can help us achieve maximum accuracy and credibility of the results. In fact, we spotted several on-line sensors in the field that only serve the purposes of beauty instead of performing their primary tasks.

In addition to these installation procedures and additional measures for improving the qualities of the measurements, it is also essential to establish an adequate system to record and display the results. Thus, we have developed a special user-interface that is accessible on-line with a common internet browser. In this way, the technical service, as well as an individual user, has access to information on oil condition at anytime from anywhere. Besides displaying current measuring values, the web interface also provides data history in the forms of flexible multi-axis charts. The system also includes an alarm function that notifies the user in case the minimum or maximum value has been reached.

Our system has already been proved in the field. One of our partners has managed to extend the lubricant change interval four-fold, whilst another partner noticed a sudden ingress of water into the hydraulic system, which allowed him to stop the system immediately and prevent major damage to his system.

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O identifikaciji parametrov sinhronskega generatorja med obratovanjem z uporabo linearnega ekvivalenta

GORAZD BONE, URBAN RUDEŽ & RAFAEL MIHALIČ

Povzetek V članku je obravnavana zmožnost identifikacije parametrov sinhronskega generatorja iz dinamičnih meritev na priključnih sponkah z uporabo linearnega ekvivalenta. Predstavljena je metoda, ki to izvede z izčrpnim pregledovanjem. Uporabljeni model generatorja ima po dve dušilni navitji na vsaki od osi rotorjev. Ker so meritve izvedene na priključnih sponkah je dinamika rotorjevega kota in vrtilne hitrosti nepoznana. Za namen študije se je simuliralo delovanje sinhronskega generatorja priključenega na togo mrežo. V simulaciji se je vzbujalna napetost stopničasto spremenila. Za iskanje parametrov sinhronskega generatorja je bilo uporabljeno izčrpno preiskovanje možnih parametrov, saj se s to metodo lahko najde vse možne kombinacije parametrov, ki zadovoljujejo kriterije identifikacije. Ob ugotovitvi, da nekateri parametri ne vplivajo na nekatere merjene signale, se je pojavila možnost uporabe razcepljene identifikacije. Brez omenjene razcepitve izčrpna metoda iskanja ne bi bila izvedljiva. Ker je bilo v študiji ugotovljeno, da zelo različni parametri dajejo zelo podobne rezultate za dinamične signale avtorji zaključijo, da parametrov modela generatorja osmega reda ne moremo identificirati z identifikacijskimi metodami, ki uporabljajo linearne ekvivalente.

Ključne besede: • identifikacija • parameter • sinhronski generator • linearni ekvivalent • meritev •

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On-Line Identifiability of a Synchronous Generator by Linearized Equivalent

GORAZD BONE, URBAN RUDEŽ & RAFAEL MIHALIČ

Abstract In this paper the identifiability of synchronous generator's parameters from time domain measurements at the terminals using a linearized equivalent is examined and a decoupled brute force algorithm for identification is presented. The generator model has two windings on both, the quadrature and the direct axis of the rotor. Measurements are carried out at the terminals; therefore the instantaneous values for rotor's angle and rotational speed are unknown. A synchronous generator operating in a single machine infinite bus (SMIB) system was simulated. Field voltage was simulated to undergo a rectangular pulse change and the electrical quantities at the generator's terminals were measured. To search the values of generator's parameters brute force algorithm was used, since it provides an insight into all possible parameter sets which satisfy the identification criteria. After it has been established that some measured variables are insensitive to changes of certain parameters, a multistage approach was justified; without it, brute force search would not be feasible. Since the dynamics obtained with various parameter sets nearly coincides with that of the original simulation it is concluded that the synchronous generator's parameter identification using the eighth order model in a linearized set up is not generally possible.

Keywords: • identifiability • parameter • synchronous generator • linearized equivalent • measurement •

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1 Introduction

Identifying the parameters of a synchronous generator from online measurement, as an alternative to standstill testing in which the generator needs to be put offline, is a research topic that has been given much attention both in the field of research [1]–[15] and industry [16], [17]. The general approach in time domain identification is to apply a disturbance to the device, measure an input and an output and estimate the values of the model's parameters by analyzing relations between the two at different times [18], [19]. Normally, a vector made up of differences between the measured and the modeled output at matching times is constructed. Identification minimizes this error vector in some, usually second, norm sense.

The observed synchronous generator model is nonlinear. Although there are cases where the identification scheme regards nonlinearities directly [10], [11], [13], it is often the case that the model is linearized and a linear identification scheme is used. The advantage of linearization is in simplifying the identification and the justification for using a linearized identification scheme is in the fact that a synchronous machine to be identified should not be brought to disturbances large enough to forbid linearization in normal operation.

The input variables for a synchronous generator are the mechanical torque and the field voltage. In the identification process only the field voltage is normally taken as the input and the system is regarded as a SISO (Single Input Single Output) system. This is justified by the longer time constants present in the mechanical system. The disturbance applied was a field voltage perturbation. If a direct change to the field voltage was to be done in practice the excitation controller would need to be bypassed. Otherwise the field voltage controller would have to be included in the identified model.

A generator operating in a SMIB system was considered. A series of linear simulations with various parameters sets was performed and the responses were compared to the response of the original nonlinear simulation. Although it might be better to apply white noise as the input disturbance and operate with a long duration of the dynamics observed, the disturbance considered in this work was a rectangular pulse; which we believe to be more easily reproduced in reality, and the duration of dynamics observed was 6 seconds; which must be short enough to suppose there were no changes in the power system which would affect the dynamical response. The amplitude of the field voltage pulse is 0.1 percent of initial value, which is so small it might be impossible to achieve in reality and its effects on the active power dynamics difficult to measure. The small size of the perturbation was to minimize the linearization error and to analyze identifiability with regards to modeling error alone. With larger perturbations linearization would provide additional error which would further hinder identifiability. Having observed that different sets of parameters produce similar results the brute force search was decided upon since it enables finding the parameter sets which correspond to the dynamics. The brute force search feasibility was eased noting that all parameters do not influence all measurements which enabled a multistage approach.

2 Technical work preparation

2.1 Synchronous Generator Model

The generator's parameters were taken from [20] with a small resistance added to the stator's coils. The inertia constant was 2.89 *s* and the electrical parameters were as shown in Table 17.1.

In [20] the equivalent circuit parameters are directly provided, the inertia constant H however was obtained by summing all the inertias present on the shaft. The generator was connected directly to an infinite bus, loaded with 0.2 pu active and 0.1 pu reactive power load. The synchronous generator model used has two coils in each of the two, the direct and the quadrature, axis of the rotor's equivalent circuit. This model has been chosen because it is most commonly used in power system simulation studies since sub-synchronous resonance effect was first documented [21]. Saturation effects were neglected and the inductance matrix was constant. Upon transforming it into the d-q rotating system and neglecting the zero component, the voltage equation, with time dependence not indicated, is as in [22]:

$$\mathbf{U}_{\mathrm{dq}} = \dot{\mathbf{\Psi}}_{\mathrm{dq}} / \omega_{\mathrm{s}} + \mathbf{R}_{\mathrm{dq}} \cdot \left(\mathbf{L}_{\mathrm{dq}}\right)^{-1} \cdot \mathbf{\Psi}_{\mathrm{dq}} - \mathbf{S} \cdot \omega_{\mathrm{r}} \cdot \mathbf{\Psi}_{\mathrm{dq}}, \tag{1}$$

where $\mathbf{S}$ is a square matrix containing mostly zero inputs with the values +1 and –1 being present at only two places corresponding to the ordering of vectors $\mathbf{\Psi}_{\mathrm{dq}}$ and $\mathbf{U}_{\mathrm{dq}}$. In (1) all variables are taken in pu apart from time, which is in seconds. If time were taken in pu [22] with base equal to $1/\omega_{\mathrm{s}}$, the equation would simplify into

$$\mathbf{U}_{\mathrm{dq}} = \dot{\mathbf{\Psi}}_{\mathrm{dq}} + \mathbf{R}_{\mathrm{dq}} \cdot \left(\mathbf{L}_{\mathrm{dq}}\right)^{-1} \cdot \mathbf{\Psi}_{\mathrm{dq}} - \mathbf{S} \cdot \omega_{\mathrm{r}} \cdot \mathbf{\Psi}_{\mathrm{dq}}. \tag{2}$$

Despite this possible simplification (1) was used in this work considering time is more informative if taken in seconds than in a more abstract pu value. From (1) follows

$$\dot{\mathbf{\Psi}}_{\mathrm{dq}} = \left[\mathbf{S} \cdot \omega_{\mathrm{r}}(\mathrm{t}) - \mathbf{R}_{\mathrm{dq}} \cdot \left(\mathbf{L}_{\mathrm{dq}}\right)^{-1}\right] \cdot \omega_{\mathrm{s}} \cdot \mathbf{\Psi}_{\mathrm{dq}} + \mathbf{U}_{\mathrm{dq}} \cdot \omega_{\mathrm{s}}. \tag{3}$$

Eq. (3) is a state space representation in the sense

$$\dot{\mathbf{\Psi}}_{\mathrm{dq}} = \mathbf{A} \cdot \mathbf{\Psi}_{\mathrm{dq}} + \mathbf{B} \cdot \mathbf{U}_{\mathrm{dq}}. \tag{4}$$

The matrix $\mathbf{A}$ in (4) is not constant as can be seen from (3) and so, the system is nonlinear. Equation (4) describes the electrical states. Two additional equations are needed to obtain a full description, the time derivatives of the speed and the angle. The speed of rotation has the derivative

$$\dot{\omega}_{\mathrm{r}} = \frac{\left(T_{\mathrm{m}} - T_{\mathrm{e}}\right)}{2H}, \tag{5}$$

where T_{e} follows the equation:

$$T_{\mathrm{e}} = I_{\mathrm{q}} \Psi_{\mathrm{d}} - I_{\mathrm{d}} \Psi_{\mathrm{q}}, \tag{6}$$

where I_{d}, I_{q}, Ψ_{d} and Ψ_{q} are currents and fluxes in d and q axis respectively. The rotor angle has the following derivative

$$\dot{\delta} = (\omega_{\mathrm{r}} - 1) \cdot \omega_{\mathrm{s}}. \tag{7}$$

The final relations required in above equations are (8) and (9)

$$\mathbf{I}_{\mathrm{dq}} = \left(\mathbf{L}_{\mathrm{dq}}\right)^{-1} \cdot \mathbf{\Psi}_{\mathrm{dq}} \tag{8}$$

$$\mathbf{U}_{\mathrm{dq}} = U_{\mathrm{T}} \cdot \sqrt{\frac{3}{2}} \cdot \begin{bmatrix} -\sin(\delta) \\ \cos(\delta) \end{bmatrix}, \tag{9}$$

where U_{T} stands for the amplitude of voltages of a symmetric three-phase infinite source.

Table 17.1
Parameters of synchronous generator

Param.	L_{ad}	L_{aq}	L_{σ}	R_{s}	$L_{\mathrm{F}\sigma}$	$L_{\mathrm{D}\sigma}$	$L_{\mathrm{Q}\sigma}$	$L_{\mathrm{G}\sigma}$	R_{D}	R_{F}	R_{Q}	R_{G}
Value [pu]	1.66	1.58	0.13	10^{-3}	0.062	$55 \cdot 10^{-4}$	0.326	0.095	$\frac{1.54}{120\pi}$	$\frac{0.53}{120\pi}$	$\frac{5.3}{120\pi}$	$\frac{3.1}{120\pi}$

2.2 Synchronous Generator's SMIB Simulation Scheme

Equations (3) and (5) through (9) define the dynamics of the machine. As they form a nonlinear system, a nonlinear integration scheme must be used. A predictor-corrector approach was used for simulation in our study [23], with Euler's explicit method being the predictor and trapezoidal rule the corrector. The integration step was constant. Although it would be possible to compose a single matrix equation for the model and then use the predictor-corrector scheme over it, it is recommended that a separate variable, with a slower dynamics, is taken as the predictor and the corrector is then iterated with that value taken in its first run [24], [25], [26]. With a numerical integration setup it is possible to obtain the values of generator's state variables in the next time step ($t + \Delta t$), provided the values at current time (t) are known. The setup used in our work is described below:

1. Predict ω_{r} at time $t + \Delta t$ from (5) by explicit Euler.
2. Store calculated speed into a designated variable.
3. Calculate δ at $t + \Delta t$ from (7) by Trapezoidal rule.
4. Calculate $\mathbf{\Psi}_{\mathrm{dq}}$ at $t + \Delta t$ from (3) by Trapezoidal rule.
5. Calculate electrical torque at $t + \Delta t$ from (6).
6. Use (5) to obtain a corrected value for speed by trapezoidal rule considering new value of torque found in step 4 (torque value present at time $t + \Delta t$).
7. Compare values of speed from step 6 with that of step 2; if they coincide within a predetermined tolerance proceed to the next time step of simulation and restart this setup, otherwise return to step 2 of this setup.

It usually requires two iterations at each time step of the simulation, which is the case found also in [25]. By solving the differential equations for their steady states [22] one obtains the initial conditions of the generator, which provide the necessities to start the simulation.

2.3 Synchronous Generator Linearization

Obtaining linear block diagrams has been regarded as useful when analyzing power system dynamics with automatic voltage regulator (AVR) and power-system stabilizer (PSS) included. Some research papers on the topic are available [27]–[30], however, the references found model the machine using nameplate parameters. As the equivalent circuit model was used in this work, the equations of the equivalent circuit model had to be linearized.

Linearization required the equations to be put into a single matrix equation of which only first order sensitivity was considered [22], [31]. For this purpose, a software package capable of symbolic derivation was used and an expression of the following form was obtained

$$\Delta\dot{\mathbf{V}} = \mathbf{A}_{\text{Total}} \cdot \Delta\mathbf{V} + \mathbf{B}_{\text{Total}} \cdot \Delta v_{\text{F}}, \tag{10}$$

where **V** contains all the variables; magnetic fluxes, speed and angle. The Laplace' transfer function for every state variable [32] can be obtained from

$$\Delta\mathbf{V}(s) = \left(s \cdot \mathbf{I} - \mathbf{A}_{Total}\right)^{-1} \cdot \mathbf{B}_{\text{Total}} \cdot \Delta v_{\text{F}}(s). \tag{11}$$

To solve (11), Matlab's backslash operator was used. Upon having linearized the state variables the transfer functions of measured quantities must be obtained. The identification process then focuses on finding the values of parameters present in this transfer function that mimic the behavior of measurements for given input dynamics. Having supposed the measurement be carried out only at the terminals of the machine the only measurable quantities were the voltages and currents in the "abc" (three phase) frame. The synchronous machine however is modeled in the "dq" frame. The quantity used for identification must have an analytical expression obtainable in both frames. Two such commonly used quantities are the active and reactive powers as seen in Table 17.2, although any other quantity could be used provided its analytical expression can be obtained in both frames.

Table 17.2
PARAMETERS OF SYNCHRONOUS GENERATOR

Quantity	Frame "abc"	Frame "dq"
Active power	$u_a \cdot i_a + u_b \cdot i_b + u_c \cdot i_c$	$u_d \cdot i_d + u_q \cdot i_q$
Reactive power	$(u_a - u_b) \cdot i_c + (u_c - u_a) \cdot i_b + (u_b - u_c) \cdot i_a$	$u_d \cdot i_q - u_q \cdot i_d$

The linearized active and reactive powers are obtained from

$$\begin{aligned} \Delta P_{\text{e}} &= \Delta U_{\text{d}} I_{\text{d0}} + U_{\text{d0}} \Delta I_{\text{d}} + \Delta U_{\text{q}} I_{\text{q0}} + U_{\text{q0}} \Delta I_{\text{q}} \\ \Delta Q_{\text{e}} &= \Delta U_{\text{d}} I_{\text{q0}} + U_{\text{d0}} \Delta I_{\text{q}} - \Delta U_{\text{q}} I_{\text{d0}} - U_{\text{q0}} \Delta I_{\text{d}} \end{aligned}, \tag{12}$$

where a zero in the subindex indicates initial value.

The right hand side in (12) must be expressed in terms of state variables. For this it is necessary to obtain linearized equivalents of voltages and currents from (8) and (9) and insert them into (12). The equation thus obtained must then have the transfer functions of the state variables in (11) inserted. The resulting equation is in the form of

$$\begin{aligned} \Delta P_{\text{e}}(s) &= f_1(s) \cdot \Delta v_{\text{F}}(s) \\ \Delta Q_{\text{e}}(s) &= f_2(s) \cdot \Delta v_{\text{F}}(s) \end{aligned}. \tag{13}$$

Functions f_1(s) and f_2(s) from (13) can be written in the form:

$$f_1(s) = \frac{num_{\text{P}}(s)}{den(s)} \quad , \quad f_2(s) = \frac{num_{\text{Q}}(s)}{den(s)}, \tag{14}$$

The numerators and the denominators of f_1(s) and f_2(s) are polynomials in *s*. For the brute force search their evaluation was sped up by replacing parts of expression more commonly recurring with newly defined variables. Even with the mentioned introduction of variables the expressions required for their evaluation are very extensive and will therefore be omitted from the paper.

2.4 The Identification Scheme

The identification process consists of three stages. At each stage the parameters are varied, the transfer function for these parameters is evaluated, and the response of the transfer function is compared to the original dynamics. If the responses are similar the parameter set is saved for the next stage. After finishing all three stages, the obtained parameter sets corresponded to all considered measurement criteria. The mentioned stages are described below individually.

At the first stage, steady state reactive power amplification caused by field voltage step change was observed. According to the final value theorem [33] the amplification equals the ratio of the terms with zero power of *s*. To confirm that the derived expression is correct one might consider ensuring that any dynamical parameter (resistances and scattering inductances of damping coils or inertia) are absent from it. The parameter sets that best corresponded to the steady state amplification of reactive power, with regards to relative error, were saved.

At second stage, parameters sets to match reactive power dynamics were saved. The second stage of identification rests on the fact that the dynamics of reactive power is virtually unaffected by any changes done to either the damping coil scattering inductances or to the inertia. This is displayed in Figure 17.1 which compares the dynamic responses of the original generator with two other cases, where the generator inertia and damping coil scattering inductances had been greatly changed.

At the third stage of identification the active power dynamics was matched and the corresponding parameters were found. After the third and final stage the parameter combinations that correspond to all three stages of identification procedure were saved.

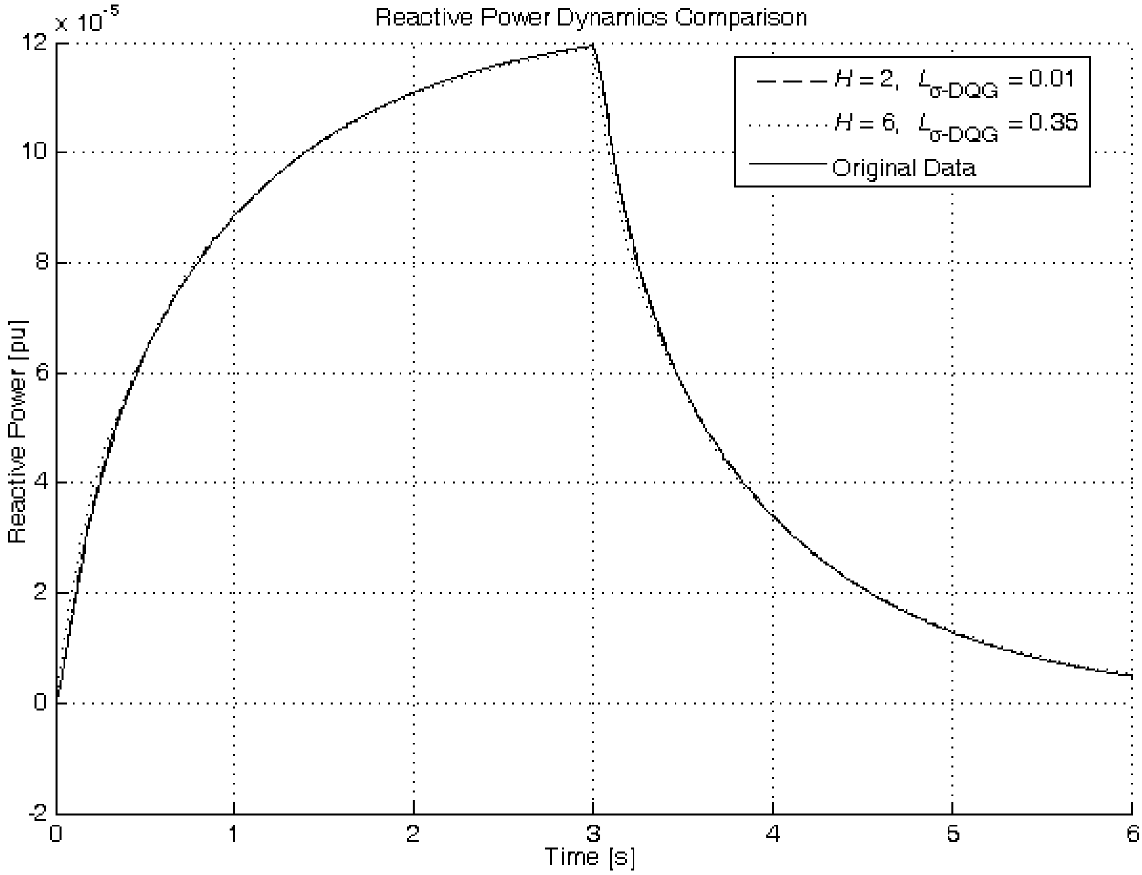

Figure 17.1. Reactive power dynamics comparison with varied inertia constant and damping scattering.

Before the linear simulation at stages 2 and 3 the transfer functions had their orders reduced. The order reduction was carried out by truncation, so that two elements, with highest powers of *s*, of the numerators and denominators in (14) were removed. The denominator's order thus became 6 and the numerator's 5. This truncation caused no visible deviation of dynamical behavior. For the linear simulation, analytical solution (matrix exponential), was used; the transfer functions in (14) were written in observable canonical state space form, the state space matrix was then diagonalized by multiplication with the eigenvector matrices and the matrix exponential was calculated for the diagonalized matrix, which simplifies into a diagonal matrix of exponentials.

2.5 The Parameter Span and Resolution

While the possible values of nameplate parameters are commonly provided in the literature, the same is not true for equivalent circuit parameters. Those parameter spans that can be found in the literature were used while the spans for all other parameters, as well as the resolution, were developed as described below.

The spans for inertia constant, for the stator's resistance and the leakage, as well as the total inductance in both the *d* and the *q* axis of the stator are provided in [22]. From the span of leakage inductance and the span of total inductance the mutual inductance span in both axes was obtained. The field coil resistance was assumed to be known. For this to be possible the field coil current and voltage can be measured directly; the ratio of the two is the field coil resistance. The rest of the parameters spans were decided by briefly reviewing some datasets found in the literature [20],[21], [22].

The values of inertia considered ranged from 2.5 to 6 s with the step of 0.1, the values of leakage inductance ranged from 0.1 to 0.2 pu with the step of 0.01 pu and the values of mutual inductance in the *d* axis ranged from 1 to 2.2 pu with the step of 0.01 pu. The abovementioned steps were decided upon since they correspond to the least significant digit provided in the data while the span is found in [2]. The span of the *q* axis mutual inductance was varied from 80 % to 99% of the mutual inductance in the *d* axis with the step of 1%. The span of the *q* axis mutual inductance was decided by assuming knowledge of rotor's nonsaliency, while the step size was decided upon due to the fact that the dynamics changed only slightly if the parameter changed by that step.

The values considered for the stator's resistance were 0.001, 0.01 and 0.1 pu. The span encompasses that reported in [22] and the step size, a factor of 10, ensured that the dynamics still did not change severely.

The field leakage inductance was varied in the range from 0.035 to 0.49 pu, with the step of 0.035 pu. The damping coil resistances were varied according to the below definition, which pertains to all three damping coils

$$R_{\mathrm{D,Q,G}} = (0.5 \cdot 1.3^{\mathrm{K}})/\omega_{\mathrm{s}} \ , \ K \in [0,1,...,9] \cdot \qquad (15)$$

The damping coils' scattering inductances assumed the following values which again pertain to all three coils

$$L_{\sigma-\mathrm{D,G,Q}} = [.001\ .02\ .04\ .06\ .09\ .12\ .15\ .19... \\ .23\ .27\ .32\ .37\ .42\ .48\ .54] \ . \qquad (16)$$

The span of the damping coils' resistances and scattering inductances as well as the field scattering inductance was chosen so that the datasets found are well within the limits considered here and the resolution was decided upon so that the dynamics of the machine of two consecutive parameter values did not differ severely.

3 Results

The number of parameter sets that passed the identification process was over 10'000. The obtained parameter sets ranged very broadly as can be seen in Table 17.3. Figures 17.2 and 17.3 compare the simulated dynamical response of the original generator to the simulation with the parameter sets that had undergone the three identification phases. In Figures 17.2 and 17.3 only the responses of every seventh of the parameter sets were plotted, as the authors had noticed that plotting more responses will not increase the broadness of deviation between compared dynamics, it would however increase computer memory consumption. The two figures show over 1600 curves each. Identifiability can be defined as uniqueness of measured response with regards to a parameter set [34]; in case of system identifiability, if two dynamical responses are identical they have to have been made by the same parameters. In case of a deterministic set up or some known noise this might be accomplishable; however, the difficulty with identifiability becomes clear when possible noise present in a synchronous machine is taken into consideration.

In [35] the authors reviewed the modeling fidelity of a synchronous machine by comparing the rotor angle dynamics of a physical synchronous machine to a simulated equivalent. The authors found some noticeable discrepancy between the two as can be seen from figure 17.4 taken from [35].

Table 17.3
SPAN OF PARAMETERS OBTAINED AFTER PROCEDURE

Parameter	**From**	**To**	**Correct**	**Error from, to [%]**
L_{ad}	1.61 pu	1.9 pu	1.66 pu	-3.0 , 14.5
L_{aq}	1.41 pu	1.67 pu	1.58 pu	-10.7 , 5.7
L_{σ}	0.12pu	0.18 pu	0.13 pu	-7.7 , 38.5
R_s	10^{-3} pu	10^{-3} pu	10^{-3} pu	0
$L_{F\sigma}$	0.035 pu	0.105 pu	0.062 pu	-43.5 , 69.4
$L_{D\sigma}$	0.001 pu	0.02 pu	0.0055 pu	-81.8 , 263.6
$L_{Q\sigma}$	0.001 pu	0.54 pu	0.326 pu	-99.7 , 65.5
$L_{G\sigma}$	0.001 pu	0.54 pu	0.095 pu	-98.9 , 468.4
R_D	0.0029 pu	0.011 pu	0.0041 pu	-29.0 , 169.3
R_Q	0.0064 pu	0.014 pu	0.0141 pu	-54.5 , 0
R_G	0.0064 pu	0.014 pu	0.0082 pu	-22.2 , 71.5
H	2.7 s	3.1 s	2.8941 s	-6.7 , 10.6

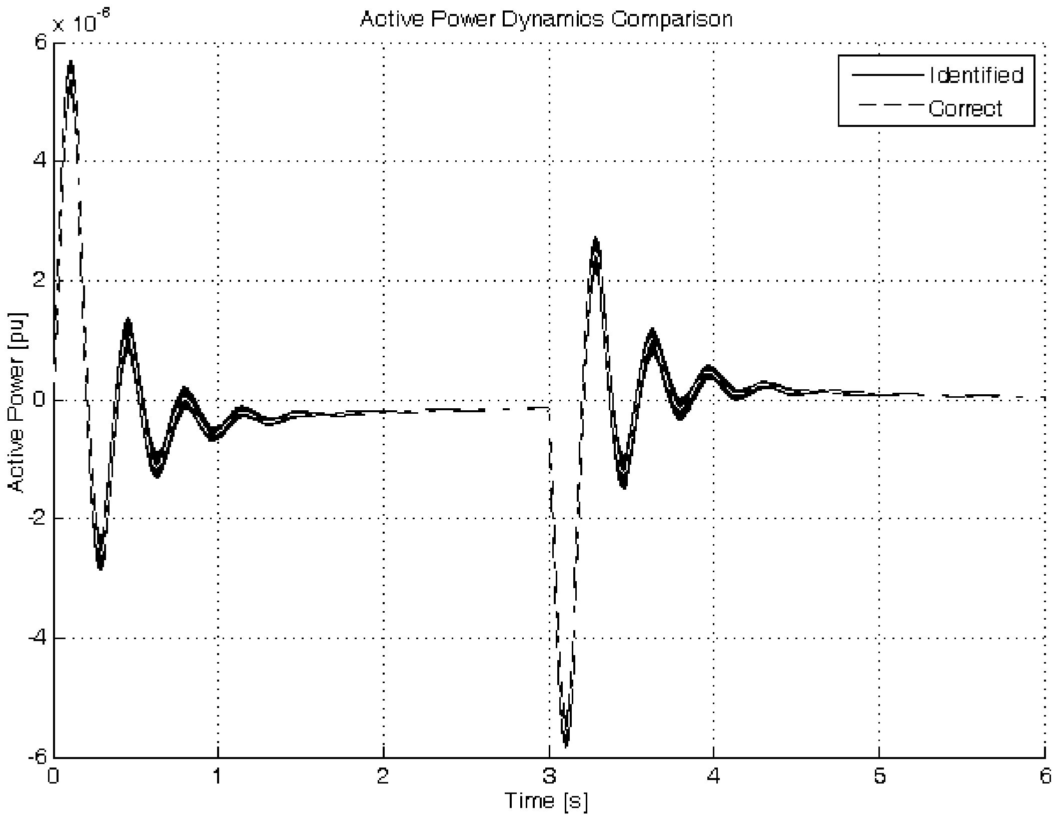

Figure 17.2. Active power dynamics for parameters obtained.

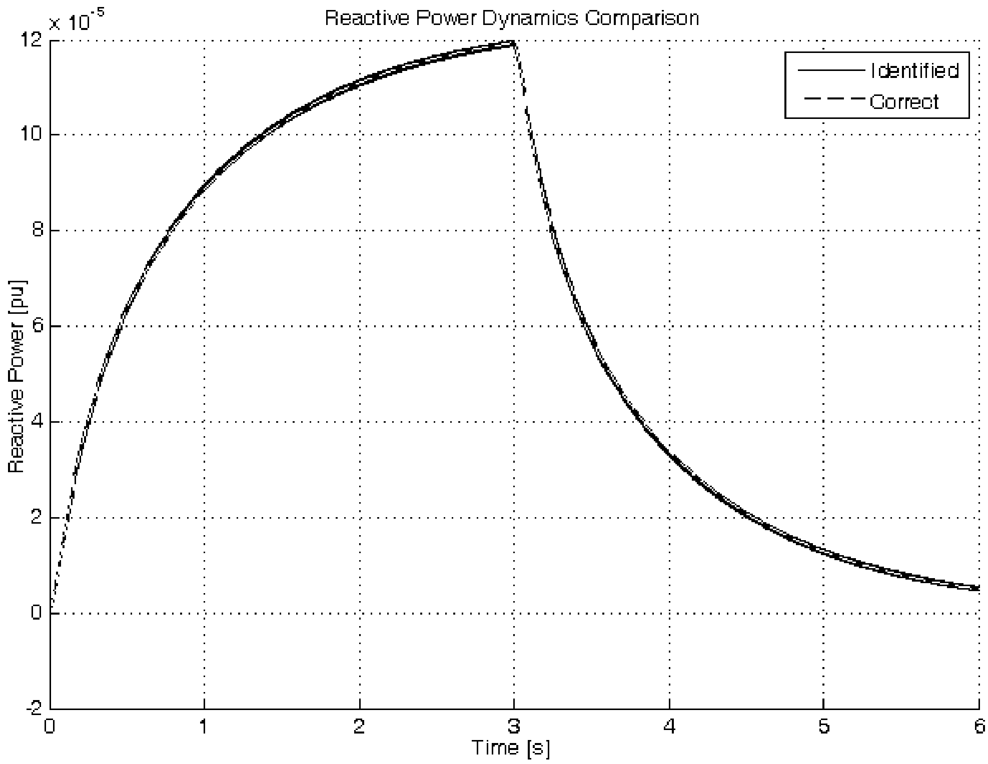

Figure 17.3. Reactive power dynamics for parameters obtained.

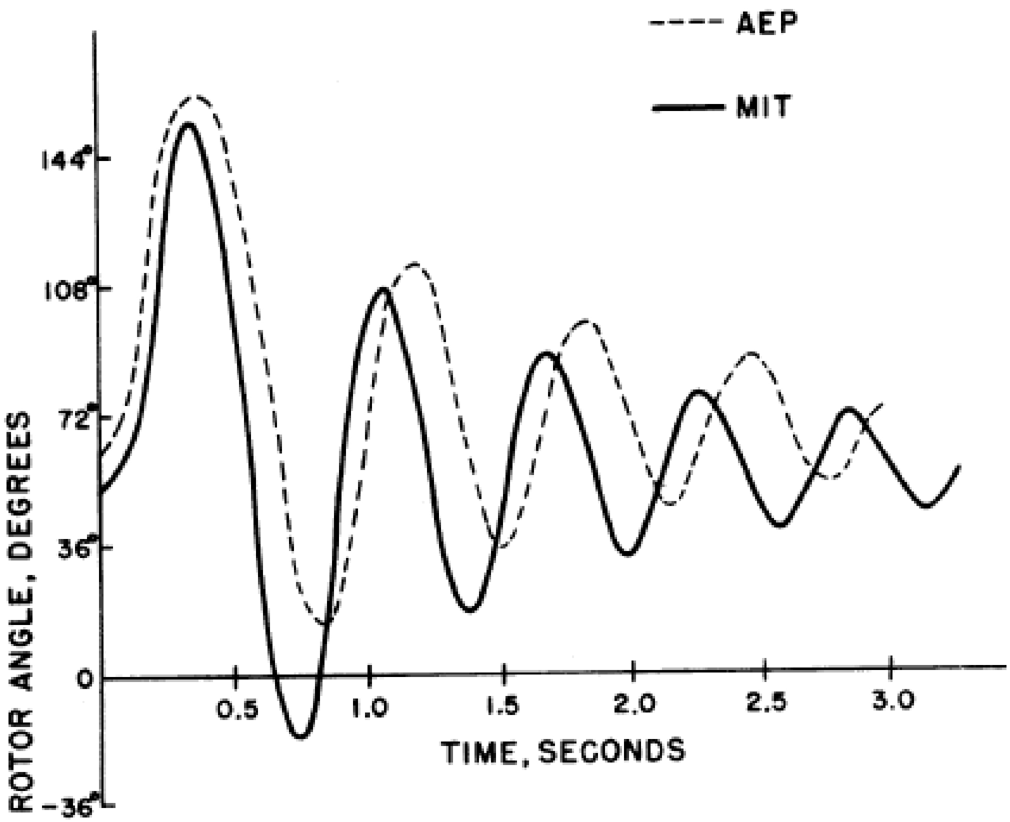

Figure 17. 4. Comparison of rotor's angle dynamics, simulated by the American Electric Power (AEP)Transient Stability Program – actual model at Massachusetts Institute of Technology (MIT) [35].

4 Conclusions and remarks

By comparing Figures 17.2, 17.3 and 17.4 it can be concluded that the error due to incorrect parameters might be very small with regards to the modeling error. The modeling error is inherent to the machine identified and, although not present when dealing with identifying simulated machines, is to be expected in case a physical machine is to be identified.

Apart from modeling infidelity the identification process of a real synchronous machine would have to deal with noisy measurements of both input and output variables, the distribution of which may be not be known. Linearization itself would also bring additional error if larger deviation values of the field voltage were used. Additionally the SMIB model used is also a source of error as the real identified generator will be operating in a system with no infinite bus to keep the voltage at the terminals perfectly constant. Any fluctuations of the terminal voltage will produce some additional noise for the model. Lastly the governor might also affect the dynamics.

It appears that very precise values of identified parameters are unattainable by linear SISO identification in which the field voltage was varied in the simple manner as in this work, as the accuracy with which one can measure the dynamics of a theoretical model is not perfect. It might be possible to obtain better results with longer duration of white noise input, however the realization of white noise disturbance upon field voltage might be practically difficult and the time duration necessary might be problematic since larger time scales have higher probability of having experienced some change in the system which would influence dynamics.

The works [6] and [15] may serve as indicative of the possibility parameter unambiguity, with [6] further hinting at a possibility of a multistage identification scheme. In [15], where the authors used a somewhat different set up for the identification process, a problem with generator identifiability is found and explained as insensitivity of the error norm to the change in the parameter vector in some direction, at the point of the correct solution. In [6] where the authors concentrated on a two stage set up, it is noted that a small field voltage change is a disturbance too small for larger currents in damper windings to be induced and that the damper coil parameters cannot be asserted by it. From Table III one might conclude that the damping coils' parameters were completely unidentifiable this way. This is not to be interpreted as though the dynamics were insensitive to the damping coils; the damping coils affect the dynamics of the generator, however, for every particular value of a certain damping coil's scattering it is possible to obtain the set of all other parameters so that the dynamics matches the original.
In our work the identifiability of the parameters of a synchronous generator from a linearized scheme was examined. For this purpose a new systematic method to identify the parameters of a generator by a linear equivalent using the eighth order model was developed. During the development phase of this method the authors focused on measurements on the terminals bearing in mind that some generators might not be equipped to measure a detailed dynamics of the internal variables. The decoupling mechanism which makes the brute force search feasible is provided. As the brute force search traverses all the parameters combinations the end result is a collection of parameters that correspond to the measured dynamics.

Nomenclature

$\mathbf{U}_{dq\ abc}$	Voltage vector in dq,abc frame respectively in pu
$\mathbf{\Psi}_{dq}$	Vector of coil fluxes in the dq frame in pu

$\mathbf{R}_{dq}$	Coil resistances vector in the dq frame in pu
$\mathbf{L}_{dq}$	Coil inductances vector in the dq frame in pu
ω_{sr}	Rotating speed: rated in rad/s and physical in pu
δ	Rotor angle in rad.
$T_{M,E}$	Torque in pu; mechanical and electrical respectively.
Δv_F	Field voltage step change in pu.
$R_{D,F,G,Q}$	Resistance of coil D, F, G and Q respectively in pu.
H	Inertia constant in s.
$u,i_{a,b,c}$	Phase to ground voltage and line current of phases a, b and c respectively, pu.
$u,i_{d,q}$	Stator voltage and current of the *d* and *q* axis, respectively in pu.
$L_{ad, aq}$	Mutual inductance in *d* and *q* axis, respectively in pu.
$L_{d,q,F,D,G,Q}$	Self-inductance of coil d, q, F, D, G, respectively in pu.

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Model hitre regulabilne naprave za distribucijska omrežja

JERNEJA BOGOVIČ & RAFAEL MIHALIČ

Povzetek Ena izmed možnih rešitev za izboljšanje napetostnih razmer v elektroenergetskem sistemu (EES) je vključevanje hitrih regulabilnih naprav. V samem procesu načrtovanja vključitve pa se pojavi potreba po izračunu napetostnih razmer in pretokov energije, za kar potrebujemo ustrezne modele hitrih regulabilnih naprav.

V preteklosti so že bili izdelani modeli hitrih regulabilnih naprav, ki so primerni za Newton-Raphsonovo metodo. Vendar pa Newton-Raphsonova metoda ni primerna za uporabo v distribucijskih oziroma radialnih omrežjih zaradi težav s konvergenco. Zaradi naštetih vzrokov bomo v članku opisali nov model hitre regulabilne naprave, ki bo primeren za U-I metodo. Nov model hitre regulabilne naprave bo testiran na dveh testnih omrežjih, IEEE 34-vozliščnem testnem sistemu in IEEE 123-vozliščnem testnem sistemu, pri čemer bojo v sistem vključeni tudi razpršeni viri električne energije.

Ključne besede: • model • regulabilna naprava • distribucijsko omrežje • napetostne razmere • pretoki energije • FACTS •

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1 Uvod

Regulacija napetosti ter jalove moči znotraj določenih vrednosti je ena izmed sistemskih storitev, ki igrajo pomembno vlogo pri obratovanju elektroenergetskega sistema (EES). Ena izmed možnosti za učinkovito regulacijo napetosti in jalove moči je vključitev hitrih regulabilnih naprav v EES [1]. V članku je predstavljen trifazni model statičnega sinhronskega serijskega kompenzatorja (SSSC) za regulacijo napetosti za izračun napetostnih razmer in pretokov energije v radialnih omrežjih. Za modeliranje SSSC smo se odločili, ker je v preteklosti, pri uporabi SSSC v izračunih napetostnih razmer in pretokov energije, prihajalo do težav s konvergenco [2]. Pri ostalih modelih hitrih regulabilnih naprav tudi v primeru večjega števila regulirnih parametrov (UPFC) ni prišlo do težav z konvergiranjem izračuna napetostnih razmer ter pretokov energije. Enako načelo, če konvergira za SSSC, bo tudi za ostale hitre regulabilne naprave, je uporabljeno tudi v tem članku. Metodologijo, ki jo uporabimo za modeliranje SSSC lahko uporabimo tudi za ostale hitre regulabilne naprave, pri tem pa se ne bomo soočali s težavami glede konvergence. Bi pa na tem mestu poudarili, da uporaba hitrih regulabilnih naprav v radialnih omrežjih ni pogosta, vendar bi lahko v primeru uporabe koncepta pametnih omrežij, prišlo do preboja hitrih regulabilnih naprav.

Ne glede na vzrok vključitve SSSC v radialna omrežja je potrebno analizirati vpliv novo vključene naprave, za kar pa potrebujemo ustrezen model SSSC. Nekaj načinov modeliranja SSSC je na voljo v [2–5], ki jih v grobem lahko razdelimo na tokovne in napetostne modele. Za slednje je značilno, da imajo težave z konvergenco že v zazankanih omrežjih. Poleg tega pa tako napetostni kot tudi tokovni modeli SSSC nista primerna za uporabo za Newton-Raphsonovo metodo v radialnih omrežjih. Vzrok je v velikem razmerju R/X, kar ima za posledico singularnost Jacobijeve matrike [6] in posledično težave s konvergenco Newton-Raphsonove metode [7]. Vse to pa ima za posledico, da so poleg Newton-Raphsonove metode neuporabni tudi modeli hitrih regulabilnih naprav. Se pa zaradi težav s konvergenco Newton-Raphsonove metode v izračunih napetostnih razmer ter pretokov energije v radialnih omrežjih najpogosteje uporablja efektivna in robustna metoda, ki je U-I metoda.

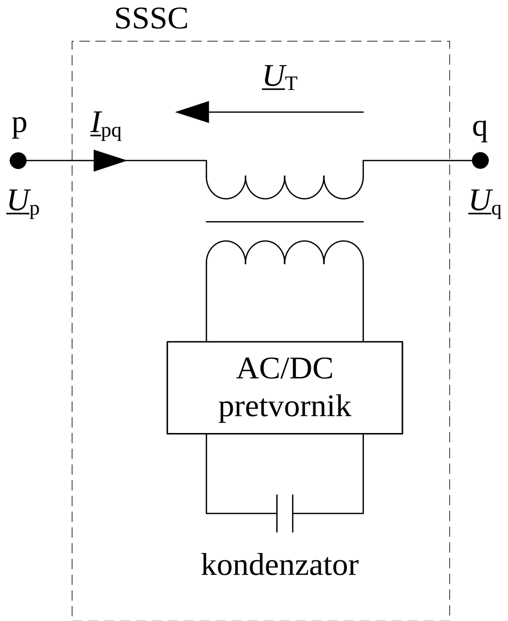
U-I metoda je najpogosteje uporabljena metoda za izračun napetostnih razmer in pretokov energije, ki temelji na glavni lastnosti radialnih omrežij t.j. definiranih poteh pretokov energije od vira do porabnika. Sam princip U-I metode je izračun tokov in padcev napetosti. V prvem koraku izračunamo tokove, ki jih v sistem »vsiljujejo« bremena, čemur sledi izračun vejskih tokov. Ko imamo izračunane vejske tokove, sledi izračun padcev napetosti iz smeri vira proti koncu omrežja oziroma do porabnikov [8]. Prednost U-I metode je, da je enostavna za razumevanje in tudi samo uporabo, slabost pa, da je uporabna le za radialna omrežja.

U-I metoda je doživela že kar nekaj nadgradenj od prve omembe. Ena izmed nadgradenj je uporaba v zazankanih omrežjih, uporaba za modeliranje napetostno odvisnih bremen, uporaba v sistemih, ki imajo vključene razpršene vire električne energije in pa nadgradnja metode, da je uporabna v trifaznih analizah napetostnih razmer ter pretokov energije [6]. V članku bo za testiranje ustreznosti modela SSSC uporabljena modificirana metoda iz [9], pri čemer so razpršeni viri električne energije modelirani kot v [10]. Modeli SSSC so modelirani tako, da upoštevajo vse lastnosti naprave SSSC, še zlasti pa vezavo transformatorja, kar je bistvena nadgradnja. V [11] je uporabljena le funkcija, ki minimizira vsiljeno napetost, ne upošteva pa vezave transformatorja.

Novi modeli SSSC bojo v članku predstavljeni in testirani za namen izboljšanja napetostnih razmer v radialnih omrežjih z razpršenimi viri električne energije za izračun napetostnih razmer in pretokov energije z U-I metodo. V okviru članka bo v drugem poglavju predstavljen model SSSC za U-I metodo, v tretje poglavju bojo predstavljeni rezultati napetostnih razmer in pretokov energije v radialnih omrežjih z vključenimi SSSC in razpršenimi viri, v četrtem poglavju pa bo sledil kratek zaključek.

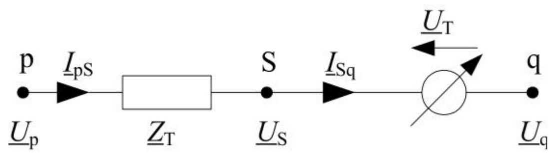
2 Model SSSC

SSSC je serijska hitra regulabilna naprava, ki je sestavljena iz AC/DC pretvornika z kondenzatorjem in je preko transformatorja vezana v EES (slika 18.1). V nekaterih primerih je na mestu kondenzatorja uporabljena baterija [12]. SSSC v zazankanih omrežjih omogoča regulacijo pretokov delovne in jalove moči po vodu, regulacijo vsiljene ali vozliščne napetosti in impedance (reaktance) voda. V radialnih omrežjih pa so možnosti regulacije precej okrnjene le na regulacijo vsiljene in vozliščne napetosti, pri čemer je uporaba SSSC smiselna le v namen regulacije vozliščne napetosti.



Slika 18.1: Shema SSSC

V preteklosti je bilo razvitih že kar nekaj načinov modeliranja SSSC za izračun napetostnih razmer ter pretokov energije z Newton-Raphsonovo metodo. Kljub temu da tej modeli niso primerni za uporabo v samih radialnih omrežjih, pa se lahko sama logika modeliranja SSSC uporabi za modeliranje za U-I metodo. Pri modeliranju SSSC za U-I metodo smo izhajali iz modela predstavljenega v [2], kjer je SSSC predstavljen kot impedanca (predstavlja izgube) in napetostni vir. Uporaba takšnega koncepta je najbolj primerna za U-I metodo, saj se zaradi takšnega modeliranja v model uvede dodatno vozlišče S, ki navidezno loči izgube od regulacije oziroma vira napetosti (slika 18.2).



Slika 18.2: Tokovni model SSSC za Nawton-Raphsonovo metodo

Da bi zagotovili ustreznost modela SSSC za U-I metodo, je potrebno pri modeliranju upoštevati zahteve glede vsiljene delovne moči, glede vezave transformatorja in reguliranih veličin. Na možnost reguliranih veličin ima največji vpliv vezava transformatorja in kondenzator. Ker slednji ni hranilnik delovne moči, je delovna moč, ki se pretaka med enosmerno stranjo SSSC in sistemom enaka nič. V kolikor ima SSSC skupen kondenzator za vse tri faze, je delovna moč, ki se pretaka definirana kot nič za vse ti faze skupaj (1), v kolikor pa ima vsak faza svoj kondenzator pa je delovna moč definirana kot nična za vsako fazo posebej (2).

$$\sum_{p=a,b,c} P_{SSSC}^{p} = 0 \tag{1}$$

$$P_{SSSC}^{a} = P_{SSSC}^{b} = P_{SSSC}^{c} = 0 \tag{2}$$

pri čemer P_{SSSC}^{p} predstavlja delovno moč med EES in kondenzatorjem SSSC v fazi p.

Poleg kondenzatorja pa na število možnih reguliranih veličin vpliva še sama vezava transformatorja, ki povezuje SSSC z EES. V kolikor je SSSC z EES povezan preko transformatorja vezanega v vezavo zvezda, potem glede vsiljene napetosti za vsako fazo posebej ni nikakršne omejitve. V kolikor pa je vezava transformatorja trikot, je potrebno upoštevati, da je vektorska vsota vseh treh vsiljenih napetosti enaka nič (3).

$$\sum_{p=a,b,c} \underline{U}_{SSSC}^{p} = 0 \tag{3}$$

pri čemer je $\underline{U}_{SSSC}^{p}$ vsiljena napetost SSSC v fazi p.

Zadnji korak pri modeliranju SSSC pa je definiranje reguliranih veličin. Ob upoštevanju vseh zgoraj naštetih lastnosti SSSC, je parameter, ki ga lahko reguliramo le eden (le za eno fazo) ali pa so parametri trije (za vsako fazo posebej). Regulirane veličine so definirane za regulacijo vsiljene napetosti z (4), za regulacijo vsiljene jalove moči (5) in za regulacijo vozliščne napetosti z (6).

$$U_{inj}^{p} = U_{inj,ref}^{p} \tag{4}$$

$$Q_{inj}^{p} = Q_{inj,ref}^{p} \tag{5}$$

$$U_{node}^{p} = U_{node}^{p} \tag{6}$$

V primeru da ima SSSC v vsaki fazi svoj kondenzator in je s sistemom povezan z transformatorjem, ki je vezan v zvezdo, potem je definiranje SSSC za U-I metodo enostavno. V kolikor pa je vezava transformatorja trikot in ima SSSC skupen kondenzator za vse tri faze, potem je definiranje SSSC nekoliko bolj kompleksen proces. Uporabljena je modifikacija U-I metode, ki v koraku za izračun parametrov SSSC preide v reševanje sistema nelinearnih enačb z Newtonovo metodo.

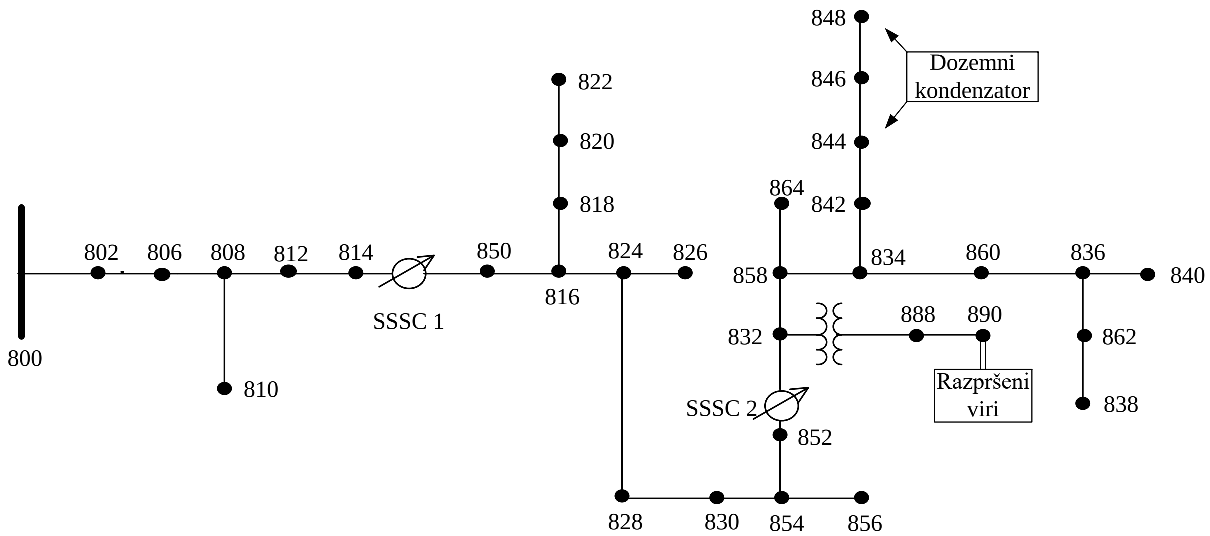
3 Rezultati

Trifazni model SSSC smo testirali na dveh radialnih testnih omrežjih. V vseh testnih primerih je uporabljen SSSC, ki je v sistem povezan preko transformatorja vezanega v trikot. Za izračun napetostnih razmer in pretokov energije smo uporabili matematični program Matlab. Za izračun parametrov SSSC je bila uporabljena integrirana Matlabova funkcija *fsolve*. Razpršeni viri so definirani kot močnostni viri kakor v [11].

3.1 IEEE 34-vozliščni testni sistem

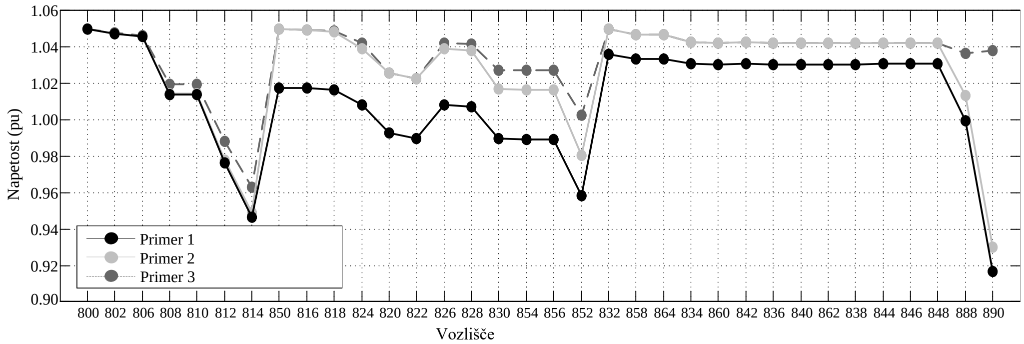
IEEE 34-vozliščni sistem je eden izmed standardnih sistemov, ki se nahaja v Arizoni (ZDA). V testnem sistemu sta vključena dva SSSC, prvi se nahaja med vozliščema 814 ter 850, drugi pa med vozliščema 852 in 832. Na teh dveh lokacijah sta v osnovnem sistemu vključena dva napetostna regulatorja. Razpršeni viri električne energije (sončne elektrarne) maksimalne moči 220 kW v posamezni fazi so v sistem vključeni v vozlišču 890.

Testirali smo tri različne situacije. V prvem primeru smo testirali osnovni sistem, kjer sta vključena v sistem dva napetostna regulatorja in dva dozemna kondenzatorja. V drugem primeru sta napetostna regulatorja zamenjana z dvema SSSC, dozemna kondenzatorja pa sta izključena. V tretjem primeru pa sta prav tako napetostna kondenzatorja zamenjana z dvema SSSC, dozemna kondenzatorja sta izključena, razpršeni viri električne energije pa so vključeni v sistem, pri čemer proizvajajo maksimalno inštalirano moč, ki je 220 kW v vsaki fazi. Za namen opazovanja konvergence z vključenim SSSC v sistem, smo delovno moč razpršenih virov spreminjali od 0 kW do 220 kW po koraku 10 kW.



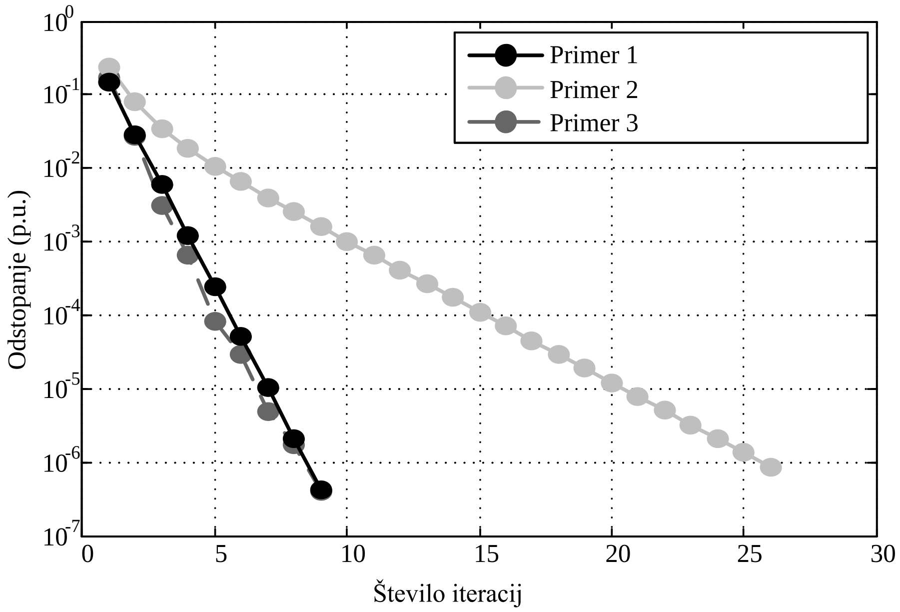
Slika 18.3: IEEE 34-vozliščni testni sistem

Slika 18.4 prikazuje napetosti v fazi L1 v vsakem vozlišču za vse tri testne situacije. Potek napetosti za osnovni sistem je prikazan s črno barvo. Za drugo situacijo je potek napetosti označen s svetlo sivo barvo, za tretjo situacijo pa je potek prikazan s temno sivo črtkano črto. Na podlagi rezultatov lahko zapišemo, da je najboljše napetostno stanje v primeru, ko so v sistem vključena SSSC in razpršeni viri (primer 3). V kolikor razpršeni viri ne proizvajajo energije (primer 2) je napetostno stanje še vedno boljše, kot v primeru, ko sta za namen regulacije v sistem vključena napetostna regulatorja (primer 1).

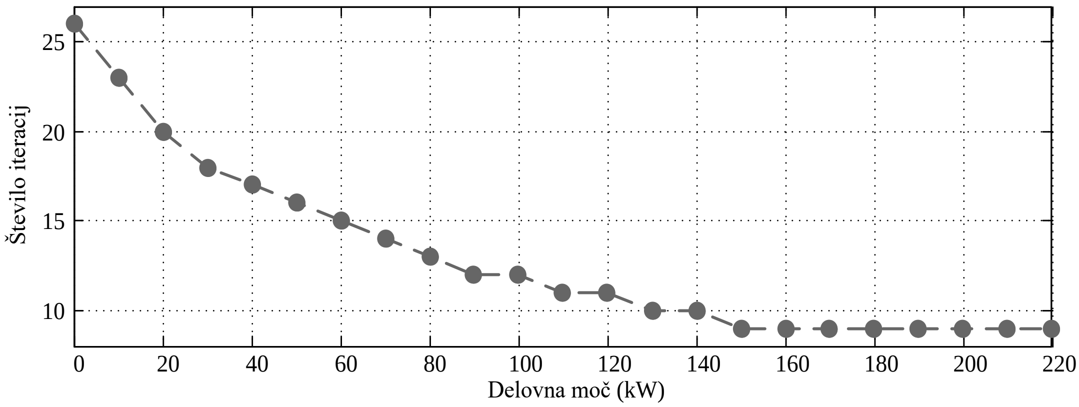


Slika 18.4: Napetostni profil za različne primere

Slika 18.5 prikazuje število iteracij, ki so potrebne za dosego želenega odstopanje napetosti v dveh zaporednih iteracijah (ε = 10-6 pu). Za tretji primer smo želeno odstopanje dosegli v devetih iteracijah, kar je enako število iteracij, kot jih je v osnovnem primeru (primer 1). Število iteracij pa je bistveno večje v primeru, ko razpršeni viri ne proizvajajo električne energije (primer 2).



Slika 18.5: Število iteracij za različne primere



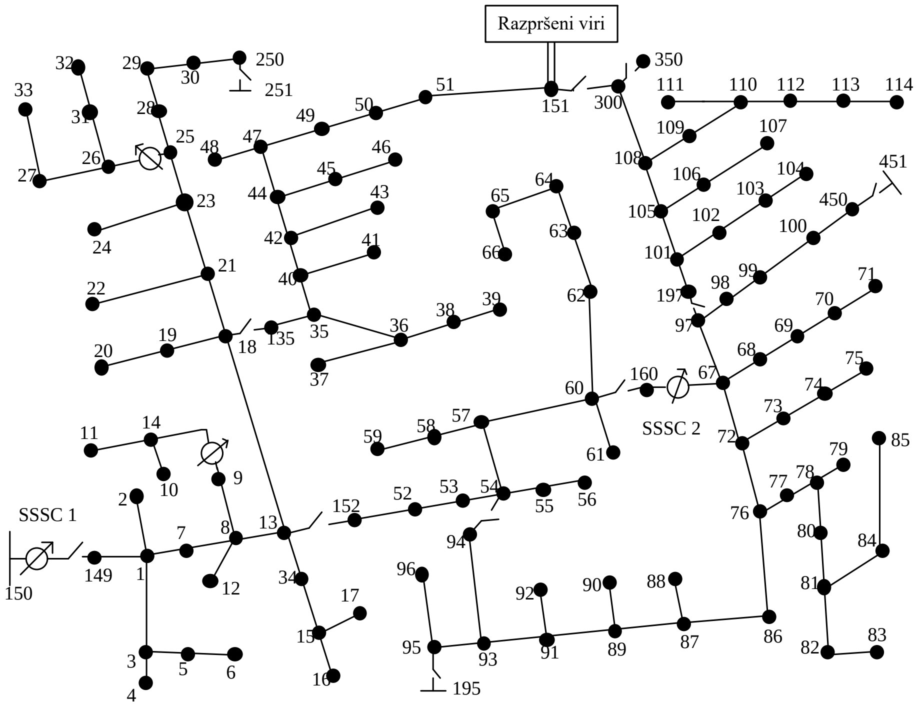
Slika 18.6: Number of iterations for different production of DG with included SSSCs into the feeder

Slika 6 prikazuje število iteracij za dosego želenega odstopanja v odvisnosti od delovne moči razpršenih virov električne energije. Opaziti je obratno sorazmerje, število iteracij upada z naraščanjem moči. Kljub temu da je SSSC poznan po težavah s konvergenco, pa lahko zaključimo, da nov model ne nakazuje teh težav.

3.2 IEEE 123-vozliščni testni sistem

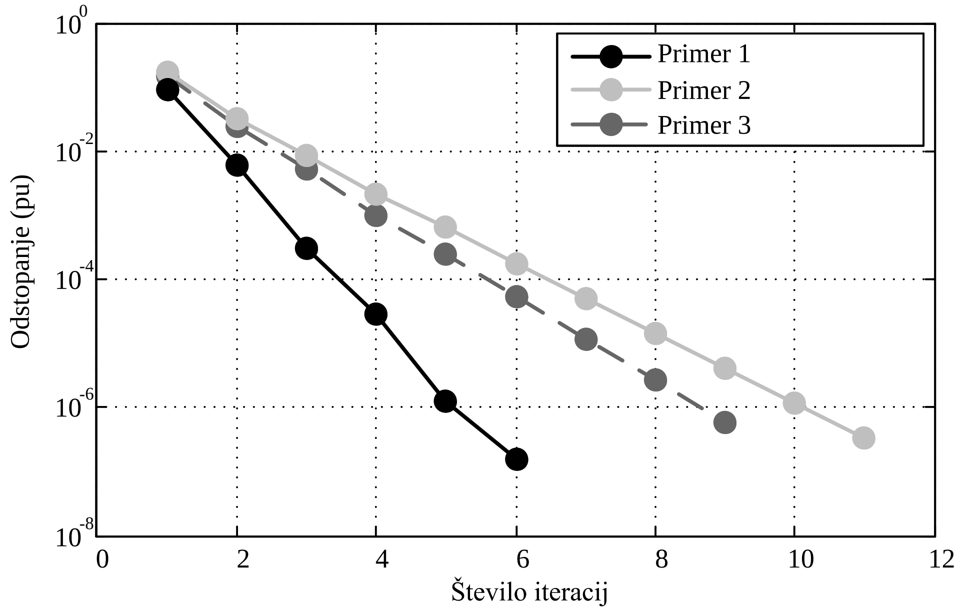
IEEE 123-vozliščni sitem je eden izmed večjih testnih distribucijskih sistemov. V testnem sistemu sta vključena dva SSSC. Prvi se nahaja med vozliščema 150 in 149, drugi pa med vozliščema 160 in 67. V osnovnem sistemu sta na tem mestu vključena napetostna regulatorja.

Razpršeni viri električne energije inštalirane moči 300 kW v vsaki fazi so v sistem vključeni v vozlišču 151. Kakor v primeru 34-vozliščnega sistema, so tudi v tem sistemu testirane tri različne situacije, osnoven sistem, primer 2 z vključenima dvema SSSC in primer 3 z vključenima SSSC in razpršenimi viri električne energije. V obeh primerih, ko so v sistem vključeni SSSC, so dozenmi kondenzatorji izključeni.

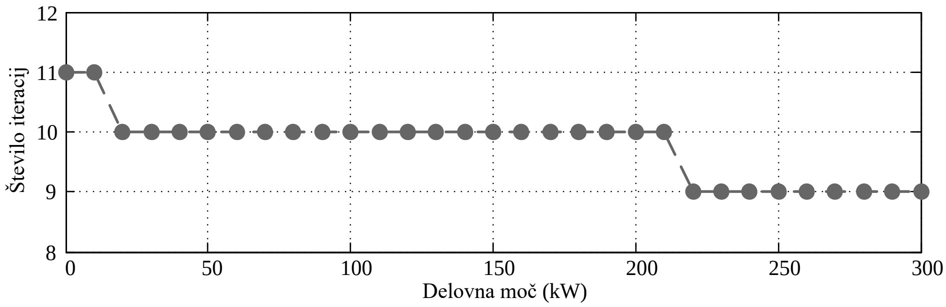


Slika 18.7: IEEE 123-vozliščni testni sistem

Slika 18.8 prikazuje odstopanje napetosti med dvema zaporednima iteracijama za vse tri testne primere. V primeru osnovnega sistema je število iteracij šest, nekaj več iteracij pa je potrebnih v primeru, ko sta napetostna regulatorja nadomeščena z dvema SSSC. Število iteracij pa je skoraj enako ali razpršeni viri proizvajajo ali ne proizvajajo električno energijo (slika 18.9).

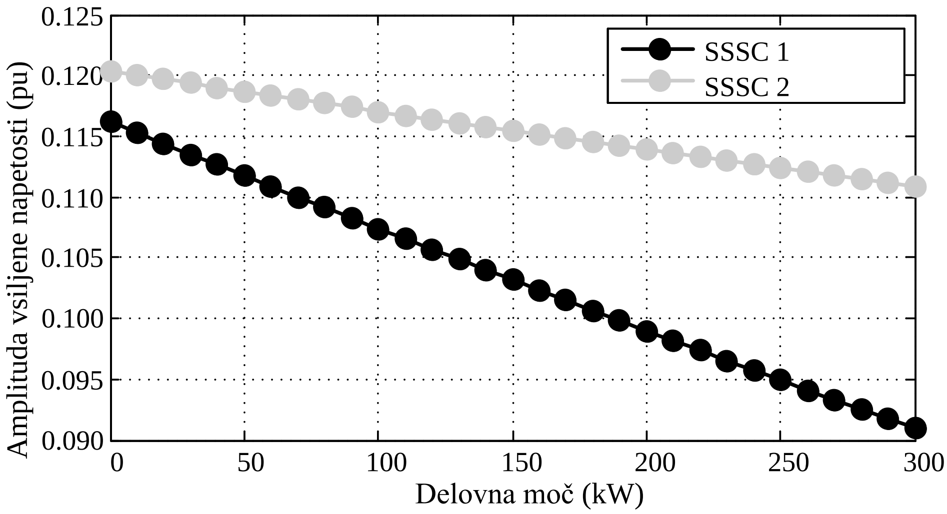


Slika 18.8: Odstopanje med dvema iteracijama za različne testne primere



Slika 18.9: Število iteracij v odvisnosti od proizvodne razpršenih virov

Slika 18.10 prikazuje amplitudo vsiljene moči za oba SSSC za različno delovno moč razpršenih virov. S črno so prikazane amplitude vsiljene moči prvega SSSC (vključen med vozliščema 150 in 149), z sivo pa so prikazane vsiljene moči drugega SSSC (vključen med vozliščema 160 in 67). Vrednosti vsiljenih moči so okoli 10 % nazivne napetosti.



Slika 18.10: Amplituda vsiljene napetosti v odvisnosti od moči razpršenih virov

4 Zaključek

V članku je prikazan nov model SSSC, ki omogoča regulacijo vozliščne napetosti. Model smo testirali na dveh testnih sistemih; IEEE 34-vozliščnem testnem sistemu in IEEE 123-vozliščnem sistemu. SSSC smo testirali na primerih, kjer razpršeni viri ne proizvajajo električne energije (primer 2) in v primerih, kjer razpršeni viri proizvajajo maksimalno moč (primer 3). Dodatno smo opazovali še število iteracij v odvisnosti od različne proizvodnje moči razpršenih virov.

Rezultati prikazujejo, da SSSC izboljša napetostne razmere v sistemu. Poleg tega se število iteracij za izračun napetostnih razmer ter pretokov energije ne poveča bistveno, v kolikor imamo v sistemu vključene SSSC, kljub temu da je SSSC poznan kot naprava, ki ima težave z konvergenco pri izračunih napetostnih razmer in pretokov energije.

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Flexible Alternating Current Transmission System Devices Compensator for Distribution System

JERNEJA BOGOVIČ & RAFAEL MIHALIČ

Abstract One of the possible solutions for improving voltage conditions in an electric power system (EPS) is applying power electronics based or so called flexible alternating current transmission system (FACTS) devices. However, the appropriate inclusion of a FACTS device into the EPS is not a straightforward procedure. On the contrary, it requires several steps. One of the first steps is the power flow analysis, which requires an appropriate FACTS device modelling.

In the past the models of FACTS devices for Newton-Raphson (NR) power-flow and current-injection calculation methods have been developed. The NR analysis, however, is not always suitable for distribution networks due to convergence problems. This is why new three-phase models of FACTS devices for the forward/backward sweep method are presented in this paper. Their application is demonstrated on an IEEE 34 and 123 bus test systems, in order to clearly present the approach virtues for FACTS modelling in distribution networks with included distributed generation units (DGs).

Keywords: • model • regulator • distribution system • voltage conditions • power flow • FACTS •

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1 Introduction

Voltage and reactive power control in accordance with minimum standards are one of several system services and are an important part of safe, reliable and efficient operation of an electric power system (EPS). One of possibilities for active voltage and reactive power control is including power-electronics-based or so called flexible alternating current transmission system (FACTS) devices into a power network [1]. In this paper application of a three-phase static synchronous series compensator (SSSC) for a voltage control in a steady-state operation of a distribution system is demonstrated. This particular device has been chosen, because in the past it was known for some difficulties with convergence in power-flow calculations [2]. It turned out that even with the multi-parameter devices, for which the synonym is a unified power flow controller (UPFC), are less problematic regarding convergence as SSSC. Therefore even new approaches had to be developed (the so called current approach). The similar logic is followed in this paper, i.e. “if SSSC converges well” also other devices will. Authors are aware that FACTS devices are not often used in the distribution systems, however it is imaginable that in the future SmartGrids concept may play an important role.

The impact of SSSC on power flows has to be considered, regardless of the reason why it is included in the EPS. For that reason an appropriate model of SSSC for power-flow calculations is needed. Numerous models of SSSC for steady state can be found in the available literature [2–5]. They can be divided on current and voltage based models the later having difficulties with convergence. But still most of them are appropriate for Newton-Raphson (NR) power-flow calculation method. However, EPS’s with a high R/X ratio may create ill-conditioned problems for the NR (or Newton-type) power-flow algorithms [6] and consequently seriously affecting method’s convergence [7]. As this makes the NR method inappropriate for this kind of EPS, the same goes for mentioned SSSC models. As a result, in order to perform power-flow calculations in a distribution system, an efficient and robust method should be used, such as backward/forward sweep method.

The backward/forward sweep methods are most commonly used methods for power-flow calculations in radial distribution networks because they take advantage of a natural feature of the radial networks, i.e. a unique path from any given bus to the source. The basic principle consists of two basic steps: forward sweep and backward sweep. The forward sweep is based on a voltage-drop calculation caused by the current flow via impedance elements from the sending end to the far end of a feeder. The backward sweep on the other hand is based on a calculation of the node injected current and it summation in the opposite direction, i.e. from the far end of the feeder to the sending end [8]. Its advantage is its simplicity in understanding and use; however its disadvantage is applicability limited to radial systems.

Several modifications of backward/forward sweep methods have been created since the first proposal. They made the method suitable also for solving systems with a weakly meshed topology, systems with voltage dependent loads, systems with DG and three-phase systems (also three-phase four-wire systems, including neutral grounding [6]). In this paper a modification of a backward/forward sweep method from [9] is used, with a supplement of DG [10] for testing a new three-phase model of SSSC. Despite conclusions from [11], where model is based on the minimization of the inverter capacity function due to injected voltage, approach in this paper includes the connection of transformer to the EPS as well.

A new three-phase model of SSSC is presented with a task of improving voltage condition in a radial network with included DG. The model is suitable for use in radial network power-flow calculations with forward/backward sweep method. The paper is structured as follows. In section 2 SSSC model is presented, in section 3 the performed power-flow calculations and accompanying results are presented and finally, with respect to applied test system, the conclusions are drawn in section 4.

2 SSSC model

SSSC is a series FACTS device, which consists of an AC/DC converter with a capacitor, which is connected to the EPS via series transformer or transformers (see Figure 19.1). In some cases the capacitor is replaced with a power source. SSSC is capable of controlling active or reactive power-flow at the line, injected voltage magnitude, bus voltage magnitude and impedance (reactance) in meshed systems [12]. However, in radial systems these functions are limited only to injected voltage magnitude and bus voltage magnitude, whereas only the second ability seems reasonable to exploit.

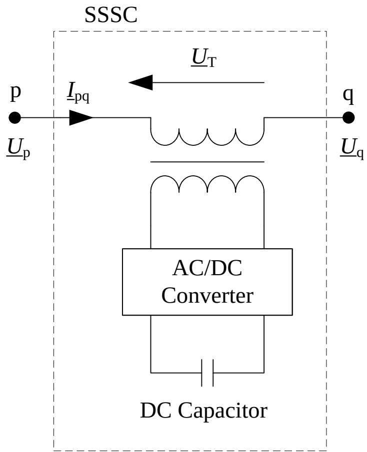

Figure 19.1: Scheme of SSSC

As it was already mentioned, different kinds of SSSC models for power-flow calculations were developed in the past. However, with respect to NR method, they can be treated as unsuitable, as they cause serious convergence issues in radial systems with high R/X ratio. Nevertheless, existing equations can be modified to fit the purpose of forward/backward sweep method. The concept from [2], where the SSSC is presented with a voltage source and a series impedance (mathematical representation of the losses) has been taken as the starting point. This kind concept is the most suitable to use with backward/forward sweep method because of the existence of an additional node (denoted with letter "S") between the impedance and the voltage source (see Figure 19.2).

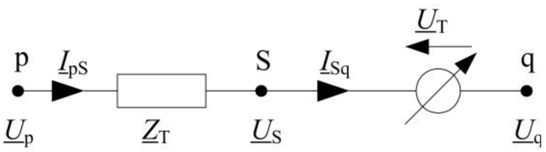

Figure 19.2: Current-based SSSC model

To ensure mathematical correctness of the current-based SSSC device representation, its controllable variables must fulfil some requirements, related to the active-power balance equations, transformer winding connection and the controlled parameters. The numbers of free parameters of controllable variables depend on the implementation of SSSC into EPS. Due to the lack of energy source in the converter DC side, the active-power supplied by the inverter to the system is zero. If SSSC has common DC part for all three-phases the active-power balance equation for SSSC refers to all three-phases (1). If each phase has its own DC part, the active-power balance equations refer to each phase separately (2).

$$\sum_{p=a,b,c} P_{SSSC}^{p} = 0 \tag{1}$$

$$P_{SSSC}^{a} = P_{SSSC}^{b} = P_{SSSC}^{c} = 0 \tag{2}$$

where P_{SSSC}^{p} represents SSSC injected active-power in phase p.

Besides DC part performance, the number of free parameters depends on implementation of the series transformer. If it is Y-connected there is no restriction regarding injected voltage at each phase. For Δ-connection (most appropriate for unsymmetrically loaded EPS) on the other hand, there is a limitation about injected voltage for real and imaginary part (3).

$$\sum_{p=a,b,c} \underline{U}_{SSSC}^{p} = 0 \tag{3}$$

where $\underline{U}_{SSSC}^{p}$ represents injected voltage of SSSC for each phase p.

In accordance with all previously mentioned dependencies due to implementation of SSSC, the controlled parameters refer to all three-phases or are limited to only one phase. The already mentioned SSSC controlled parameters are mathematically described with (4) for injected voltage, (5) for injected reactive power and (6) for nodal voltage.

$$U_{inj}^{p} = U_{inj,ref}^{p} \tag{4}$$

$$Q_{inj}^{p} = Q_{inj,ref}^{p} \tag{5}$$

$$U_{node}^{p} = U_{node}^{p} \tag{6}$$

For independent SSSC-based control of variables, where each SSSC phase has its own DC part regardless of the winding connection of the series transformer, the derivation of equations is rather straightforward. But for SSSC with a common DC part and Δ-connected series transformer, the procedure is more complex. For that reason a new modification of backward/forward sweep method is required, which is presented in continuation. The modification involves quasi-Newton method to solve the system of equations representing SSSC.

3 Results

The three-phase model of SSSC was tested on two different EPS test systems listed below. In all of them the SSSC with common DC part and Δ connected series transformer is used. The power flow was calculated by Matlab and the implemented function *fsolve* was used to detail SSSC. For representation of DG PQ model is used as in [11].

3.1 IEEE 34-bus test system

The IEEE 34-bus test system is an actual feeder located in Arizona, US. In the presented case, two SSSC devices are connected to the IEEE 34-bus test system, the first is placed between nodes 814 and 850 and the second between 852 and 832. The reader should note that initially the voltage controllers are integrated. The DG (photovoltaic (PV) power plant) is connected to the feeder in node 890 and it injects maximum 220 kW of active-power per phase.

Three different situations were tested. The first situation is the basic situation, where two voltage controllers and two shunt capacitors are included into the model. In the second situation the voltage controllers are replaced with two SSSC devices and shunt capacitors are disconnected. In the third situation controllers are replaced with SSSC devices, shunt capacitors are disconnected and DG produces the maximum installed power of 220 kW per phase. To observe impact of SSSC on convergence power-flow calculations were performed for different kW generation of a DG unit ranging from 0 kW up to 220 kW by step of 10 kW.

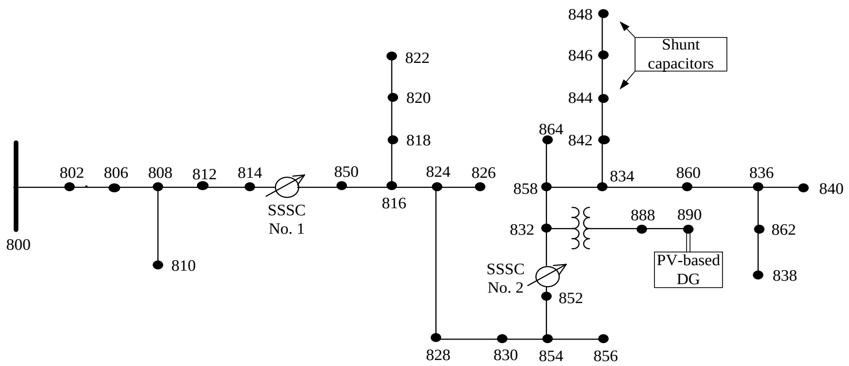

Figure 19.3: IEEE 34-bus test system

Figure 19.4 shows the results of a voltage profile at phase L1 throughout the test system for all three situations. With the solid black line the results for basic situation are shown. With solid grey line the results for the second situation and with dashed grey line the results for the third situation are shown. The voltage profile is most favourable with SSSC units and included DG. In case when DG does not produce any power the voltage profile is still better compared to the basic case although the shunt capacitors are disconnected.

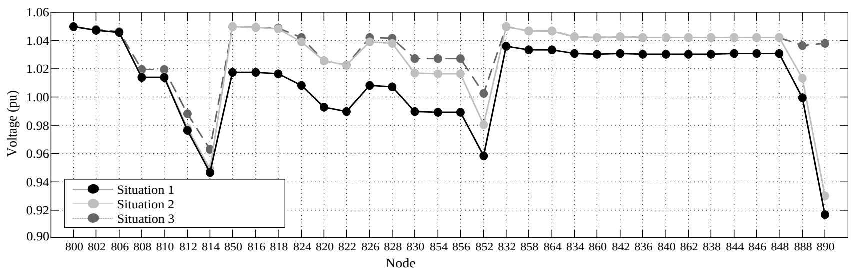

Figure 19.4: Voltage profile at each node for different situations

Figure 19.5 presents the number of iterations needed to achieve the desired mismatch of ε = 10-6 pu between voltage differences in two subsequent iterations. The desired mismatch was achieved in nine iterations for situation 3, which equals to the number of iterations in the basic situation. The number of iterations to achieve desired mismatch is much larger if the DG does not produce any power.

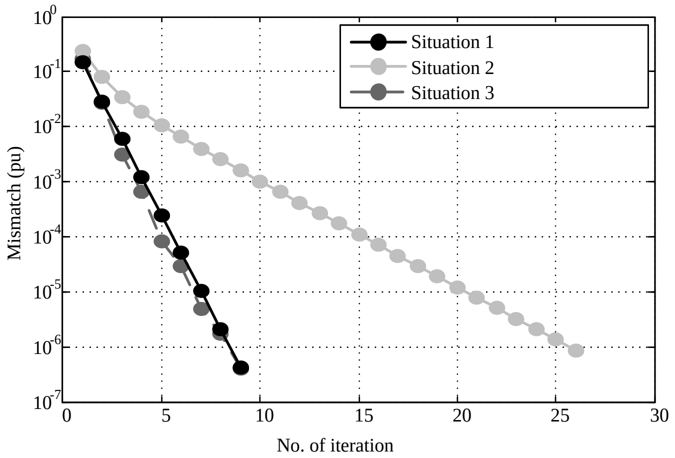

Figure 19.5: Mismatch for IEEE 34-bus test system for different situations

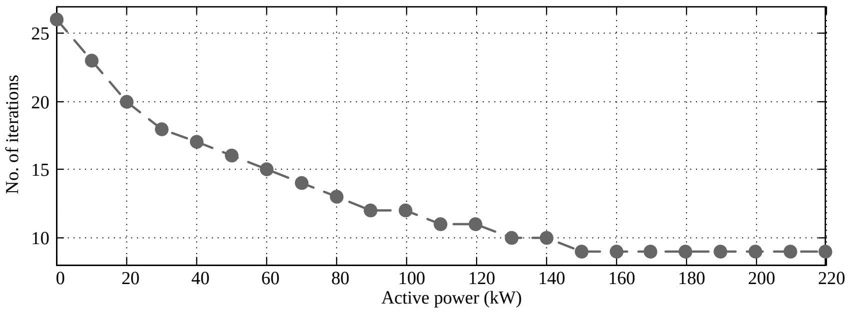

Figure 19.6: Number of iterations for different production of DG with included SSSCs into the feeder

Figure 19.6 illustrates the number of iterations for different injected amounts of DG active-power. The number of required iterations decreases with increasing generation. Although a SSSC device is known for its problems with convergence, the proposed model shows no sign of convergency problems in all tested situations for 34-node test feeder.

3.2 IEEE 123-bus test system

IEEE 123-bus test system is one of the largest test feeders that presents distribution system. In test system two SSSC devices are included. The first is placed between nodes 150 and 149 and the second between nodes 160 and 67. Initially the voltage controllers are integrated.

The DG unit (PV power plant) is included into the system at node 151 and injects maximum 300 kW of active-power per phase. As in previous test example, three different situations are observed: the basic situation, situation No. 2 with included SSSCs and situation No. 3 with included SSSCs and DG at maximum production. As in section 3.1 shunt capacitors are disconnected if SSSCs are installed.

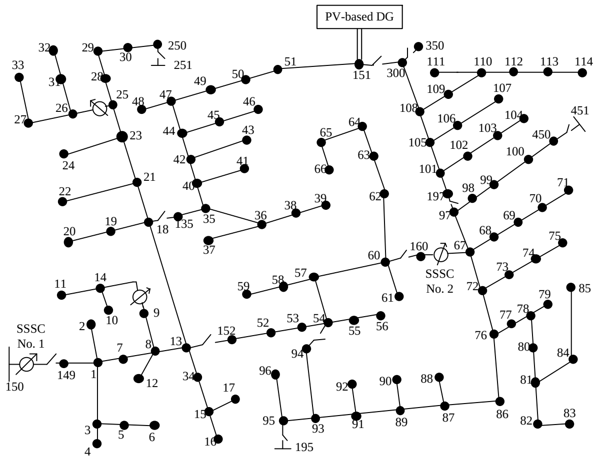

Figure 19.7: IEEE 123-bus test system

Figure 19.8 illustrates the voltage mismatch for three different situations. The desired mismatch is achieved in six iterations if the voltage controllers and shunt capacitors are included in the EPS. Insignificantly more iterations of voltage controllers and shunt capacitors are replaced by SSSCs. Figure 19.9 presents the number of iterations needed to achieve desired mismatch and is almost the same regardless of the production of a DG unit.

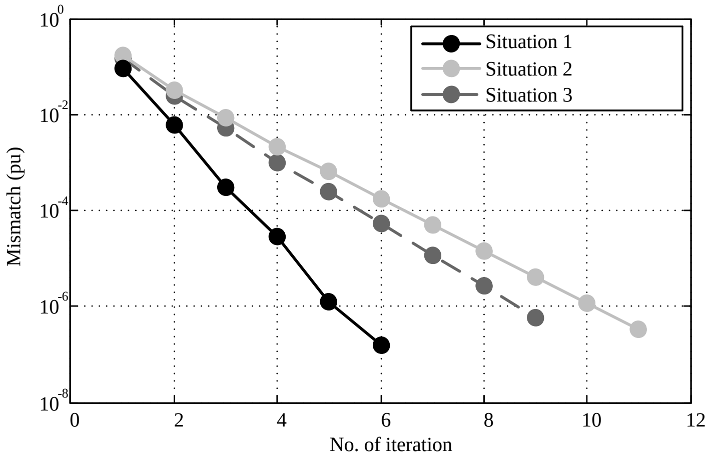

Figure 19.8: Mismatch for IEEE 123-bus test system for different situations

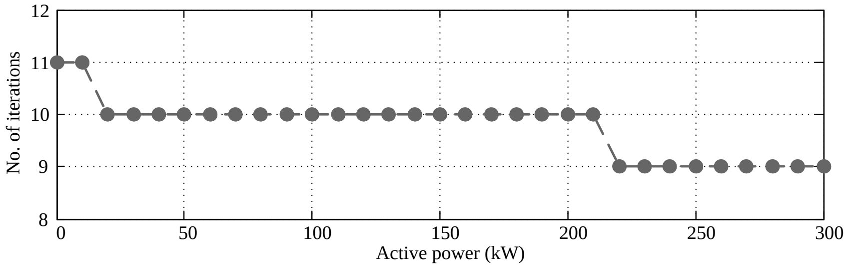

Figure 19.9: Number of iterations for different production of DG with included SSSCs into the feeder

Figure 19.10 shows the injected voltage for both SSSCs for different DG generation. The black line represents the injected voltage at first SSSC (between nodes 150 and 149) and the grey line illustrates the injected voltage at second SSSC (between nodes 160 and 67). The values of injected voltage are around 10 % of rated voltage.

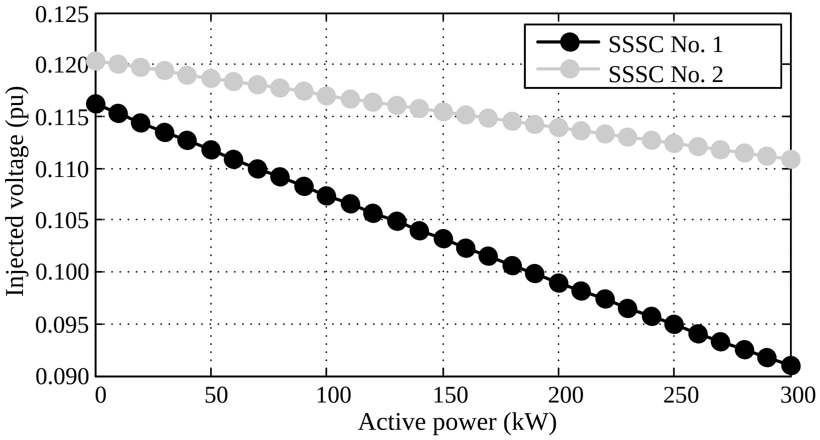

Figure 19.10: Injected voltage of SSSCs for different production of DG

4 Conclusion

The new model of SSSC for nodal voltage control is presented in this paper. The model is tested on two different test-systems; IEEE 34-bus test system and IEEE 123-bus test system for two different situations. The third situation involves DG with maximal power output and the second situation with no DG contribution. Power-flow calculations for different DG production with included SSSC were performed to observe for possible convergency issues.

The results show that the SSSC-based voltage control invokes better voltage conditions with respect to the base case with active controllers. The number of required iterations is in most cases the same if the SSSC or voltage controllers are included in the system even though SSSC is known to have convergency issues in power-flow calculations.

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Analiza vpliva umestitve predvidene SVC naprave v slovenski elektroenergetski sistem s stališča dušenja ENTSO-E med-sistemskih nihanj

URBAN RUDEŽ & RAFAEL MIHALIČ

Povzetek V procesu načrtovanja morebitnih bodočih investicij v slovenski elektroenergetski sistem se je pojavila potreba po obsežni analizi vplivov naprave iz družine FACTS na dušenje nizkofrekvenčnih med-sistemskih nihanj v ENTSO-E kontinentalni interkonekciji, in sicer statičnega var kompenzatorja (SVC). Po prvotni zamisli bi bila SVC naprava predvidena ureditvi lokalnih stacionarnih napetostnih razmer na 220 kV in 400 kV napetostnih nivojih v regiji. Ker napravo odlikuje hiter dinamičen odziv, je bilo smiselno preveriti tudi možnost uravnavanja razmer v širši električni okolici, torej na obratovanje ENTSO-E interkonekcije, katerega del je tudi slovenski elektroenergetski sistem. Analiza je bila izvedena na kompleksnem modelu omrežja za analizo dinamičnih pojavov, sestavljenega iz javno dostopnega ENTSO-E modela ter interno izdelanega (ter v preteklosti preverjenega) modela elektroenergetskega sistema Slovenije. Modeliranje omenjene naprave je bilo izvršeno na podlagi objavljenih raziskovalnih publikacij tako tujih kot domačih raziskovalcev. Z upoštevanjem preproste regulacijske strategije so rezultati v splošnem pokazali na pozitiven vpliv na stabilnost za majhne motnje ter identificirali tista med-sistemska nihanja, katerih dušenje je mogoče z napravo, priključeno na visokonapetostno omrežje Slovenije, uspešno dušiti.

Ključne besede: • elektroenergetski sistem • FACTS • dušenje • nizkofrekvenčno • med-sistemsko • nihanje • interkonekcija •

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Impact of Considered SVC Implementation in the Slovenian Power System on Inter-Area ENTSO-E Oscillation Damping

URBAN RUDEŽ & RAFAEL MIHALIČ

Abstract During the planning process of possible future investments into the Slovenian power system, a need arose for the comprehensive analysis related to low-frequency inter-area oscillation damping of a static var compensator (SVC) device. The SVC device was initially considered for solving local steady-state voltage issues on highest 220 kV and 400 kV voltage levels in the region. As the SVC device features fast dynamic response, it seemed reasonable to verify whether its implementation benefits the operation of the entire ENTSO-E interconnection as well. The presented analysis was performed using a complex model for dynamic studies, comprising publicly available ENTSO-E model and internally constructed Slovenian power-system model, which was successfully tested and verified in the past. Modelling of the SVC device was achieved by means of available research publications dealing with the subject, both foreign as well as domestic. By implementing a simple damping strategy, the results showed a positive effect on a small-signal stability and indicated which inter-area oscillations can be successfully damped when considered devices are connected to the Slovenian high-voltage transmission network

Keywords: • power system • FACTS • damping • low-frequency • inter-area • oscillation • interconnection •

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1 Introduction

It has been decades since national power systems in continental Europe started to interconnect in order to increase the level of operational security of individual power systems. However not until the introduction of Wide Area Monitoring Systems (WAMS) were Transmission System Operators (TSOs) able to monitor the operation of the entire ENTSO-E (European Network of Transmission System Operators for Electricity) interconnection as a whole, as it has grown significantly since then, encompassing almost the entire European continent. Relatively poor number of interconnections between countries compared to strong electrical connections within the countries themselves, resulted in conditions that often lead to low-frequency inter-area oscillations, which are electromechanical in their nature. There are a few publication available that study those periodically re-appearing such as [1] and [2].

Recently, ENTSO-E announced the availability of initial dynamic study model of the continental Europe [3], being prepared in several commercially accessible simulation software tools. The model exhibits three most often reoccurring inter-area oscillations, covering both oscillation directions: west-to-east and north-to-south. At the moment, this model appears to represent the best possible public-domain means for analysing the potential of low-frequency oscillation damping in ENTSO-E interconnection by applying different devices and control strategies.

Authors of this work did no concentrate on providing most suitable control strategy for achieving best possible impact of damping. Rather, the focus was put on finding out whether Slovenian power system's location within ENTSO-E interconnection is suitable for fast-acting devices, such as static car compensator (SVC), to impact the damping of inter-area oscillations significantly. The original idea for the installation of an SVC device however, originates in the need for solving steady-state voltage issues in the region, encompassing Slovenian and Croatian power system. It has been observed lately that during the low system loading, the operational voltage on 220 kV and 400 kV voltage levels reach alertly high values that might endanger the equipment in time. So the question arose whether the installation of fast-acting device instead of simple (static) reactors would have any positive consequences that would reach beyond the national borders.

To this end, a previously verified dynamic model of the Slovenian power system [5] was implemented into the already mentioned dynamic study model of ENTSO-E. Then one of targeted interconnection-wide oscillations was triggered. In the final phase, a model of an SVC device with a simple and straightforward control strategy for power oscillation damping (POD) was being relocated across several European countries of interest in order to see how impact on the damping changes with the location.

2 Applied Dynamic Models

2.1 ENTSO-E interconnection dynamic model (Dynamic Study Model)

In the last two years or so, the initial dynamic model of continental Europe was made publicly available by the European Network of Transmission System Operators for Electricity (ENTSO-E) [3].

The model-building process introduced several specifics, which limits the model's application solely to representing:

- mean frequency transients (spinning reserve, primary control),
- general oscillatory behaviour (i.e. modal analysis), which was monitored by European Wide-Area Monitoring Systems in the last couple of years. As was published in [1], three inter-area modes can be mostly detected in ENTSO-E, referred to as the "north-south" mode with the approximate frequency of 0.35 Hz and two "east-west" modes with the approximate frequencies of 0.13 Hz and 0.19, respectively. After performing a special tuning process on the model, it is said to exhibits all three modes, even though it turned out they are slightly different ("north-south" being 0.40 Hz instead of 0.35 Hz and "east-west" being 0.09 Hz instead of 0.13).

This means that by following the foreseen appropriate use of the model it should be able to reflect the typical (average) dynamic behaviour of the whole continental Europe. As a result, if studies other than that mentioned in the above two bullets are to be carried out, more detailed (correct) model of the local-system configuration is to be used. This is why national power systems corresponding to individual countries are modelled separately, in order to easily replace them with detailed model (however, load-flow convergence might not be that straightforwardly achieved). This was done in the presented analysis, where a detailed model of a Slovenian power system (presented in section 0) was applied. Authors assume that this might be one of the reasons for slightly different oscillation frequencies (see the second bullet above).

Among above-mentioned specifics of the model, the following are most evident:

- only machines with the active-power production above 250 MW (in the selected steady-state conditions) are modelled as synchronous machines, the rest are considered as a constant (negative) impedance. As a result, only approximately 9 % of all machines are appropriately modelled,
- synchronous machine models are equipped with a simplified (standard) models for control devices, encompassing automatic voltage controller, governor and power-system stabilizer,
- only machines with the active-power production above 0 MW (in the selected steady-state conditions) include the full set of control models (otherwise, only automatic voltage controller is considered),
- multiple parallel generation units connected to the same busbar are aggregated into a single machine,
- parallel transmission lines are aggregated into a single equivalent line,
- the system topology and steady-state data correspond to year 2020 (authors cannot be completely sure of that since in [4] this is written quite dubiously),
- etc.

More detailed information about the model itself and its verification can be found in [4]. However, there is another feature that should be separately mentioned as the authors find it quite important: the naming of all power-system elements (synchronous generators, transformers, transmission lines, busbars, etc.) is coded in such a way that only the country of origin is evident (using international country codes such as "SI" for Slovenia or "DE" for Germany). The rest of the name does not follow the currently enforced data exchange format prescribed by the ENTSO-E. Instead, an unknown coding procedure produced something one might also refer to as “random numbers”.

One is able to access the model by submitting a special request form to ENTSO-E in which a commitment is made to inform ENTSO-E about the result of the specific study or a project which requires the model. At the time of writing this paper, the model is available in several formats corresponding to different widely used simulation tools, such as PowerFactory, Netomac, PSS/E, etc.

2.2 Slovenian power-system dynamic model

The dynamic model of the Slovenian power system was developed at the University of Ljubljana, encompassing not only the 400 kV, 220 kV and 110 kV network levels of the Slovenian power system but certain parts of 400 kV and 220 kV networks of neighbouring countries as well (north of Italy, south of Austria, Hungary, Croatia, Bosnia and Herzegovina and Serbia). The model became especially valuable after being successfully verified for several contingencies that took place in the past:

- nuclear power plant Krško outage (March 2011),
- phase-shifting transformer in substation Divača outage (April 2011),
- transition into island operation of the 110 kV north-wester part of the Slovenian power system (June 2011),
- etc.

The verification process was conducted by comparing the model response with WAMS captured real-system response for the same contingency [5]. After some tuning the model adequately represented the system response for the whole variety of contingencies, without any additional changes in the model. Lately, the model was additionally verified for a special transient phenomenon that took place in substation Krško in 2015 [6]. It was a case of a long-lasting sympathetic inrush current phenomenon, which was also successfully reconstructed by considering Phasor Measurement Unit model together with current transformer saturation characteristics.

2.3 Static VAR compensator equivalent model

The dynamic simulations were performed in a so-called stability (commonly known as RMS) calculation mode, where symmetrical conditions between phases are assumed. Therefore, a detailed model of the SVC device was not required. Instead, an *equivalent* model was constructed by using a variable-admittance element (referred to as “VAR-Y”), as shown in the left part of Fig. From the scheme it is evident that the equivalent model of an entire SVC device consists of two parallel elements: fixed capacitance and a variable inductance, which is a model representation of a thyristor controlled reactor (TCR). As the TCR technology is not indented for a direct connection to voltage levels above 35 kV, a power transformer is included in the model as well.

The SVC control strategy is implemented within the “VAR-Y” controller. The model enables two kinds of controls, i.e. *voltage control* (at the specified bus) and *power-oscillation damping* (POD) control. The first is determined by device’s static characteristics (presented on the right-hand side of Figure 20.1), which determines the injection of capacitive and inductive currents for different values of the busbar voltage. So clearly, the SVC device is able to operate in either capacitive or inductive regime as long as the limitations of the TCR part are not exceeded. After that, TCR either operates in a fully closed or opened mode. The POD control on the other hand was modelled in terms of a differential control block with a limitation. This means that a kind of a bang-bang strategy was employed, which periodically bounces the SVC's operating point from one limit to another with the frequency of the present oscillation. As the control input variable, active-power flow on the selected transmission line was used.

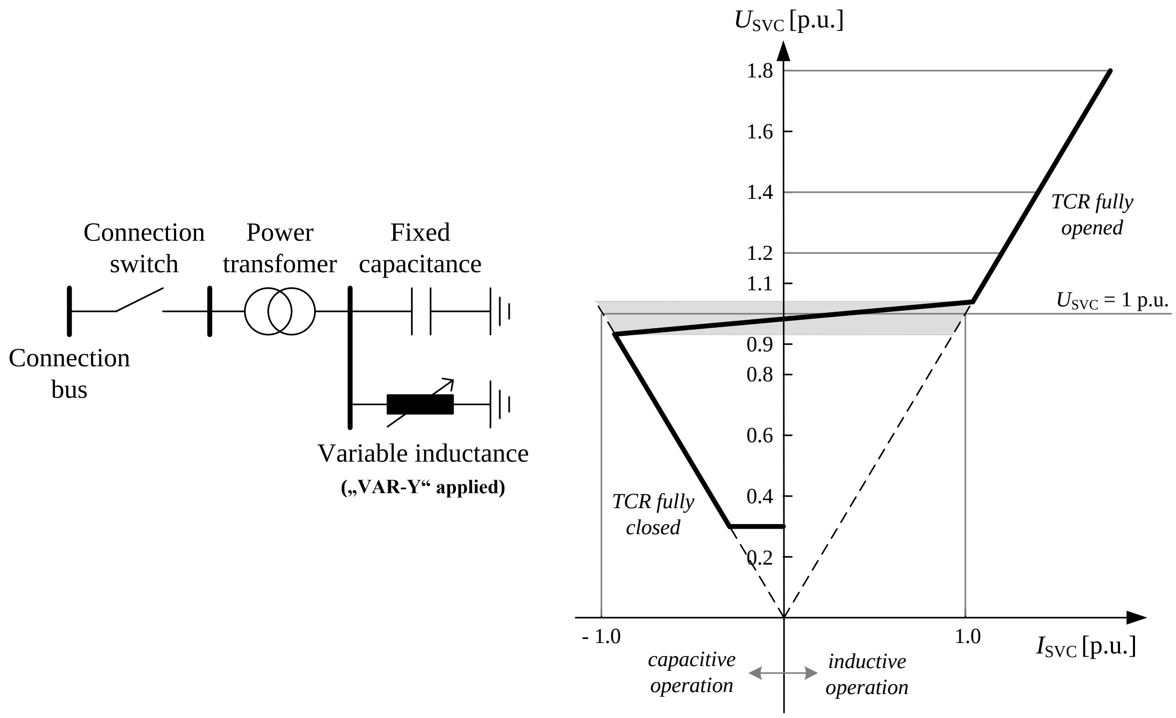

Figure 20.1: left: equivalent SVC model, right: static SVC characteristics

3 Inter-Area Oscillation Damping Analysis

3.1 Stimulating the appropriate oscillation

According to [7] and [8], the active-power oscillations in the power system can be categorized into two groups, depending on the source or the mechanism of its occurrence:

- *free oscillations (or negative-damping oscillations)*, resulted by negative damping ratio of power systems. Their appearance coincides with situations, when the excitation control starts to counteract the positive damping of generators' damping windings (this is usually the case when the reactance of transmission system is large or power output of generators is high). Damping of such oscillations is usually dealt with installation of power-system stabilizer (PSS) control,
- *forced oscillations*, which are explained by the resonance mechanism. The presence of a small but periodic disturbance with the frequency near any of the system's natural frequencies, causes quite fast increase in oscillation amplitudes. Similarly, the removal of the disturbance quickly results in oscillation annulation. This is why most commonly used approach to diminish forced oscillations is to separate the source of the disturbance.

In the presented study, the ENTSO-E power system model exhibits a very strong damping of its natural inter-area oscillations. This is why in the *first step*, appropriate changes were made to excitation-control parameters in order to decrease the damping. In case of north-south oscillations, these changes were applied to synchronous generators on northern and southern parts of Europe and similarly, in case of west-east oscillation, same changes were done to generators on western and eastern parts of Europe.

In the *second step* however, the targeted oscillation with the selected frequency was stimulated by insertion of a sine-shaped active-power injection in the north or west, respectively. The frequency of the injection followed the targeted frequency. After several periods, the power injection was withdrawn, but the oscillation with the exact selected frequency was sustained for an arbitrary amount of time. An example of such process for the stimulation of north-south oscillation with the frequency of 0.40 Hz is depicted in Figure 20.2. The upper graph represents the rotor angle deviation (from its steady-state values) of a Slovenian nuclear power plant Krško, whereas the lower graph depicts the same quantity corresponding to two other synchronous machines – one in Denmark (thin solid line) and the second in Italy (thick solid line). Due to anonymization of ENTSO-E dynamic model it is difficult to clearly specify which two generation units are in question.

Several conclusions can be drawn from Figure 20.2:

- the sine-shaped active-power injection appears at about t = 2 seconds and lasts for approximately 20 seconds,
- after active-power injection elimination the oscillations with the frequency of 0.40 Hz is sustained until the very end of the simulation (i.e. until t = 130 seconds),
- without performing any interventions, the oscillation amplitude remains constant throughout the simulation,
- generators from Italy and Denmark oscillate with an approximate 180° phase shift. As they are located at the very northern and southern physical ENTSO-E limits, this means that the oscillating energy exchange is indeed between the northern and southern groups of synchronous generators.

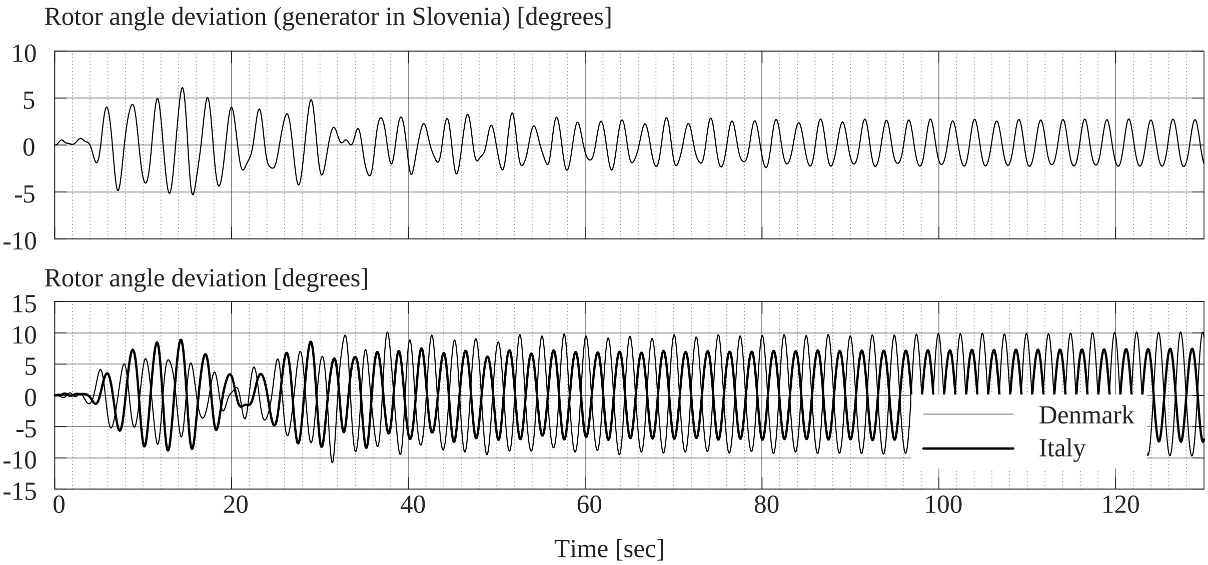

Figure 20.2: stimulating the north-south ENTSO-E sustained oscillations

3.2 SVC impact

In order to verify whether the SVC device, placed in the high-voltage Slovenian network, can indeed improve the damping of described inter-area oscillations, first the appropriateness of modelling had to be confirmed. To this end, the reactive-power rating of SVC was set to $200_{cap}/100_{ind}$ Mvar, the SVC connection point was varied across most of the ENTSO-E network and the SVC impact to oscillation amplitude was observed for:

- damping of west-east oscillation in the following countries: Greece, Bulgaria, Bosnia and Herzegovina, Slovenia, Austria and Switzerland (results presented in Figure 20.3),
- damping of north-south oscillation in the following countries: Netherlands, northern part of Germany, southern part of Germany, Czech republic, Slovenia and Italy (results presented in Figure 20.4).

In Figure 20.3 and Figure 20.4, a rotor angle oscillation with respect to time is depicted for two cases: without POD activation (grey oscillating curve) and with a POD activation at t = 90 second (black oscillating curve). In case of east-west oscillation (Figure 20.3), a rotor angle of a machine in Spain is depicted, whereas in case of north-south oscillation (Figure 20.4) a machine in Denmark is under investigation. Along with two oscillating variables, a set of thick black lines is provided as well. These lines correspond to oscillation amplitude with respect to time for different SVC placement among the already provided list of countries.

It can be clearly seen from the simulation results that closer the SVC is located to the very borders of oscillation (so closer to the group of generators having the highest mode shape), faster the oscillation amplitude can be decreased. Even though such conclusion was expected, it was interesting to find out that by placing the SVC to the very electrical centre of the oscillation, absolutely no damping effect can be detected. In terms of west-east oscillation, Austria appears at the centre of oscillation, whereas Slovenia is located just slightly towards the east. Consequently, regardless of POD controller activation, the SVC in 400 kV network of Austria has no noticeable effect on oscillation damping. On the other hand, SVC in the Slovenian 400 kV network has some slight influence on damping, as can be seen from Figure 20.3. Similarly, the oscillation centre in terms of north-south swings appears to be somewhere in the south of Germany. For the reader’s convenience it is reasonable to mention that in the first step of north-south oscillation modelling (see section 0) a perfectly-sustained oscillation was hard to achieve due to a strong sensitivity of oscillation on changes in excitation control parameters. Consequently, author’s had to be satisfied with increasing oscillation amplitude for cases with no interventions (no SVC) that eventually lead to small-signal instability.

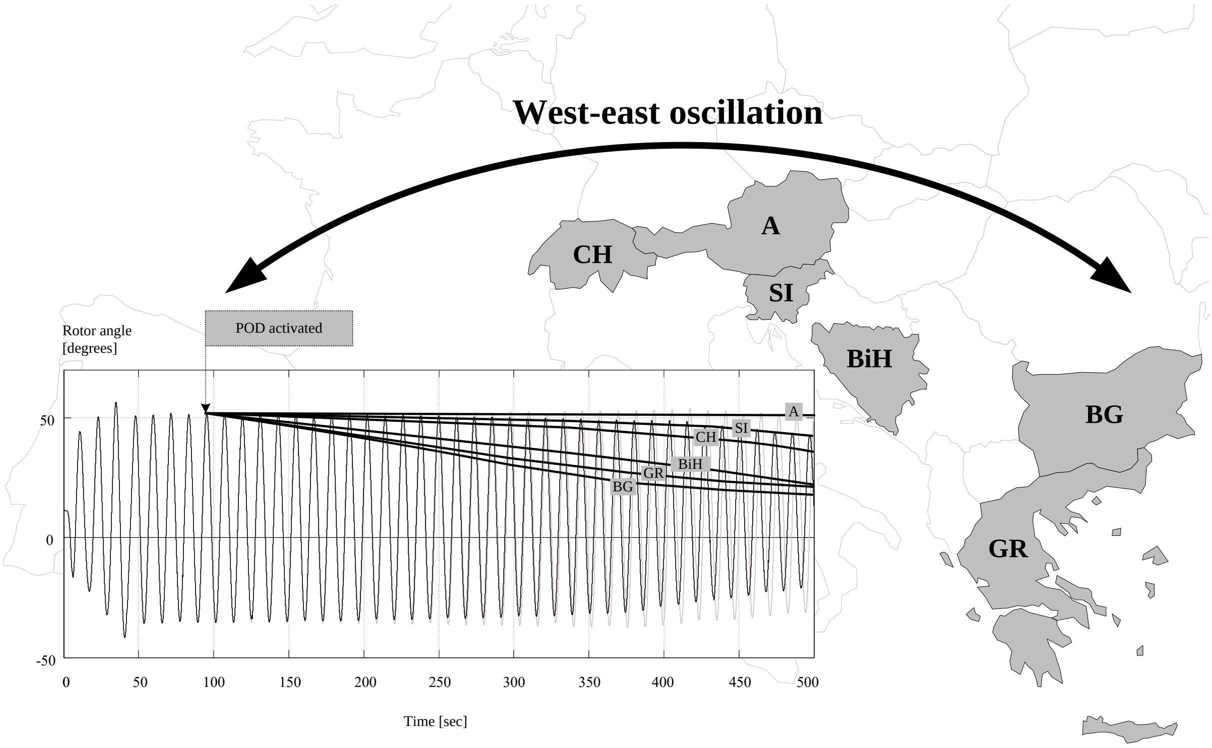

Figure 20.3: Impact of SVC device on east-west ENTSO-E oscillation damping

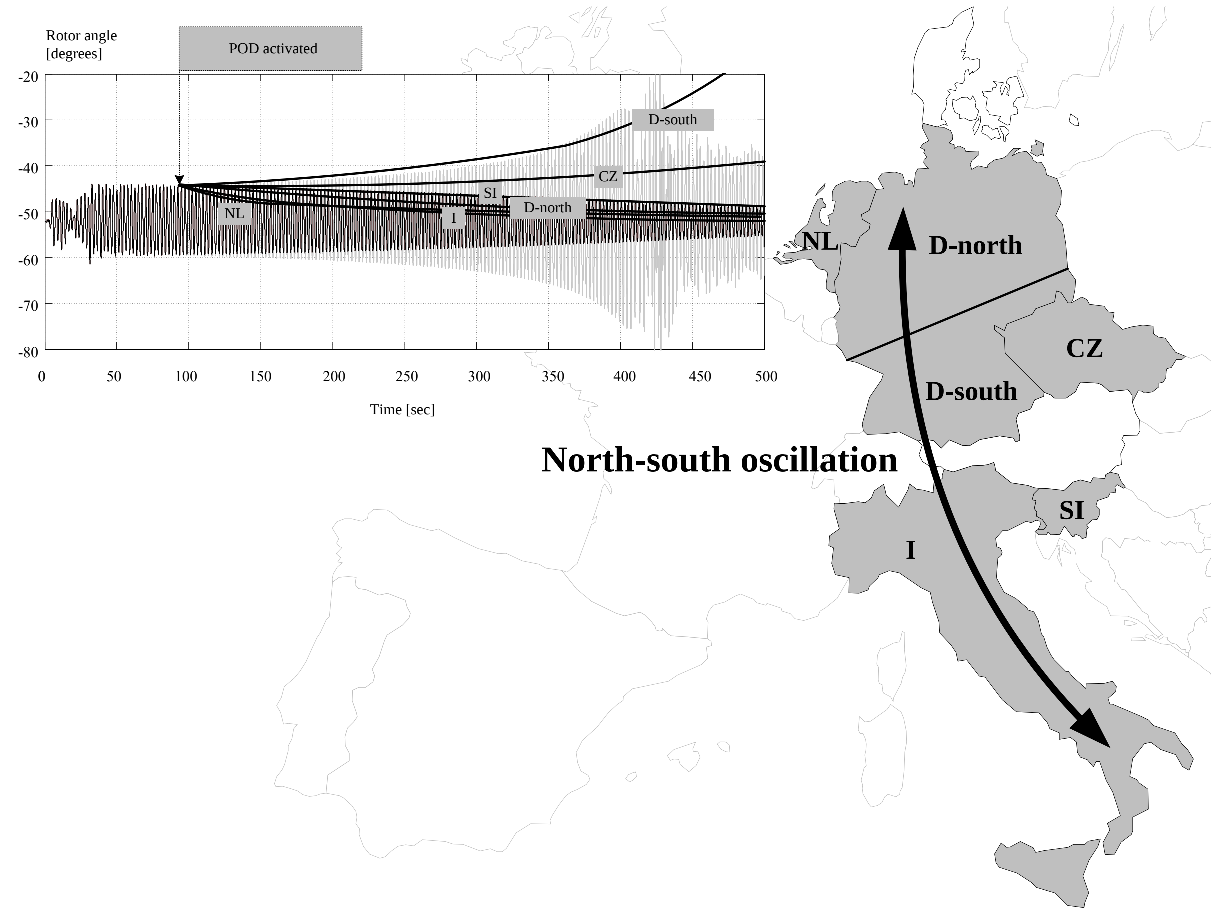

Figure 20.4: Impact of SVC device on north-south ENTSO-E oscillation damping

The results confirmed that the installation of an SVC device of a reasonable rating into 400 kV Slovenian network can have a significant effect on at least certain ENTSO-E oscillations. In addition, the analysis also showed (results not proved due to space limitation) that a similar effect can be achieved regardless of the SVC position within Slovenian 400 kV network.

4 Conclusions

Interconnecting smaller power systems into large interconnections might improve several operational aspect, but can as well be a trigger for appearance of new problems, one of them being small-signal stability. In the last couple of years, TSO's across Europe managed to detect and monitor characteristic inter-area oscillations that repeatedly appear in ENTSO-E, with the help of their national WAMS systems. As a result of consequential construction of a dynamic ENTSO-E model, TSOs and researchers are able to analyse these oscillation even further. It turned out that while trying to find answers to solving regional voltage issues in the Slovenian power system, the use of SVC device might contribute to small-signal stability issue in wider ENTSO-E sense as well, despite SVC's not being most appropriate for solving steady-state voltage problems. The presented analysis showed that Slovenia's almost central location within ENTSO-E is *in general* not that favourable for damping of oscillations, emerging from the very outer ENTSO-E limits. Nevertheless, *in specific scenarios* (i.e. north-south ENTSO-E oscillation) it might contribute to damping significantly.

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Analiza vpliva razpršenih virov električne energije na distribucijsko omrežje Zgornje Savinjske doline

DAMJAN HRASTNIK

Povzetek V sodobnih sistemih vodenja distribucijskih omrežij je ena izmed glavnih funkcij izračun pretokov energije. V tem članku je izračun pretokov energije po eni izmed obstoječih metod uporabljen v kombinaciji z optimizacijskim algoritmom na realnem primeru distribucijskega omrežja Zgornje Savinjske doline, natančneje na daljnovodih Rastke in Logarska dolina. Ovrednoten je vpliv električne energije, proizvedene iz razpršenih virov, na obravnavano omrežje. S postopkom optimizacije so določene referenčne vrednosti za generacijo delovne in jalove moči razpršenih virov, ki so priključeni na nizkonapetostni strani transformatorskih postaj. Pri tem je analiziran vpliv generacije delovne in jalove moči na profil napetosti ter na izgube v obravnavanem srednjenapetostnem omrežju.

Ključne besede: • analiza • razpršeni vir • distribucijsko omrežje • pretok energije • zgornja Savinjska dolina •

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Analysis of the Impact of Distributed Power Generation on Distribution Network in Upper Savinjska Dolina

DAMJAN HRASTNIK

Abstract The load flow calculation is one of the main functionalities incorporated in modern distribution network management systems. In this article, an already known load flow calculation method, combined with an optimization procedure, is applied and tested in the case of real distribution network in Zgornja Savinska dolina (upper part of valley Savinjska dolina), more precisely on distribution lines Rastke and Logarska dolina. The impact of electrical energy produced in distributed generation units on discussed distribution network is evaluated. The optimization procedure is applied to determine the reference values for active and reactive power generation in distributed generation units connected to the low voltage side of distribution transformers, where the impact of generated active and reactive power on voltage profile and distribution network losses in medium voltage network is analyzed.

Keywords: • analysis • distributer power generation • distribution network • load flow • upper Savinjska dolina •

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1 Uvod

Distribucijsko omrežje električne energije je eden izmed ključnih členov v verigi oskrbe z električno energijo in predstavlja del večje celote, ki jo imenujemo elektroenergetski sistem. Povezuje prenosno omrežje s končnimi odjemalci električne energije. V obdobju zadnjih nekaj let se je predvsem zaradi ugodne subvencije s strani Republike Slovenije ter evropske direktive po povečanju proizvodnje električne energije iz razpršenih virov delež le-teh močno povečal. Distribucijska omrežja, ki jih poznamo iz zgodovine, so zasnovana na način, da pretoki energije s sponk distribucijskega energetskega transformatorja le-to pripeljejo do končnih odjemalcev. S povečevanjem števila razpršenih virov prihaja do spreminjanj smeri pretokov električne energije. Iz tega sledi, da napetostni profili in pretoki energije niso definirani samo z bremeni, ampak tudi z vplivi razpršenih virov. Pametna vključitev razpršenih virov v omrežje prinaša veliko prednosti [2]. Glavni problem obratovanja distribucijskih omrežij, v katera so priključeni razpršeni viri, predstavlja doseganje ustreznega profila napetosti ter obvladovanje izgub. S porastom deleža razpršenih virov se tako spreminjajo tudi osnovne obratovalne lastnosti distribucijskih omrežij.

Trenutno proizvodnjo električne energije iz razpršenih virov je zelo težko uskladiti z lokalno porabo, zato se predvsem v primerih, kjer je delež razpršenih virov visok, pojavljajo viški električne energije. Ti se pretakajo vzdolž srednjenapetostnih vodov v smeri proti razdelilnim transformatorskim postajam oziroma razdelilnim postajam. Tako se klasični padajoči napetostni profil od razdelilnih transformatorskih postaj v smeri odjema, ki je značilen za vode, kjer razpršena proizvodnja ne nastopa, bistveno spremeni. Pojavljati se pričnejo lokalni odseki srednjenapetostnih vodov, kjer lahko napetosti prekoračijo dopustne vrednosti, napetost pa je lahko celo višja na koncu voda kot na njegovem začetku. Tem spremembam je bilo potrebno ustrezno prilagoditi sodobne sisteme nadzora in vodenja distribucijskega omrežja.

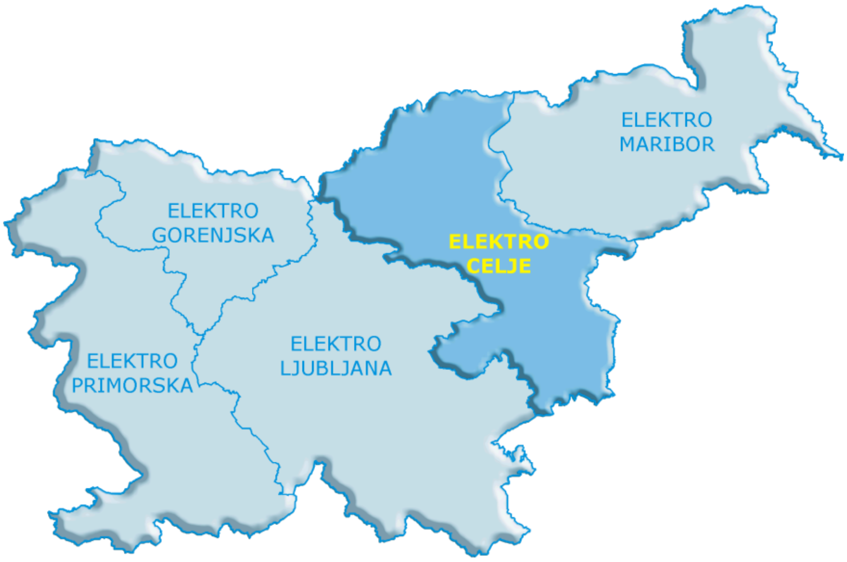
V članku bo obravnavan praktični primer obratovanja dveh radialnih srednjenapetostnih distribucijskih vodov na področju Zgornje Savinjske doline v dejanskih razmerah. Konkretno bosta obravnavana 20 kV daljnovod Rastke in 20 kV daljnovod Logarska Dolina, priključena v razdelilno postajo Ljubno. Zaradi znatnega deleža priključenih razpršenih virov, ki vključujejo elektrarne vodnega potenciala oziroma male hidroelektrarne (MHE) ter elektrarne sončnega potenciala oziroma male fotovoltaične elektrarne (MFE), občasno nastopajo težave z napetostnim profilom, tako lokalno na nivoju transformatorskih postaj, na srednjenapetostnih vodih, kot tudi v razdelilni postaji Ljubno.

Izhodiščno podlago za opredelitev problemov z napetostnim profilom bo predstavljala analiza merilnih rezultatov iz obstoječih merilnih sistemov AMI (Automated Metering Infrastructure oz. napredne merilne infrastrukture), nameščenih v transformatorskih postajah, in sicer na nizkonapetostni strani SN/NN transformatorjev. Na osnovi podatkov o parametrih in topologiji obravnavanega omrežja, ki jih vsebujeta programsko orodje DMS in geografski informacijski sistem (GIS), je izdelan simulacijski model v programskem orodju DMS in programskem paketu Matlab.

Na osnovi modela omrežja bodo analizirane razmere za najbolj kritičen čas v dnevu, ko je vpliv proizvodnje in vpliv razpršenih virov največji, obenem pa je največja tudi poraba električne energije oziroma obremenitev omrežja. Razpršeni viri električne energije so modelirani kot bremena z negativnim predznakom in z možnostjo spreminjanja faktorja moči. Na ta način so z izdelanim modelom ovrednoteni pretoki energije ter njihov vpliv na napetostni profil in izgube pri distribuciji električne energije. Referenčne vrednosti delovne in jalove moči bodo določene ob upoštevanju znane proizvodnje električne energije iz razpršenih virov ter obremenitve omrežja, ki so bile pridobljene iz sistemov AMI. Na opisan način določene referenčne vrednosti delovne in jalove moči bodo zagotovile ustreznost napetostnega profila v obravnavanem obratovalnem stanju, ne da bi bila pri tem omejena oziroma reducirana generirana delovna moč razpršenih virov. Obratovalno stanje je določeno na osnovi izračuna pretokov energije, referenčne vrednosti sprememb delovne in jalove moči razpršenih virov pa na osnovi optimizacijskega iskalnega postopka diferenčne evolucije. Cilj je ovrednotenje učinkov generacije delovne in jalove moči razpršenih virov na izbrano distribucijsko omrežje, natančneje, na napetostni profil omrežja in izgube.

2 Elektro Celje, Zgornja Savinjska dolina in razdelilna postaja Ljubno

Na podlagi pogodbe o najemu elektrodistribucijske infrastrukture in izvajanju storitev za operaterja distribucijskega sistema električne energije, družbe SODO, d. o. o., izvaja distribucijsko dejavnost v Sloveniji naslednjih 5 elektrodistribucijskih podjetij [1].



Slika 21.1: Elektrodistribucijska podjetja v Sloveniji

Distribucijsko območje Elektra Celje obsega tri osrednjeslovenske regije; Savinjsko, Koroško in Spodnjeposavsko. V omenjene regije spada skupaj 40 občin v celoti ter dve delno. Velikost distribucijskega območja znaša 4.345 km², kar predstavlja približno 22 % površine Slovenije, s 383.000 prebivalci in približno 169.000 odjemalci. Stanje elektroenergetskih opreme in vodov z dne 31. 12. 2014 je prikazano v tabeli 21.1.

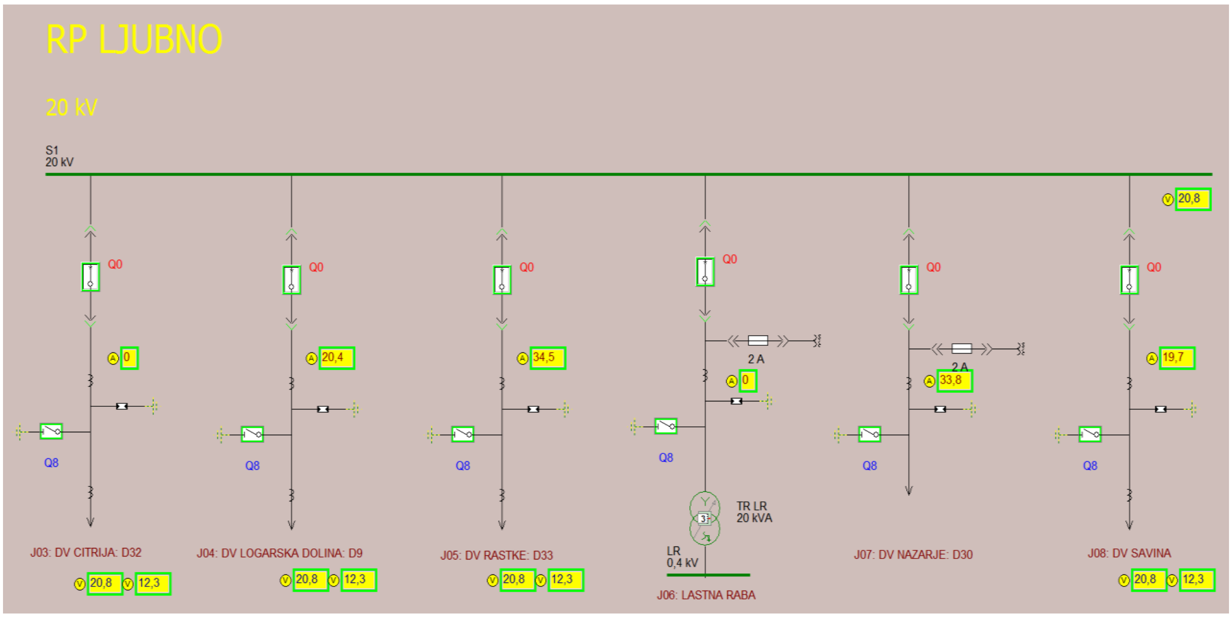
2.1 Zgornja Savinjska dolina

Zgornja Savinjska dolina je dolina v porečju zgornjega toka reke Savinje s tipično alpsko pokrajino. V povirju Savinje na Solčavskem obsega Kamniško-Savinjske Alpe z alpskimi dolinami Matkov kot, Robanov kot, Logarsko dolino ter del Karavank z Olševo. Med visokimi alpskimi kraškimi planotami Golte, Menina planina in Dobrovlje sta vglobljeni gornjegrajska in mozirska kotlina. Na koncu mozirske kotline se dolina Savinje zoži pri Soteski (naselje pri Ljubiji) ter se zatem razširi in preide v Spodnjo Savinjsko dolino. Teritorialno obsega površino 507 km², število prebivalcev je približno 16.500. Lokalne skupnosti oziroma občine so Mozirje, Nazarje, Rečica ob Savinji, Gornji Grad, Ljubno, Luče, Solčava [4]. Kot je značilno za alpske pokrajine, tudi skozi to dolino teče reka s svojimi številnimi pritoki. Na teh je bilo predvsem v preteklosti zgrajenih in v distribucijsko omrežje priključenih večje število razpršenih virov vodnega potenciala oziroma tako imenovanih malih hidroelektrarn (MHE). Kot velja za večino alpskih rek s pritoki, le-te vodni potencial izrabljajo praktično skozi celo leto.

V obdobju zadnjih nekaj let se je predvsem zaradi ugodnih subvencij s strani Republike Slovenije ter evropske direktive o energetski učinkovitosti povečeval delež proizvodnje električne energije iz razpršenih virov. Tudi na področju Zgornje Savinjske doline se je precej povečal predvsem delež MFE. Ne glede na omenjeno glavni del proizvodnje električne energije iz razpršenih virov še vedno predstavljajo MHE, razmerje med MHE in MFE je približno 9 : 1 v korist MHE.

2.2 Razdelilna postaja Ljubno

Razdelilna postaja Ljubno je, kot že samo ime pove, razdelilna postaja, katere funkcija je razdeljevanje električne energije, ki priteče po dovodnem daljnovodu in se razdeli med srednjenapetostne izvode. Napajana je preko dvosistemskega daljnovoda 2x20 kV iz razdelilne postaje Nazarje, ta pa iz razdelilne transformatorskih postaje 110/20 kV Mozirje. V razdelilni postaji Ljubno sta priključena dva dovodna daljnovoda, natančneje povezovalni in napajalni. Povezovalni vod J07: DV Nazarje je namenjen čistemu napajanju razdelilne postaje Ljubno, drugi tako imenovani povezovalni vod J08: DV Savina, je kosmasti vod, ki v normalnem obratovalnem stanju ne napaja te razdelilne postaje in je namenjen rezervnemu napajanju. Slika 21.2 prikazuje enočrtno shemo razdelilne postaje Ljubno z dejanskim stanjem meritev v trenutku zajema slike.



Slika.21.2 : Enočrtna shema razdelilne postaje Ljubno

Razdelilna postaja oziroma objekt je v osnovi sestavljen iz 6 srednjenapetostnih celic, od katerih je ena napajalna celica (J07: DV Nazarje), ena celica lastne rabe (J06: Lastna raba), ostale štiri celice (J03: DV Citrija, J04: DV Logarska Dolina, J05: DV Rastke in J08: DV Savina) so klasične srednjenapetostne izvodne celice.

Postaja je bila zgrajena leta 1998 in z vzdrževalnimi deli obnovljena leta 2015. Število transformatorskih postaj SN/NN, ki so iz objekta napajani v normalnem obratovalnem stanju, je 108, število vseh napajanih odjemalcev pa 1682. Skupna dolžina vseh srednjenapetostnih vodov iz razdelilne postaje Ljubno znaša 102,21 km. Daljnovoda, ki sta modelirana in podrobneje analizirana, sta daljnovod Rastke in daljnovod Logarska dolina, na katera je priključen večinski del razpršenih virov v obliki MHE in MFE.

Daljnovod Rastke napaja 16 SN/NN transformatorskih postaj in je večinoma zračne izvedbe. Skupna dolžina izvoda je 17,23 km. Na izvod je priključenih 11 proizvodnih enot (elektrarn), ki so tipa MHE in MFE. Njihova instalirana moč znaša 2,8 MW.

Daljnovod Logarska Dolina napaja 66 SN/NN transformatorskih postaj in je enako kot daljnovod Rastke večinoma zračne izvedbe. Skupna dolžina izvoda je 72,53 km in predstavlja najdaljši radialni vod v celotnem distribucijskem omrežju Elektra Celje, d. d.. Na izvod je priključenih 37 proizvodnih enot (elektrarn) v obliki MHE in MFE. Njihova instalirana moč znaša 2,2 MW.

Skupna priključena moč razpršenih virov v razdelilni postaji Ljubno znaša približno 5 MW. Večinski del predstavljajo MHE, medtem ko je delež MFE v primerjavi z MHE znatno manjši in znaša približno 450 kW. Iz tega sledi, da je razmerje moči razpršenih virov MHE in MFE približno 9 : 1. V primeru velike proizvodnje električne energije iz razpršenih virov obeh tipov (ugodne hidrološke razmere, visoko osončenje) se občasno pojavijo težave z napetostnim profilom. Te se pojavijo na samih zbiralkah razdelilne postaje Ljubno, na srednjenapetostnih izvodih ter lokalno, torej na nivoju transformatorskih postaj. Razpršeni viri delujejo povsem avtonomno, nepovezano in neodvisno eden od drugega.

V večini primerov se za kompenzacijo uporablja fiksna kompenzacija faktorja moči s klasičnimi kondenzatorskimi baterijami, kar še dodatno slabša razmere pri obvladovanju napetostnega profila.

3 Podatki in modeliranje omrežja

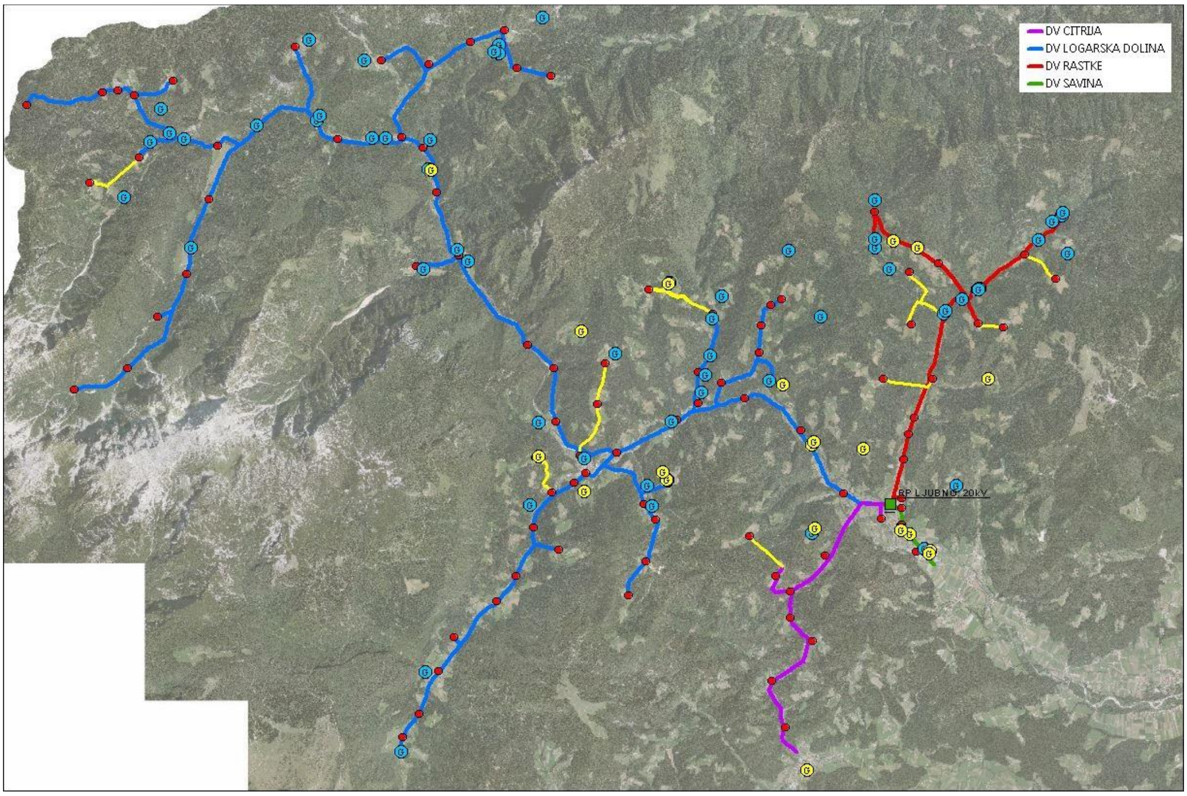
Za analizo pretokov energije je potrebno natančno poznati posamezne elemente omrežja, ki so predstavljeni z ustreznimi matematičnimi modeli. Modeliranje elementov omrežja predstavlja bistveni del analize, točnost rezultatov izračuna pretokov energije pa zavisi predvsem od dobrega in natančnega modela omrežja ter podatkov.

V normalnih obratovalnih stanjih predpostavimo, da imamo opravka z uravnoteženim, trifaznim sistemom. V uravnoteženem trifaznem sistemu so vse tri gonilne napetosti simetrične, zaradi simetrične obremenitve pa tvorijo tudi toki faznih porabnikov in toki skozi elemente sistema simetričen sistem. V primeru trifaznega simetričnega sistema lahko vode, bremena in razpršene vire modeliramo samo enofazno, za preostali dve fazi pa predpostavimo enake razmere [5].

V članku uporabljeni tako imenovani statični del podatkov elektroenergetska omrežja je pridobljen iz GIS-a, praktični primer prikazuje slika 21.3.

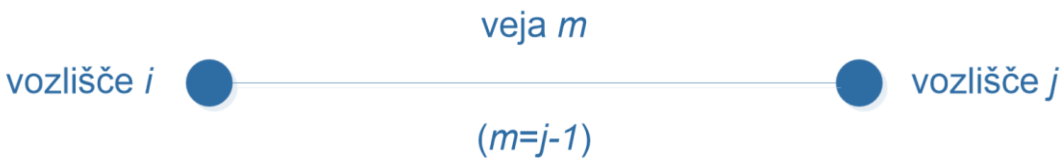
Na njej so z različnimi barvami označeni vsi objekti, srednjenapetostni vodi in razpršeni viri, napajani iz razdelilne postaje Ljubno, in sicer:

- rdeča barva označuje daljnovod Rastke,
- temno modra barva označuje daljnovod Logarska dolina,
- vijolična barva označuje daljnovod Citrija,
- zelena barva označuje daljnovod Savina,
- krogi v rdeči barvi označujejo transformatorske postaje SN/NN,
- krogi v svetlo modri barvi označujejo razpršene vire tipa MHE,
- krogi v rumeni barvi označujejo razpršene vire tipa MFE.



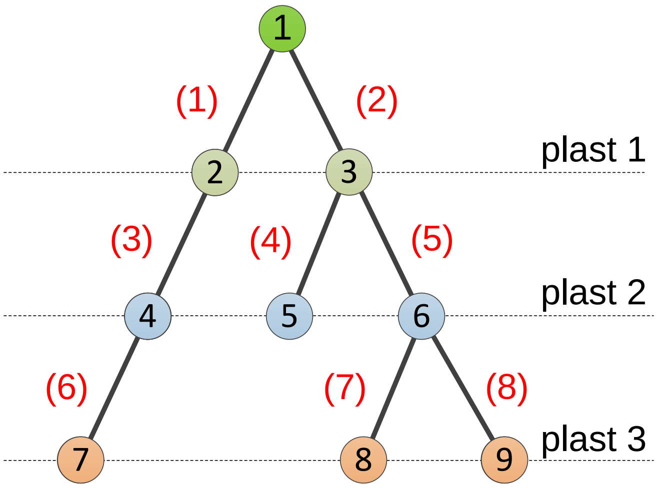
Slika 21.3: Shematični prikaz distribucijskega omrežja na področju Zgornje Savinjske doline

Podatki so se v osnovi nahajali v shape datotekah, ki so vsebovale vse potrebne atributne podatke. Te shape datoteke so bile nato uvožene v programsko orodje QGIS, z namenom nadaljnje predpriprave podatkov za ustrezen način številčenja vozlišč ter vej. Ustrezno številčenje vej in vozlišč uporabljenega modela omrežja zagotovi izkoriščanje radialne topologije omrežja, kakršna je uporabljena za primera daljnovoda Rastke in daljnovoda Logarska dolina. Veja (m), omejena z začetnim oziroma oddajnim vozliščem (i) ter končnim oziroma sprejemnim vozliščem (j), je oštevilčena le z eno številko. Veja (m) je vedno za ena manjša od številke končnega vozlišča (j), kar prikazuje slika 21.4. [6]



Slika.21.4: Enočrtni prikaz voda z vejami in vozlišči

V nadaljevanju sledi razdelitev vozlišč na plasti, natančneje se vozlišča razdeli glede na oddaljenost od bilančnega vozlišča. Z najmanjšo oziroma najnižjo številko oštevilčimo bilančno vozlišče, kar predstavljajo srednjenapetostne zbiralke razdelilne postaje Ljubno. Številčenje poteka na način, da se posameznim vozliščem plasti 1 dodeljujejo številke zaporedno od 2 naprej, dokler vsa vozlišča v 1. plasti niso oštevilčena. Nato nadaljujemo z oštevilčenjem vozlišč v naslednji, 2. plasti in tako naprej oziroma do točke, dokler ni oštevilčeno vsako posamezno vozlišče (slika 21.5). Na kratko povzeto, vozlišča, ki so direktno povezana z bilančnim vozliščem, predstavljajo vozlišča prve plasti, vozlišča, ki so direktno povezana z vozlišči 1. plasti, predstavljajo vozlišča 2. plasti itn.



Slika 21.5: Oštevilčevanje vej in vozlišč

Nadalje sledi definiranje dveh vektorjev. Začetno vozlišče oziroma oddajno vozlišče (v_z) je vozlišče, ki predstavlja začetek posamezne veje in je vedno bližje bilančnemu vozlišču glede na končno vozlišče. Končno vozlišče oziroma sprejemno vozlišče (v_k) je vozlišče, ki predstavlja konec posamezne veje in ima vedno za ena večjo številko od veje, ki jo končuje.

Na osnovi definicije v_z in v_k ter predhodno opisanega številčenja vej je definirana tabela povezav 21.1, ki opisuje primer omrežja na sliki 21.5.

Tabela 21.1: Tabela povezav vej in vozlišč

Veja m	1	2	3	4	5	6	7	8
Začetno (oddajno) vozlišče v_z	1	1	2	3	3	4	6	6
Končno (sprejemno) vozlišče v_k	2	3	4	5	6	7	8	9

V vozlišča so priključena bremena in razpršeni viri, iz posameznega vozlišča pa lahko izhaja več vej, v vsakem od njih je potrebno določiti štiri parametre. Prva dva parametra, fazna efektivna vrednost napetosti U in kot napetosti δ, predstavljata napetostne razmere vozlišča. Preostala dva parametra sta povezana s pretokom energije skozi vozlišča, predstavljena sta z delovno močjo P in jalovo močjo Q. Od štirih parametrov vozlišč sta v vsakem posameznem vozlišču poznana zgolj dva. To pomeni, da smeta biti v nekem vozlišču omrežja le dva parametra neznana, preostala dva morata biti vedno podana, poznavanje parametrov pa zavisi od tipa vozlišča.

Razpršene vire je pri izračunu pretokov energije potrebno predhodno modelirati. V osnovi jih lahko pri izračunu predstavimo kot vire konstantne delovne in jalove moči ali konstantne delovne moči in napetosti [7]. Izbira modela je odvisna od načina obratovanja razpršenega vira. Model uporabljenega distribucijskega omrežja vsebuje razpršene vire tipa MHE in MFE. Ker želimo na napetostni profil vplivati posredno, ne da bi neposredno spreminjali napetosti omrežja, so v ta namen razpršeni viri električne energije predstavljeni kot viri konstantne moči. Za posamezen razpršeni vir so podane vrednosti delovne moči P_{gen} in jalove moči Q_{gen}.

Prav tako kot ustrezno modeliranje razpršenih virov, predstavlja modeliranje bremen pomemben del izračuna. Za bremena, priključena v distribucijsko omrežje, sta po navadi podani vrednosti delovne moči bremena P_{brm} in jalove moči bremena Q_{brm}. Ti vrednosti zavisita od napetosti vozlišča, kamor je breme priključeno. V tem članku so uporabljena bremena konstantne moči, ki so simetrična trifazna.

Največkrat se izračuni pretokov energije izvajajo v sistemu enotinih vrednosti. Pred izračunom pretokov energije je tako potrebno izvesti preračun vseh parametrov omrežja (vhodni podatki), kot tudi podatkov o proizvodnji električne energije iz razpršenih virov ter porabi električne energije v sistem enotinih vrednosti.

3.1 Testni model daljnovodov Rastke in Logarska dolina

Za analizo vpliva razpršenih virov na distribucijsko omrežje Zgornje Savinjske doline potrebujemo v ustrezni obliki pripravljen model omrežja. Primerno urejen model bo ob ustrezni predstavitvi vhodnih podatkov preglednejši. Ob tem bo program, namensko pripravljen za branje podatkov, obdelavo in optimizacijo vhodnih podatkov v programskem paketu Matlab, deloval optimalno. Postopek obdelave podatkov za potrebe priprave Excelove datoteke vhodih podatkov je v celoti enak tako za daljnovod Rastke, kot tudi za daljnovod Logarska dolina.

Končni model omrežja je zapisan v Excelovi datoteki vhodnih podatkov, praktični primer tabele je za daljnovod Rastke prikazan s tabelo 21.2. Za vsakega od dveh obravnavanih daljnovodov je ločeno pripravljena ustrezna tabela z urejenimi vhodnimi podatki. Tabeli v nadaljevanju bere programska koda, ki je pripravljena v programskem paketu Matlab. Osnovna oziroma izvorna programska koda v programskem paketu Matlab je bila uporabljena v [5], [6] in [8]. V tem članku je bila ta spremenjena in ustrezno prilagojena modelu omrežja, branju vhodnih podatkov, drugačnim kriterijem, vrednostim baznih podatkov, dodatnem upoštevanju razpršenih virov tipa MHE, različnim obratovalnim stanjem omrežja,…

Tabela 21.2: Excelova datoteka vhodnih podatkov omrežja daljnovoda Rastke

oddVoz	sprVoz	kabel	r (ohm/km)	x (ohm/km)	I_{max} (A)	dolVod (m)	Ime_TP	TP S_n (kVA)	sonce P_{gen} (kW)	voda P_{gen} (kW)	P_{fe} (W)
1	2	tuje omrežje	0,94	9,41	1000	1	tujeOM	0	0	0	0
2	3	XHE48 1X150	0,12	0,22	540	76,60	0	0	0	0	0
3	4	AL/FE 35/6	0,82	0,38	145	150,94	0	0	0	0	0
4	5	AL/FE 35/6	0,82	0,38	145	119,51	0	0	0	0	0
4	6	AL/FE 35/6	0,82	0,38	145	311,31	0	0	0	0	0
5	7	AL/FE 35/6	0,82	0,38	145	60,73	0	0	0	0	0
6	8	AL/FE 35/6	0,82	0,38	145	475,44	0	0	0	0	0
7	9	TR160	37,63	91,67	1000	1	T314	160	0	0	383
8	10	AL/FE 35/6	0,82	0,38	145	571,60	0	0	0	0	0
8	11	TR35	339,00	313,29	1000	1	T475	35	0	0	114
10	12	TR35	339,00	313,29	1000	1	T476	35	11,73	0	114
10	13	AL/FE 35/6	0,82	0,38	145	365,56	0	0	0	0	0
13	14	TR100	71,85	143,16	1000	1	T580	100	0	0	321
13	15	AL/FE 35/6	0,82	0,38	145	901,92	0	0	0	0	0
15	16	AL/FE 35/6	0,82	0,38	145	53,93	0	0	0	0	0
15	17	AL/FE 35/6	0,82	0,38	145	1478,04	0	0	0	0	0
16	18	AL/FE 35/6	0,82	0,38	145	14,98	0	0	0	0	0
17	19	AL/FE 35/6	0,82	0,38	145	69,75	0	0	0	0	0
17	20	AL/FE 35/6	0,82	0,38	145	122,75	0	0	0	0	0
18	21	TR100	71,85	143,16	1000	1	T126	100	0	0	321
19	22	XHP48A 1X150	0,19	0,19	360	44,04	0	0	0	0	0
19	23	AL/FE 35/6	0,82	0,38	145	1	0	0	0	0	0
20	24	AL/FE 35/6	0,82	0,38	145	553,70	0	0	0	0	0
22	25	TR1600	1,95	14,65	1000	1	T406	1600	0	1316	1450
23	26	AL/FE 35/6	0,82	0,38	145	18,66	0	0	0	0	0
24	27	PAS 1X35	0,82	0,32	140	1	0	0	0	0	0
24	28	PAS 1X35	0,82	0,32	140	1	0	0	0	0	0
24	29	AL/FE 35/6	0,82	0,38	145	337,39	0	0	0	0	0
26	30	TR160	37,63	91,67	1000	1	T125	160	0	22	383
27	31	AL/FE 35/6	0,82	0,38	145	1004,88	0	0	0	0	0
28	32	AL/FE 35/6	0,82	0,38	145	582,58	0	0	0	0	0
29	33	AL/FE 35/6	0,82	0,38	145	1294,04	0	0	0	0	0
29	34	TR250	66,88	180,23	1000	1	T413	250	160	19	589
31	35	TR100	71,85	143,16	1000	1	T409	100	49,7	0	321
31	36	AL/FE 35/6	0,82	0,38	145	1145,70	0	0	0	0	0
32	37	TR160	37,63	91,67	1000	1	T410	160	0	0	383
33	38	AL/FE 35/6	0,82	0,38	145	49,39	0	0	0	0	0
33	39	TR160	37,63	91,67	1000	1	T408	160	0	0	383
36	40	TR250	66,88	180,23	1000	1	T459	250	49,7	56	589
36	41	AL/FE 35/6	0,82	0,38	145	713,94	0	0	0	0	0
38	42	AL/FE 35/6	0,82	0,38	145	337,53	0	0	0	0	0
41	43	TR250	66,88	180,23	1000	1	T415	250	0	563	589
41	44	AL/FE 35/6	0,82	0,38	145	1	0	0	0	0	0
42	45	AL/FE 35/6	0,82	0,38	145	801,08	0	0	0	0	0
42	46	AL/FE 35/6	0,82	0,38	145	51,21	0	0	0	0	0
44	47	XHE48A 1X70	0,41	0,22	250	603,47	0	0	0	0	0
45	48	TR250	66,88	180,23	1000	1	T411	250	0	205	589
46	49	TR250	66,88	180,23	1000	1	T424	250	0	317	589
47	50	TR630	21,56	87,26	1000	1	T094	630	0	0	921

V srednjenapetostnih distribucijskih omrežjih pogosto nimamo točnih podatkov oziroma profilov porabe oziroma obremenitev ter profilov proizvedene električne energije iz razpršenih virov, ampak so te vrednosti na različne načine ocenjene. V Elektru Celje, d. d. so v več kot 80 odstotkih SN/NN transformatorskih postaj vgrajeni "pametni" števci električne energije, ki merijo veličine, kot so električna energija (A), fazna napetost (U), fazni tok (I), delovno moč P in jalovo moč Q, merjene veličine pa so odvisne od tipa števca. Omenjeni delež predstavljajo transformatorske postaje, v katerih so vgrajeni SN/NN transformatorji nazivnih moči $S_\mathrm{n} \geq 50$ kVA. V članku so bili podatki o obremenitvah za vsako posamezno transformatorsko postajo na obravnavanih daljnovodih izvoženi v obliki Excelovih datotek. V njih so zapisani podatki v obliki povprečnih urnih obremenitev za celotno koledarsko leto. Enak postopek je bil izveden za vse razpršene vire tipa MHE in MFE. Za razliko od profilov obremenitev so bili slednji podatki izvoženi iz AMI-ja v obliki urnih povprečij za vsak posamezen razpršeni vir, priključen na daljnovoda Rastke in Logarska dolina. Iz pridobljenih meritev so bili pripravljeni povprečni in maksimalni profil obremenitve in proizvodnje.

4 Backward/forward sweep metoda za izračun pretokov energije

V osnovi backward/forward sweep metoda izkorišča radialno obliko distribucijskega omrežja in računa pretoke energije v dveh korakih (1. korak backward sweep in 2. korak forward sweep). Koraka se iterativno ponavlja do točke izpolnitve konvergenčnega kriterija.

Na osnovi prvega Kirchhoffovega zakona se v 1. koraku, tako imenovanem backward sweep koraku, računajo vrednosti tokov v vejah. Seštevanje tokov v vejah poteka vzvratno (ang. backward), kar pomeni, da korak poteka od najbolj oddaljenega vozlišča od bilančnega vozlišča proti bilančnemu vozlišču.

V 2. koraku, tako imenovanem forward sweep koraku, se z rezultati tokov vej, dobljenimi v 1. koraku, računajo napetosti vozlišč, in sicer od bilančnega vozlišča proti najbolj oddaljenemu oziroma končnemu vozlišču.

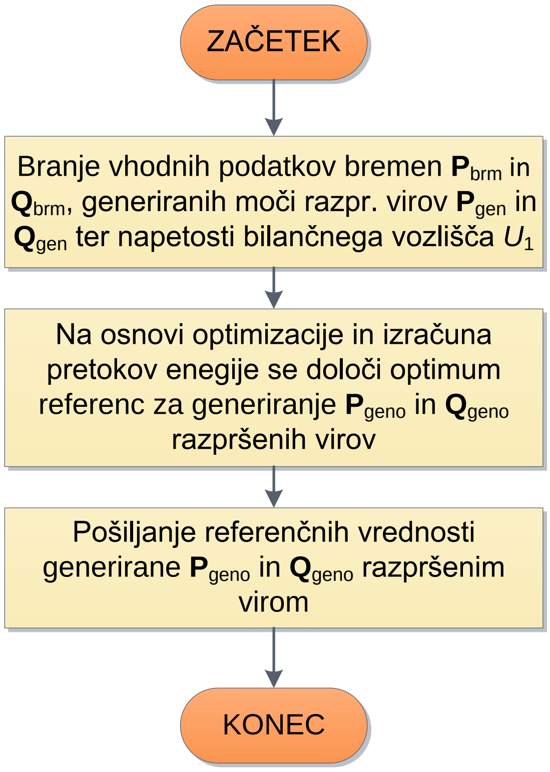
5 Optimizacija in algoritem za generiranje referenčnih vrednosti delovne in jalove moči razpršenih virov električne energije

Optimizacija je matematično gledano iskanje minimuma in maksimuma funkcije znotraj določenih mej ob izpolnjevanju ene ali več enačb in neenačb [9]. V splošnem se probleme optimizacije obravnava z iskanjem minimalne vrednosti kriterijske funkcije $q(\mathbf{x})$. Rešitev optimizacije predstavlja nabor elementov vektorja parametrov kriterijske funkcije $\mathbf{x}$, pri katerem je vrednost $q(\mathbf{x})$ najmanjša, ob istočasni izpolnitvi m števila omejitvenih neenačb in n omejitvenih enačb, katere se po navadi prevede v neenačbe.

5.1 Algoritem za generiranje referenčnih vrednosti delovne in jalove moči

Princip algoritma, je sledeč; na osnovi obratovalnega stanja (kot obratovalno stanje se razume določena obremenitev omrežja, ki vključuje porabo in proizvodnjo električne energije iz razpršenih virov), se za model omrežja izvede izračun pretokov energije. S postopkom optimizacije algoritem nato določi ustrezne referenčne vrednosti generacije delovne in jalove moči razpršenih virov. Referenčne vrednosti so določene na način, da so obenem tudi izgube v omrežju minimalne.

V primeru, ko zgolj z optimizacijo ter generacijo jalove moči razpršenih virov ne moremo zagotoviti ustreznega napetostnega profila, lahko algoritem za generacijo delovne in jalove moči razpršenih virov določi vrednosti generacije delovne moči razpršenih virov na način, da je napetostni profil omrežja ustrezen. Pogoj v tem primeru je, da je zmanjšanje oziroma redukcija generacije delovne moči razpršenih virov minimalna. Za to skrbi algoritem za generiranje referenčnih vrednosti delovne in jalove moči razpršenih virov, ki temelji na optimizacijski metodi diferenčne evolucije. V algoritmu metoda diferenčne evolucije skrbi za iskanje parametrov, ki predstavljajo referenčne vrednosti generacije delovne in jalove moči razpršenih virov. Iskani parametri so nadalje ovrednoteni s kriterijsko funkcijo $q(\mathbf{x})$, kjer je uporabljen algoritem za izračun pretokov energije. Algoritem za generacijo delovne in jalove moči razpršenih virov v nadaljevanju izračuna vrednosti napetosti vozlišč in vrednost izgub. Izračunane vrednosti napetosti in izgub sta uporabljeni lastnosti kriterijske funkcije $q(\mathbf{x})$, ki ju z uporabo algoritma minimiziramo. Slika 21.6 prikazuje eno ponovitev oziroma iteracijo algoritma, je splošno uporaben za različna obratovalna stanja.



Slika.21.6: Diagram poteka ene ponovitve oziroma iteracije algoritma za generacijo referenčnih vrednosti delovne moči $\boldsymbol{P}_{\mathbf{geno}}$ in jalove moči $\boldsymbol{Q}_{\mathbf{geno}}$ razpršenih virov

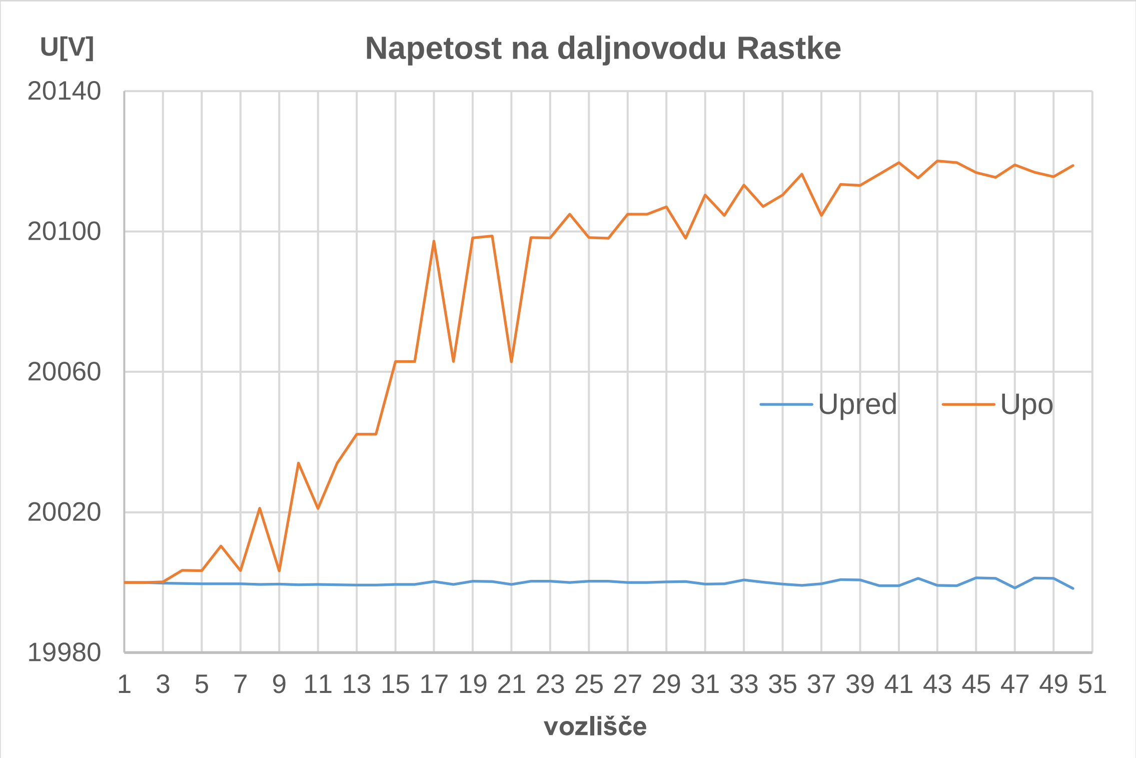
6 Rezultati

Rezultati so pridobljeni na osnovi algoritma za generacijo referenčnih vrednosti delovne in jalove moči razpršenih virov, ki je prikazan na sliki 21.7. Za razpršene vire električne energije je predpostavljeno, da vključujejo tako MHE kot MFE s faktorjem moči $\cos\varphi = 0.95$. Rezultati proizvodnje električne energije iz razpršenih virov oziroma generacije referenčnih vrednosti delovne moči $\mathbf{P}_{\mathrm{geno}}$ in jalove moči $\mathbf{Q}_{\mathrm{geno}}$ razpršenih virov so prikazani za eno iteracijo algoritma v mescu aprilu ter eno obratovalno stanje (OS) omrežja. Mesec april je bil izbran kot mesec, za katerega je značilna velika količina padavin. Ta dejavnik neposredno vpliva na količino proizvedene električne energije iz razpršenih virov in s tem poveča vpliv razpršenih virov tipa MHE na razmere v omrežju. Časovni korak izračuna obratovalnega stanja je 1 ura, natančneje, prikazani so rezultati za povprečni dan meseca aprila v izbranem časovnem oknu med 11. in 12. uro.

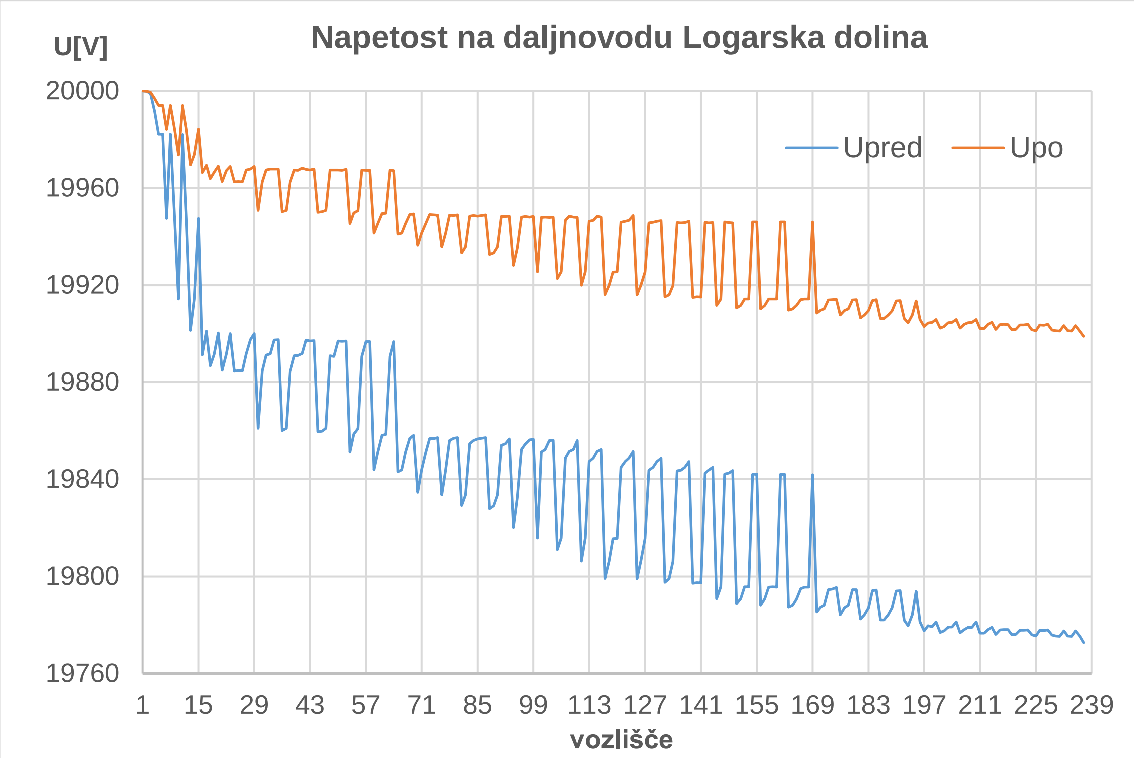
Generiranje referenčnih vrednosti delovne P_{geno} in jalove moči Q_{geno} MHE in MFE je izvedeno na osnovi optimizacije in izračunov pretokov energije z metodo backward/forward sweep. Izračun pretokov energije je izveden neodvisno za oba obravnavana daljnovoda. Nizkonapetostni izvodi in nizkonapetostni odseki teh izvodov v transformatorskih postajah so zanemarjeni, moči priključenih bremen in razpršenih virov so upoštevane na srednjenapetostnih strani. Pri tem so bile predhodno določene in izračunane vrednosti parametrov na dejanskem stanju naprav in v normalnem obratovalnem stanju omrežja, napetost bilančnega vozlišča (2) je 20 kV, vrednosti generacije jalove moči razpršenih virov Q_{gen} pred optimizacijo so 0 VAr. V prikazanem obratovalnem stanju so v omrežje priključeni tako porabniki električne energije kot tudi razpršeni viri. Omrežje je povprečno obremenjeno, razpršeni viri proizvajajo električno energijo s 50 % maksimalne možne proizvodnje, kar pomeni, da je uporabljen maksimalni profil proizvodnje, znižan na 50 %, ter povprečni profil porabe.

Cilj optimizacije v prikazanem obratovalnem stanju je zmanjšanje izgub na posameznem daljnovodu ob predpostavki, da se generacija delovne moči po optimizaciji ne spreminja, spreminja se samo generacija jalove moči. Iskani parametri z optimizacijo v obratovalnem stanju so optimalna generacija jalove moči v vozliščih, kjer so priključeni razpršeni viri.

Za ovrednotenje rezultatov bodo prikazane napetosti ter vrednosti izgub posameznega daljnovoda po mesecih. Kot rezultat optimizacije v obratovalnem stanju je v nadaljevanju najprej grafično prikazan napetostni profil posameznega daljnovoda pred in po optimizaciji, sledi tabelarični prikaz z vrednostmi delovne in jalove moči bremen, generacijo delovne moči razpršenih virov pred in jalove moči po optimizaciji ter skupna vrednost izgub na posameznem daljnovodu, natančneje skupna vrednost izgub za povprečni dan posameznega meseca v terminu med 11. in 12. uro.



Slika 21.7: Napetost pred in po optimizaciji na daljnovodu Rastke



Slika 21.8: Napetost pred in po optimizaciji na daljnovodu Logarska dolina

Sliki 21.7 in 21.8 prikazujeta potek napetosti obeh obravnavanih daljnovodov pred in po optimizaciji. Prva krivulja (črta modre barve in oznaka U_{pred}) predstavlja napetost na daljnovodu pred optimizacijo v [V], druga krivulja (črta oranžne barve in oznaka U_{po}) predstavlja napetost na daljnovodu po optimizaciji v [V].

Oblika napetostnega profila na daljnovodu Rastke je pred optimizacijo položna, kar pomeni, da je napetost v bilančnem vozlišču (2) praktično enaka napetosti končnega vozlišča (50). Natančneje, napetost bilančnega vozlišča (2) znaša pred in po optimizaciji 20 kV, napetost končnega vozlišča (50) na daljnovodu Rastke pred optimizacijo zavzema vrednost 19998 V, po izvedeni optimizaciji pa vrednost 20118 V. Napetost končnega vozlišča (50) je na daljnovodu Rastke po optimizaciji za 120 V višja kot pred optimizacijo. Naraščajoči napetostni profil po optimizaciji pomeni, da je povprečna obremenitev omrežja manjša kot je proizvedena električna energija iz razpršenih virov v primeru 50-odstotne maksimalne proizvodnje električne energije.

Napetostni profil na daljnovodu Logarska dolina je v primerjavi z daljnovodom Rastke padajoč, in to tako pred kot tudi po optimizaciji. Napetost bilančnega vozlišča (2) znaša pred in po optimizaciji 20 kV, napetost končnega vozlišča (237) na daljnovodu Logarska dolina pred optimizacijo zavzema vrednost 19772 V, po izvedeni optimizaciji pa vrednost 19899 V. Napetost končnega vozlišča (237) na daljnovodu Logarska dolina je po optimizaciji za vrednost 127 V višja kot pred optimizacijo. Padajoči napetostni profil pomeni, da je povprečna obremenitev omrežja na daljnovodu Logarska dolina višja kot je proizvedena električna energija iz razpršenih virov v primeru 50-odstotne maksimalne proizvodnje električne energije, kar velja tako pred kot tudi po optimizaciji. Z ustrezno generacijo jalove moči razpršenih virov lahko napetostni profil izboljšamo in še vedno ostanemo znotraj dovoljenih mej padca oziroma porasta napetosti.

Tabela 21.3: Delovne in jalove moči bremen ter razpršenih virov pred in po optimizaciji na daljnovodu Rastke

vozlišče	P_{brm} [W]	Q_{brm} [VAr]	P_{gen} [W]	P_{geno} [W]	ΔP_{gen} [W]	Q_{gen} [VAr]	Q_{geno} [VAr]
12	6886	3588	-5138	-5138	0	0	1800
25	314804	164013	-576458	-576458	0	0	201899
30	31480	16401	-9637	-9637	0	0	3375
34	49188	25627	-78409	-78409	0	0	27462
35	19675	10251	-21770	-21770	0	0	7625
40	49188	25627	-46301	-46301	0	0	16216
43	49188	25627	-246615	-246615	0	0	86375
48	49188	25627	-89798	-89798	0	0	31451
49	49188	25627	-138858	-138858	0	0	48634

Tabela 21.4: Delovne in jalove moči bremen ter razpršenih virov pred in po optimizaciji na daljnovodu Logarska dolina

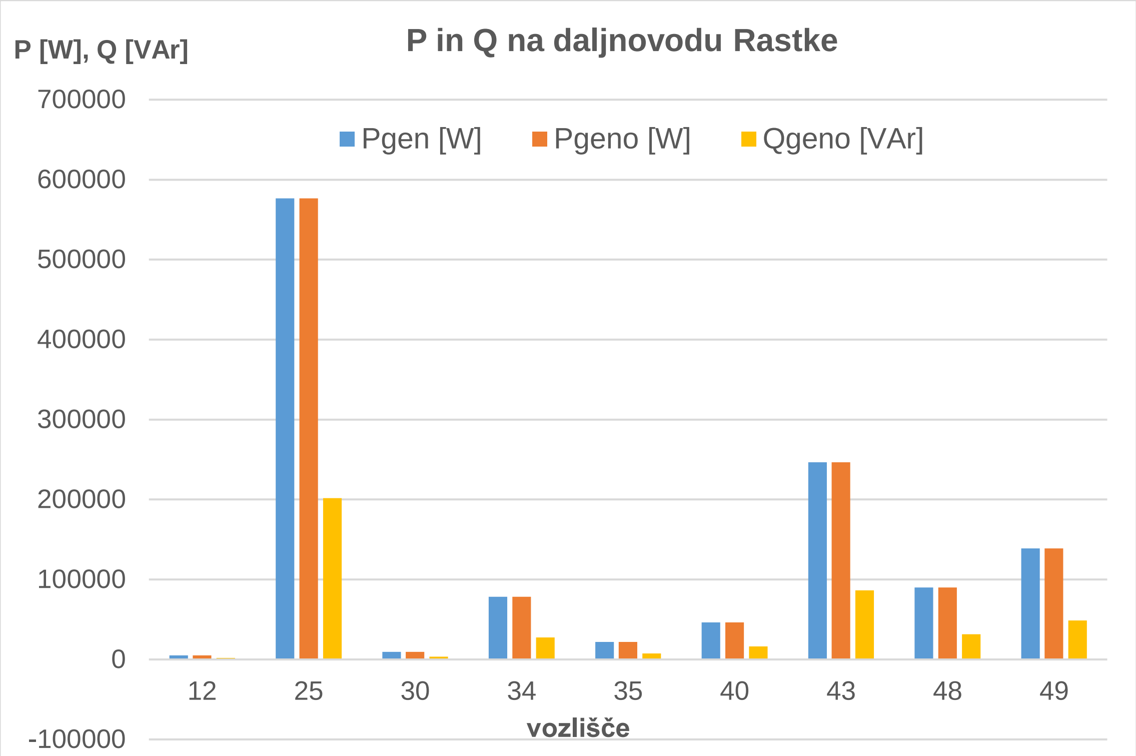
vozlišče	P_{brm} [W]	Q_{brm} [VAr]	P_{gen} [W]	P_{geno} [W]	ΔP_{gen} [W]	Q_{gen} [VAr]	Q_{geno} [VAr]
14	6886	3588	15331	15331	0	0	5694
15	9838	5125	43042	43042	0	0	15987
26	78701	41003	5694	5694	0	0	2115
41	49188	25627	313416	313416	0	0	116411
48	31480	16401	26282	26282	0	0	9762
52	123954	64580	87608	87608	0	0	32540
63	19675	10251	18363	18363	0	0	6820
72	31480	16401	4380	4380	0	0	1627
74	49188	25627	23400	23400	0	0	8691
77	9838	5125	5256	5256	0	0	1952
86	19675	10251	12265	12265	0	0	4556
87	9838	5125	10679	10679	0	0	3967
95	9838	5125	6133	6133	0	0	2278
116	9838	5125	12265	12265	0	0	4556
120	19675	10251	28034	28034	0	0	10413
124	9838	5125	57821	57821	0	0	21476
127	19675	10251	5694	5694	0	0	2115
134	49188	25627	2738	2738	0	0	1017
141	49188	25627	16207	16207	0	0	6020
149	31480	16401	9199	9199	0	0	3417
165	19675	10251	9637	9637	0	0	3579
169	78701	41003	87608	87608	0	0	32540
175	9838	5125	4380	4380	0	0	1627
178	31480	16401	39423	39423	0	0	14643
185	19675	10251	28034	28034	0	0	10413
194	6886	3588	13141	13141	0	0	4881
202	31480	16401	15331	15331	0	0	5694
210	9838	5125	10075	10075	0	0	3742
214	31480	16401	24968	24968	0	0	9274
228	9838	5125	9199	9199	0	0	3417

V tabeli 21.3 in tabeli 21.4 so prikazane vrednosti delovne in jalove moči bremen ter razpršenih virov pred in po optimizaciji daljnovoda Rastke in daljnovoda Logarska dolina. V njih predstavlja P_{brm} delovno moč bremena v [W], Q_{brm} jalovo moč bremena v [VAr], P_{gen} delovno moč razpršenega vira pred optimizacijo v [W], P_{geno} delovno moč razpršenega vira po optimizaciji v [W], ΔP_{gen} razliko delovne moči razpršenega vira v [W] izračunano z (6.1), Q_{gen} jalovo moč razpršenega vira pred optimizacijo v [VAr] ter Q_{geno} generirano jalovo moč razpršenega vira po optimizaciji v [VAr].

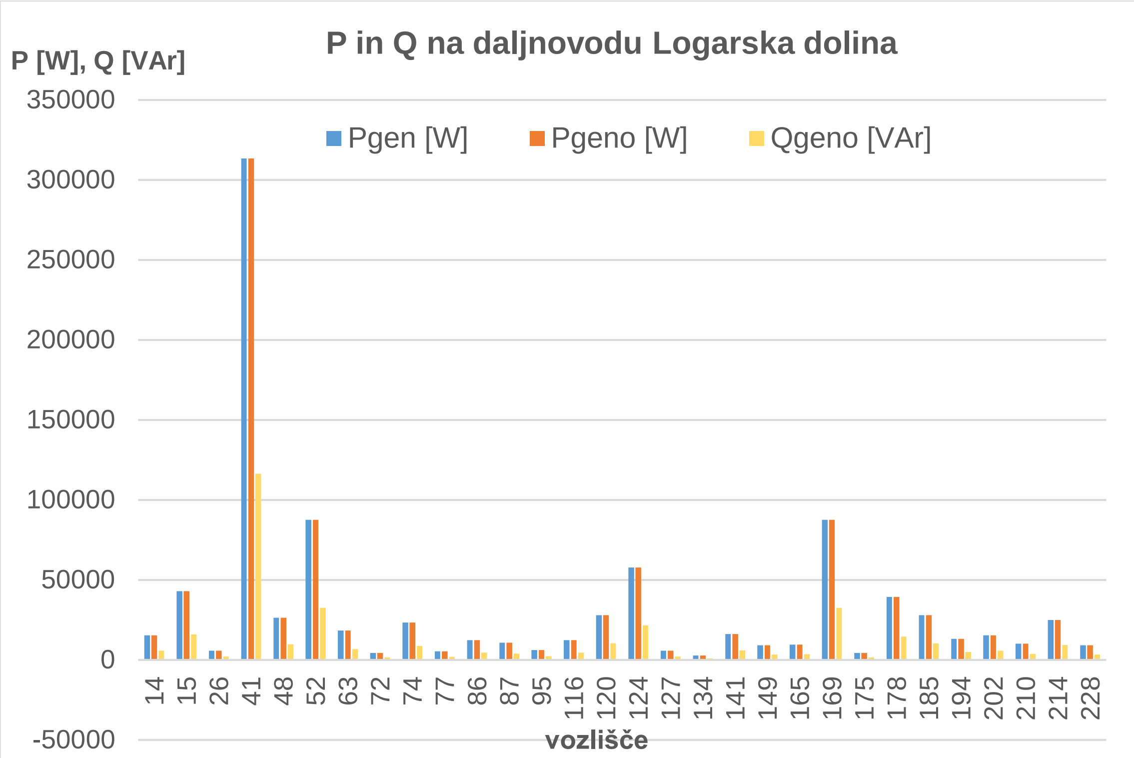
$$\Delta P_{\mathrm{gen}} = P_{\mathrm{gen}} - P_{\mathrm{geno}} \tag{6.1}$$

Iz stolpca 2 in stolpca 3 tabele 21.3 in tabele 21.4 je razvidno, da so v omrežje priključena bremena, saj so vrednosti različne od nič. Iz stolpca 4 tabele 9.10 in tabele 9.11 je razvidno, da so v omrežje prav tako priključeni razpršeni viri, saj so tudi te vrednosti različne od 0. Pomembna ugotovitev, ki sledi iz rezultatov tabele 21.3 in tabele 21.4, je, da je po izvedeni optimizaciji generirana delovna moč razpršenih virov enaka kot pred optimizacijo ($P_{gen} = P_{geno}$). To pomeni, da pri optimizaciji ni bila omejena generacija delovne moči nobenemu razpršenemu viru, referenčne vrednosti generacije jalove moči pa so bile določene ob kriteriju, da so izgube v omrežju minimalne. Vrednost jalove moči razpršenega vira pred optimizacijo Q_{gen} znaša 0 VAr, vrednosti jalove moči razpršenega vira po optimizaciji Q_{geno} so prikazane v zadnjem, 8. stolpcu tabele 21.3 in tabele 21.4.

V smislu boljše predstave rezultatov so predhodno podani rezultati v tabele 21.3 in tabele 21.4 v nadaljevanju predstavljeni grafično na sliki 21.9 za daljnovod Rastke ter sliki 21.10 za daljnovod Logarska dolina. Na sliki 21.9 in sliki 21.10 so vse vrednosti rezultatov iz tabel 21.9 in 21.10 zaradi lažje ponazoritve pozitivne.



Slika 21.9: Delovna in jalova moč razpršenih virov pred in po optimizaciji na daljnovodu Rastke



Slika 21.10: Delovna in jalova moč razpršenih virov pred in po optimizaciji na daljnovodu Logarska dolina

Izgube so prikazane v tabeli 21.5 za daljnovod Rastke in tabeli 21.6 za daljnovod Logarska dolina. V tabeli 21.5 in tabeli 21.6 predstavlja $P_{\text{izg\_pred}}$ izgube daljnovoda pred optimizacijo v [W], $P_{\text{izg\_po}}$ izgube daljnovoda po optimizaciji v [W], ΔP_{izg} razliko oziroma zmanjšanje izgub posameznega daljnovoda v [W], izračunano z (9.2), ter Q_{geno} generirano jalovo moč posameznega daljnovoda po optimizaciji v [VAr].

$$\Delta P_{\text{izg}} = P_{\text{izg\_pred}} - P_{\text{izg\_po}} \tag{9.2}$$

Tabela.21.5: Izgube na daljnovodu Rastke

OS3	januar	februar	marec	april	maj	junij	julij	avgust	september	oktober	november	december
$P_{\text{izg\_pred}}$ [W]	8892	9293	8647	9641	8805	8896	8592	8619	8626	9242	8601	8555
$P_{\text{izg\_po}}$ [W]	7590	7973	7114	8012	7517	7626	7100	6999	6521	7952	7016	6892
ΔP_{izg} [W]	1303	1320	1533	1629	1288	1270	1492	1620	2105	1290	1585	1664
Q_{geno} [VAr]	-294167	-265238	-297658	-424837	-342739	-370614	-317352	-256293	-326257	-424929	-209924	-302650

Tabela 21.6: Izgube na daljnovodu Logarska dolina

OS3	januar	februar	marec	april	maj	junij	julij	avgust	september	oktober	november	december
$P_{\text{izg\_pred}}$ [W]	29771	31528	27568	23569	25199	24613	25799	27989	25535	25106	27629	27696
$P_{\text{izg\_po}}$ [W]	26031	28792	22238	19060	22196	20088	22518	23929	22215	20222	23909	24481
ΔP_{izg} [W]	3740	2737	5330	4509	3003	4525	3281	4061	3320	4884	3720	3215
Q_{geno} [VAr]	-198764	-169150	-304706	-351222	-350854	-379389	-324866	-262361	-333982	-434990	-214895	-309816

Pomembna ugotovitev, ki sledi iz rezultatov tabele 6.3 in tabele 6.4, je, da so izgube pred optimizacijo generacije jalove moči večje kot po optimizaciji. Z ustrezno generacijo jalove moči na nivoju razpršenih virov se po srednjenapetostnih vodih pretaka manj jalove energije, s tem se znižajo skupne izgube ter ob tem izboljša napetostni profil. Ta ugotovitev velja za oba obravnavana daljnovoda.

7 Sklep

Distribucijska omrežja so bila v zadnjih nekaj letih deležna precejšnih sprememb. V njih se je v času ugodnih subvencij priključevalo veliko število predvsem malih fotovoltaičnih elektrarn (MFE) do velikosti oziroma moči 10 MW. Te vplivajo na napetostni profil omrežja ter izgube. Mesta priključitve so se preverjala po obstoječih metodah priključitve, zapisane v sistemskih obratovalnih navodilih za distribucijska omrežja (SONDO, priloga 5) in zmožnostih posameznih distribucijskih podjetij ter na tej osnovi izdajala soglasja za priključitve. Obstoječe metode spremembam omrežja zadnjih let niso sledile.

Spremembe omrežja poleg tega potrebujejo tudi spremembo v načinu vodenja, obratovanja, posluževanja ter izvajanja različnih analitičnih pristopov v različnih obratovalnih stanjih. Eno izmed takšnih programskih orodij v podjetju Elektro Celje, d. d., predstavlja programsko orodje DMS. To programsko orodje v osnovi potrebuje natančne podatke topologije omrežja, tako imenovane statične podatke omrežja, katerih vir je GIS. Drugi del podatkov je vsaj toliko, če ne celo bolj pomemben za ustrezno in kvalitetno analizo omrežja. Ta del podatkov predstavljajo dinamični podatki oziroma dejanske meritve omrežja. Samo skupek teh podatkov s poudarkom na njihovi točnosti tvori vhodne podatke za izvajanja analiz omrežja.

V članku je bil cilj na ustrezen način preveriti nekoliko drugačen pristop obvladovanja omrežja ter preveriti napetostne profile in izgube ob ustrezni generaciji delovne in jalove moči razpršenih virov. Za ta namen je bilo najprej potrebno ustrezno modelirati omrežje. Uporabljen je bil praktičen primer distribucijskega omrežja na področju Zgornje Savinjske doline, za katerega so bili pridobljeni in na voljo vsi potrebni vhodni podatki za izvedbo analize.

Pomembna ugotovitev iz rezultatov analiz se nanaša na izgube in napetostni profil omrežja. Z ustrezno generacijo jalove moči lahko vplivamo tako na napetostni profil kot tudi na izgube v omrežju. Napetostni profil se z optimizacijo in ustrezno generacijo delovne in jalove moči vzdolž voda izboljša, izgube se zmanjšajo. Proizvajalci električne energije lahko ob ustrezni generaciji jalove moči (po potrebi tudi delovne moči) distribucijskim podjetjem dodatno pomagajo pri izboljšanju napetostnega profila ter zmanjšanju izgub, saj se jalovo moč kompenzira lokalno in se jalova energija po nepotrebnem ne pretaka po omrežju.

Minimalne izgube v omrežju bi dosegli v primeru, ko bi generacija delovne moči sledila porabi električne energije v omrežju. Naslednja možnost zmanjšanja izgub je priključitev ustreznega števila razpršenih virov ustrezne moči, s katerimi bi bile glede na dnevne krivulje porabe in generacijo razpršene proizvodnje izgube minimalne.

Optimizacija proizvodnje razpršenih virov v distribucijskih omrežjih bo imela v prihodnosti precejšnjo vlogo predvsem pri obratovanju distribucijskega omrežja. Ta na eni strani zagotavlja ustrezni napetostni profil in zmanjšanje izgub pri prenosu električne energije, na drugi strani pa omogoča povečano in varno priključevanje novih oziroma dodatnih razpršenih virov električne energije v takšno omrežje ob upoštevanju SONDO in dovoljenim porastom napetosti 2 % na srednjenapetostni strani distribucijskega omrežja.

Za ugotavljanje učinkov, ki jih ima ustrezna generacija jalove moči razpršenih virov na distribucijsko omrežje, je potrebno poleg topologije omrežja nujno poznati tudi profile obremenitve omrežja in proizvodnje električne energije iz razpršenih virov.

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Primer optimizacije obratovanja distribucijskega omrežja s prevezavami, obratovanjem v zanki in generiranjem jalove moči

MATEJ PINTARIČ, MIRAN ROŠER & GORAZD ŠTUMBERGER

Povzetek Članek obravnava problematiko povečevanja priključene moči odjema v omrežju, ki že obratuje blizu mejne obremenitve. Za določitev maksimalne še sprejemljive priključne moči so v optimizacijskem postopku ukrepi prevezav, obratovanja v zanki in generacije jalove moči. Vsi so analizirani s pomočjo programa za izračun pretokov energije. Delo prikazuje rezultate izračunov pretokov energije na obstoječem razdeljevalnem omrežju. Izveden je bil izračun maksimalne moči dveh industrijskih odjemalcev, ki želita povečati odjem, na podlagi maksimalne obremenitve omrežja brez upoštevanja razpršene proizvodnje v omrežju. Izvedena je tudi analiza delovanja omrežja v zaključeni zanki pri normalni obremenitvi in obremenitvi z maksimalno močjo. Podana je rešitev problema previsokih napetosti v omrežju ob preveliki generaciji moči razpršenega vira v omrežju.

Ključne besede: • optimizacija • distribucijsko omrežje • prevezave • obratovanje v zanki • generiranje jalove moči •

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Optimization of Distribution Network Operation Based on Reconnection, Clossed-Loop Operation and Reactive Power Generation – A Case Study

MATEJ PINTARIČ, MIRAN ROŠER & GORAZD ŠTUMBERGER

Abstract The paper deals with problems of increasing the load in the distribution network that already operates near the limit load. Optimization procedure with reconnections, operation in loop and reactive power generation is being used to determinate maximal acceptable load. All analyses are made with program for load flow calculations. This paper shows results of the load flow calculations on the existing distribution network. Maximal power of two industrial consumers, which want to increase their power, was calculated based on the maximal load of the network without considering distribution generation. Operation of network in loop is also analyzed at normal network load and at maximal load. Solution to problem of too high voltage in the network, because of big distribution generation, is presented.

Keywords: • optimization • distribution network • reconnection • clossed-loop operation • reactive power generation •

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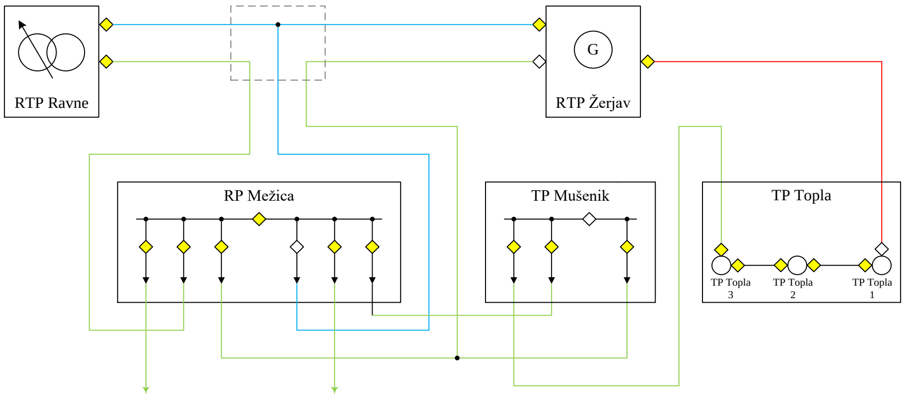
1 Uvod

Povečevanje potrebe po električni energiji povzroča širjenje električnih omrežij. Posledično je zaradi tega potrebno vedeti kako bo stanje v razširjenem omrežju, ali bodo toki vodnikov presegli dovoljeno tokovno obremenitev in ali bodo napetosti znotraj dovoljenih mej, predpisanih s standardi. Te podatke o omrežju je mogoče pridobiti z izračunom pretoka energije. Poleg povečevanja moči odjema v omrežju pa se v omrežje vključuje vedno več razpršenih proizvodnih virov. Vpliv teh virov na stanje v omrežju so podavi v [1]. Za vsako spremembo je potrebno preučiti novo stanje.

Z vključevanjem razpršenih virov v razdeljevalna omrežja, pretok energije ni več potekal v eno smer [1]. Ker takega omrežja ni mogoče več obravnavati kot pasivni element, je bilo razvitih več algoritmov za izračune pretoka energije, ker obstoječi algoritmi za prenosna omrežja niso vedno konvergirali. Primer metode "Backward Forward Sweep", BFS, je podan v članku [2]. Osnovni algoritem BFS je primeren le za popolnoma radialna omrežja, za šibko zazankana omrežja je bil ta algoritem modificiran. Ta modifikacija je prikazana v [3].

2 Razdeljevalno omrežje

Obravnavano razdeljevalno omrežje obratuje na 20 kV napetostnem nivoju. Na omrežje je priključeno 57 transformacijskih postaj na katerih je več kot 2500 odjemalcev električne energije. Podrobnejši opis in model omrežja sta podana v [4]. Slika 22.1 prikazuje poenostavljeno shemo omrežja iz katere so razvidni odklopniki, ki zagotavljajo spremembo konfiguracije, ter dva večja industrijska porabnika, RTP Žerjav in TP Topla.



Slika 22.1: Poenostavljena shema razdeljevalnega omrežja

3 Problematika v razdeljevalnem omrežju

V času delovnih ur je, zaradi velikega odjema dveh industrijskih odjemalcev, omrežje na meji prenosnih zmogljivosti. Oba industrijska odjemalca imata željo do leta 2018 povečati moč odjema, zato je bilo potrebno preveriti ali je želena obremenitev mogoča, oz. kaka je maksimalna moč, da ne prekoračimo omejitve toka in napetosti v omrežju. V RTP Žerjav je želja po povečanju moči iz 6,5 MW na 9 MW, v TP Topla pa iz 6 MW na 6,5 MW.

V omrežju se pojavljajo tudi previsoke napetosti, v času nočnih ur in remontov, zaradi velike generacije moči v RTP Žerjav.

4 Največja možna obremenitev obeh industrijskih odjemalcev

S pomočjo metode BFS [2] in diferenčne evolucije [5] smo izvedli izračun maksimalne moči v RTP Žerjav in TP Topla pri različnih maksimalnih padcih napetostni. Moči ostalih porabnikov v omrežju smo nastavili na vrednosti, ki so bile maksimalne glede na meritve iz leta 2015/16. Rezultati izračuna so podani v tabeli 22.1.

Tabela 22.1: Rezultati izračuna maksimalnih moči brez generacije moči

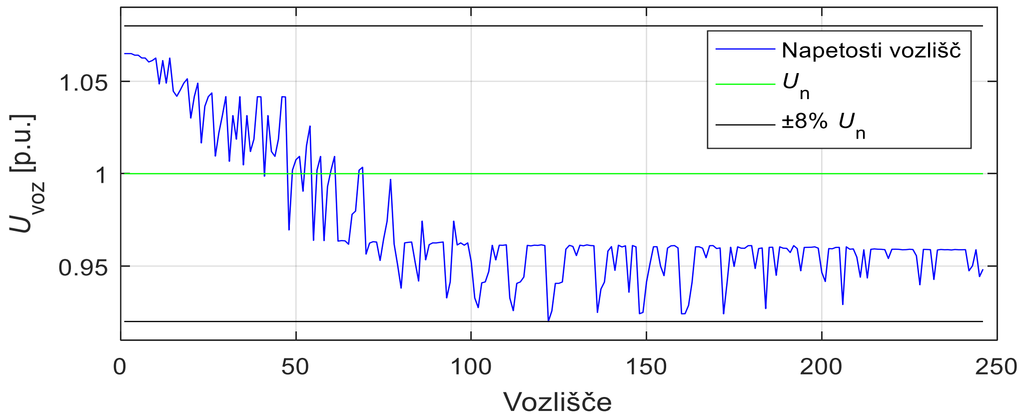
Napetostni pas	Bilančna napetost U_{bil} [kV]	Moč v RTP Žerjav $S_{Žerjav}$ [MVA]	Moč v TP Topla S_{Topla} [MVA]
±3%	20,6	/	/
±5%	21	7,46	3,56
±8%	21,3	10,57*	7,22

Napetostni pas podan v preglednici 1 je vezan na napetostni nivo omrežja 20 kV. Za ±3% sta spodnja in zgornja meja napetosti 19,4 kV in 20,6 kV medfazno. Iz rezultatov izračuna je razvidno, da izračuna pri ±3% napetostnem pasu nismo mogli izvesti, ker so padci napetosti v omrežju, brez upoštevanja RTP Žerjav in TP Topla, preveliki . Ker v RTP Žerjav obstaja neprekinjena generacija moči, smo izračun ponovili ob upoštevanju generacije moči 0,5 MVA pri različnih faktorjih delavnosti cosφ. Rezultati so podani v tabeli 22.2. Pri scenarijih, kjer je rezultat označen z *, je bila upoštevana tokovna omejitev in ne napetostna.

Tabela 22.2: Rezultati izračuna maksimalnih moči z generacijo moči

Napetostni pas	Bilančna napetost U_{bil} [kV]	Moč v RTP Žerjav, $S_{Žerjav}$ [MVA]			
		cosφ = 0,95	cosφ = 0,9	cosφ = 0,8	cosφ = 0,6
±3%	20,6	/	/	/	/
±5%	21	7,96	7,98	8,00	7,99
±8%	21,3	11,07*	11,06*	11,05*	10,99*

Primer napetostnega profila za dobljene maksimalne vrednosti pri napetostnem pasu ±8% brez upoštevanja generacije moči je prikazan na slika 22.2. RTP žerjav je prikazan v vozlišču 124 in TP Topla v vozlišču 149. Na slika 22.2, in na vseh ostalih slikah v nadaljevanju, so prikazane napetosti vozlišč normirane na napetostni nivo omrežja 20 kV.

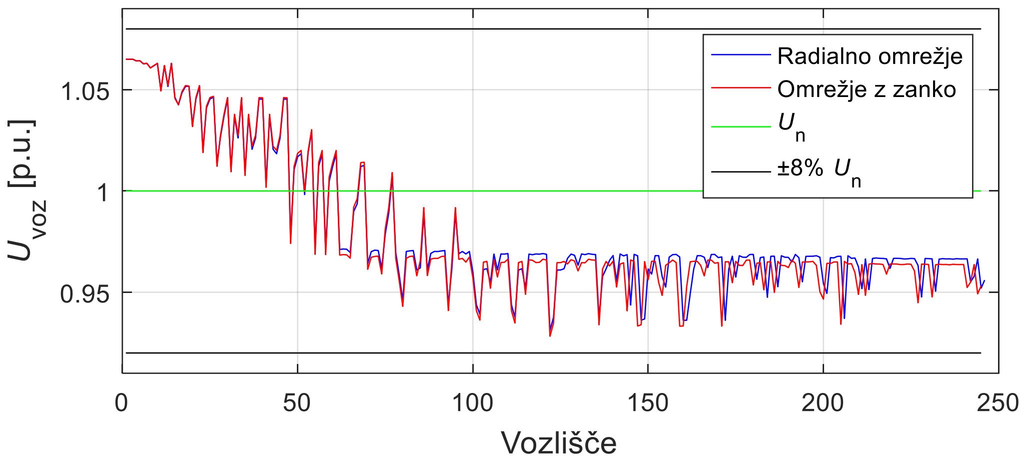


Slika 22.2: Napetostni profil omrežja pri maksimalni obremenitvi za napetostni pas ±8%

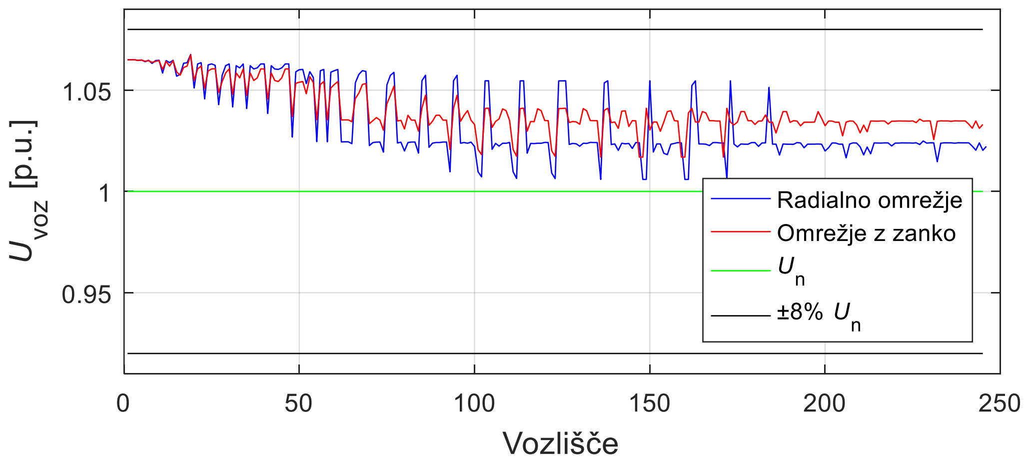
5 Obratovanje omrežja v zanki

Preverili smo ali z obratovanjem z zanko v omrežju lahko povečamo prenosne zmogljivosti. Zanka v omrežju se je zaključila preko RP Mežice in RTP Žerjav. Ta povezava je razvidna iz slika 22.1, kjer se v RTP Žerjav vklopi drugi odklopnik. Za izračun pretoka energije v omrežju z zanko smo morali uporabiti modificirani algoritem BFS [3].

Izvedli smo dva izračuna, pri maksimalni obremenitvi in normalni obremenitvi. Pri maksimalni obremenitvi smo upoštevali moč v RTP Žerjav 9 MW in v TP Topla 6,5 MW. Podatki normalne obremenitve se nahajajo v [4] in te smo izbrali za poljuben dan v aprilu, na podlagi meritev. Primerjava napetostnega profila, med obratovanjem omrežja v radialnem načinu in z zanko, je prikazana slika 22.3 in 4. Slika 22.3 prikazuje primerjavo pri maksimalni obremenitvi in slika 22.4 pri normalni obremenitvi.



Slika 22.3: Primerjava napetostnih profilov v radialnem omrežju in omrežju z zanko pri maksimalni obremenitvi



Slika 22.4: Primerjava napetostnih profilov v radialnem omrežju in omrežju z zanko pri normalni obremenitvi

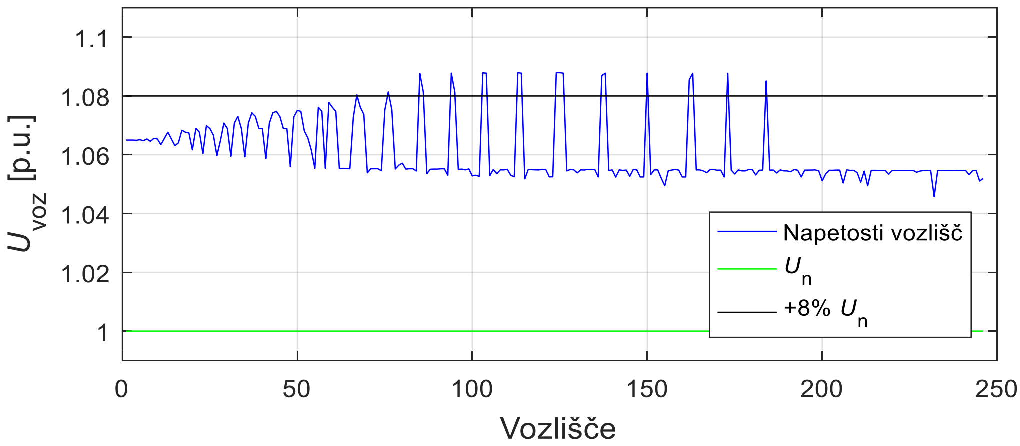
6 Previsoka napetost v omrežju

Do previsokih napetosti v omrežju pride zaradi generacije moči v RTP Žerjav, ko omrežje ni zelo obremenjeno, to je predvsem v nočnih urah in ob remontih v industriji. Problem smo reševali s spreminjanjem konfiguracije in generacijo jalove moči induktivnega značaja.

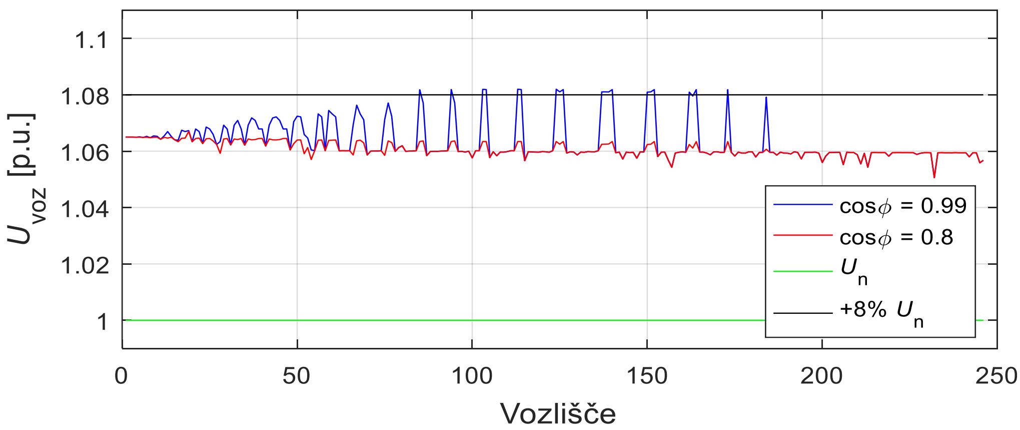
Izvedli smo izračune pretoka energije za tri spremembe konfiguracije:

a) preklop TP Topla iz TP Mušenik na RTP Žerjav
b) preklop RTP Žerjav iz RTP Ravne na RP Mežica,
c) preklop RTP Žerjav iz RTP Ravne na TP Topla.

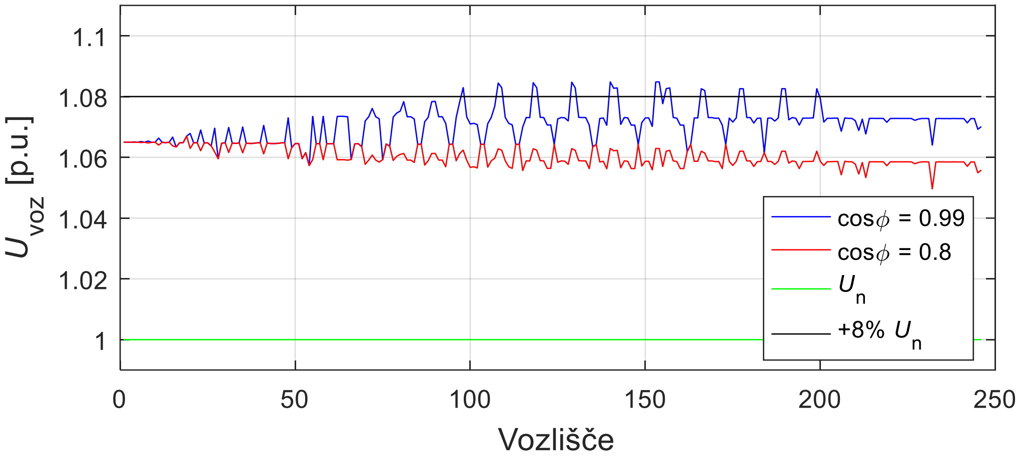
Največje povečanje napetosti v omrežju je nastopilo v času remonta industrije, ko je bila generacija moči v RTP Žerjav 3660 kVA. Podatki ostalih obremenitev so podani v [4]. Slika 22.5 prikazuje napetostni profil omrežja v tem trenutku. Slika 22.6 – 8 prikazujejo napetostne profile ob različnih spremembah konfiguracije omrežja, pri faktorju delavnosti, cosφ, 0,99 in 0,8. Z vsemi tremi rešitvami smo prišli do podobnih rezultatov glede napetosti, razlike se pojavijo v prenosnih izgubah, ki so podane v tabeli 22.3. Z zmanjšanjem faktorja delavnosti v omrežje vsilimo več jalovega toka, kar posledično pomeni večje padce napetosti in izgube.



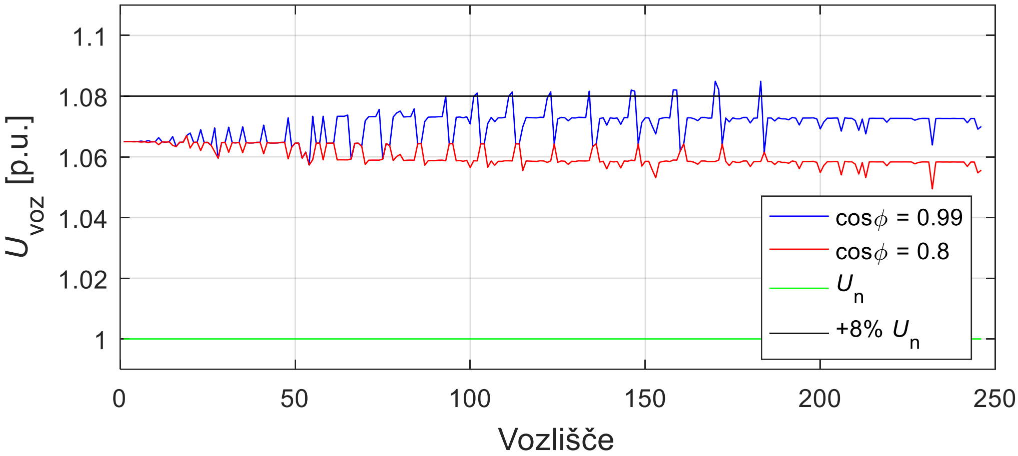
Slika 22.5: Napetostni profil omrežja ob maksimalni generaciji moči v RTP Žerjav



Slika 22.6: Napetostni profil omrežja ob spremembi konfiguracije a)



Slika 22.7: Napetostni profil omrežja ob spremembi konfiguracije b)



Slika 22.8: Napetostni profil ob spremembi konfiguracije c)

Tabela 22.3: Prenosne izgube v omrežju ob različnih spremembah konfiguracije

Konfiguracija	Prenosne izgube P_{izg} [kW]	
	cosφ = 0,99	cosφ = 0,8
a)	76,1	92,2
b)	83,5	105,5
c)	86,8	114,7

7 Sklep

V članku so podani rezultati izračunov pretoka energije na obstoječem omrežju z metodo BFS in modificirano metodo BFS za omrežja z zanko. Uporabljen je bil enofazni simetrični model omrežja. Z izračuni smo preverili trenutno stanje v omrežju, možnost povečanja obremenitve v omrežju, delovanja omrežja z zanko in stanje v omrežju ob povečani generaciji razpršenih virov.

Iz izračunov maksimalnih moči v omrežju je vidno, da je želena moč obeh industrijskih odjemalcev možna, ampak pri večjem, kot je dovoljen, padcu napetosti. Skozi vodnike, bi v takem primeru tekel tudi tok, ki je blizu nazivnega toka vodnika. Problem, bi lahko v nadaljevanju reševali s spreminjanem odcepov na transformatorjih za nizko napetost.

Obratovanje omrežja z zanko je boljše kot brez zanke, ampak le v primeru ko omrežje ni na meji prenosnih zmogljivosti. Takrat se stanje v omrežju bistveno ne spremeni.

Previsoko napetost v omrežju je bila odpravljena s pomočjo spremembe konfiguracije in generacijo jalove moči induktivnega značaja. Podane so bile tri rešitve, ki podajajo podobne rezultate, razlike se pojavljajo predvsem v prenosnih izgubah in mestih preklopa. S stališča manjših prenosnih izgub je rekonfiguracija a) najustreznejša, vendar moramo pri tem upoštevati, da izbrani faktorji delavnosti razpršenega vira niso bili optimizirani za minimalne izgube pri odpravljeni previsoki napetosti. Najenostavnejše preklope nam zagotavlja rekonfiguracija b), kjer sta oba odklopnika na istih zbiralkah.

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Algoritem za izračun napovedi trenutne moči sončne elektrarne s pomočjo nevronskih omrežij

MIHAEL SKORNŠEK & GORAZD ŠTUMBERGER

Povzetek Delo obravnava spremljanje in primerjavo obratovalnih lastnosti sončnih elektrarn. Vsa odstopanja v delovanju lahko spremljamo z dodatnimi meritvami na elektrarni, kot sta sončno obsevanje in temperatura celice. Na podlagi polletnih meritev parametrov delovanja je s pomočjo umetnega nevronskega omrežja v programskem paketu Matlab pripravljen algoritem za izračun napovedane moči sončne elektrarne v danem trenutku, s katerim lahko ovrednotimo pravilno delovanje le-te. Omenjeni algoritem predstavlja nadgradnjo sistema za spremljanje obratovanja sončne elektrarne. Večja razlika med izmerjenimi in z algoritmom določenimi trenutnimi izhodnimi močmi sončne elektrarne kaže na neustrezno delovanje posameznih elementov sončne elektrarne in potrebo po podrobnejšem preverjanju.

Ključne besede: • algoritem • napovedovanje • trenutna moč • sončna elektrarna • nevronsko omrežje •

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Algoritem for Predicting Solar Power Plant Output Power with an Artificial Neural Network

MIHAEL SKORNŠEK & GORAZD ŠTUMBERGER

Abstract This work deals with the comparison of operating propertis of photovoltaic power plants. All derogations in the operation of photovoltaic power plant can be monitored with additional measurements of solar irradiation and temperature of photovoltaic cells. Based on data acquired during six months operation of discussed photovoltaic power plant an Artificial Neural Network (ANN) has been built in order to predict output power of the power plant. The ANN complements the already existing monitoring system. When the difference between the ANN predicted and measured output power of the photovoltaic power plant is too high, a detail check of the power plant components is required.

Keywords: • algoritem • prediction • output power • solar power plant • artificial neural network •

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1 Uvod

Cilj dela je predstaviti metodologijo in potrebno opremo za primerjavo delovanja omrežnih sončnih elektrarn pri različnih pogojih obratovanja. Praktično vsaka elektrarna potrebuje nadzorni sistem, ki spremlja delovanje elektrarne, predvsem pa pravočasno javlja napake oz. odstopanja v delovanju. Nekatere okvare je zaradi njihovega obsega lažje zaznati, težave pa nam prestavljajo manjša odstopanja.

Z na novo razvitim algoritmom želimo nadgraditi nadzorni sistem tako, da bo lahko zaznal manjša odstopanja brez nepotrebnega javljanja okvar. Takšen sistem deluje na osnovi primerjave dejanske moči z napovedano vrednostjo moči elektrarne v nekem trenutku. Napovedano vrednost moči določimo na podlagi sprotnega merjenja sončnega obsevanja in temperature celice. V kolikor ta vrednost ni realna, prihaja do nepotrebnega javljanja napak, ki jih sproži nadzorni sistem. Za napoved izhodne moči sončne elektrarne uporabimo algoritem na osnovi umetnega nevronskega omrežja ustrezne strukture. Za učenje umetnega nevronskega omrežja uporabimo arhiv meritev sončne elektrarne, ki vsebuje podatke o temperaturi sončnih modulov, gostoti moči sončnega sevanja in dejanski izhodni moči sončne elektrarne. Na tak način naučeno umetno nevronsko omrežje lahko zagotovi precej dobro napoved izhodne moči sončne elektrarne.

V nadaljevanju bo predstavljen izračun napovedane izhodne moči sončne elektrarne na osnovi linearnega modela, ki izhodno moč elektrarne določi na osnovi trenutne vrednosti obsevanja in temperature fotonapetostnega modula. Tako izračunane vrednosti izhodne moči sončne elektrarne bodo primerjane s tistimi, ki jih dobimo iz predlaganega algoritma na osnovi umetnega nevronskega omrežja in rezultati meritev. Predlagani, na umetnem nevronskem omrežju temelječ, algoritem napovedi izhodne moči sončne elektrarne je mogoče s pridom uporabiti pri spremljanju obratovanja sončne elektrarne. Velikost odstopanja med napovedano in izmerjeno izhodno močjo je mogoče uporabiti pri diagnostiki obratovanja sončne elektrarne in ugotavljanju sicer skritih napak.

2 Pregled opazovanih testnih fotonapetostnih polj

Analiza obratovanja sončnih elektrarn je bila izvedena na t. i. testnih fotonapetostnih (FN) poljih [1]. Sončno elektrarno sestavlja več takšnih polj za katera je značilno, da so zgrajena iz enakih komponent in da so enakih moči, razlikujejo pa se po načinu oz. naklonu namestitve fotonapetostnih modulov, nekatera pa tudi po tipu uporabljenih razsmernikov.

Tabela 23.1: Seznam fotonapetostnih (FN) testnih polj

Oznaka	Moč [W]	Naklon modulov	Usmerjenost modulov
FN1	9.870	0°	0° (J)
FN2	9.870	25°	0° (J)
FN3	9.870	34°	0° (J)
FN4	9.870	7° (J)	0° (J)
FN5	9.870	–7° (S)	0° (J)
FN6	9.870	90°	0° (J)
FN7	9.870	sledenje soncu	sledenje soncu
FN8	9.870	20°	sledenje soncu
FN9	9.870	sledenje soncu	0° (J)
FN10	9.870	20° (talna postavitev)	0° (J)

Vsa FN polja so nameščena na enaki mikrolokaciji, saj so tako omogočeni čim bolj enaki pogoji obratovanja za namene analiz in primerjav. Za vsako od njih se izvajajo naslednje meritve:

- **Za vsako FN testno polje:**

  - trenutna moč,
  - dnevna proizvedena energija,
  - sončno obsevanje na ravnino FN polja,
  - temperatura celic FN modulov.

- **Okoljski parametri:**

  - temperatura okolice,
  - hitrost in smer vetra poleg,
  - količina padavin,
  - obsevanje na horizontalno ploskev,
  - globalno obsevanje – piranometer.

Vsi ti podatki se odčitavajo v poljubno dolgih intervalih, ki jih je mogoče nastaviti, in se shranjujejo v bazo ter hkrati prikazujejo na centralnem nadzornem sistemu. Na zahtevo je mogoče beležiti še ostale parametre, ki jih merijo razsmerniki sami. Podatki v bazi so tako dostopni za nadaljnje analize in primerjave obratovanja.

3 Validacija trenutne moči sončne elektrarne

Obratovalni pogoji sončne elektrarne se tekom daljšega obratovanja spreminjajo. Vzroki za to so lahko staranje celic fotonapetostnih modulov, trdovratnejša umazanija na njih, okvare na električnih napeljavah ali drugih elementih, spremembe na razsmernikih itd. Vsa takšna stanja povzročajo določeno izgubo moči in s tem delno zmanjšanje proizvedene električne energije. Medtem ko večje okvare lažje zaznamo (zaradi občutnega padca moči oz. proizvedene energije), je stanja z manjšimi okvarami težje zaznati, kljub temu pa so lahko na dolgi rok vzrok večjega izpada proizvodnje električne energije.

Nadzorni sistem sončne elektrarne na podlagi podatkov iz razsmernikov seveda z neko natančnostjo javlja odstopanja, npr. izpad enega niza modulov, občutno zmanjšanje moči enega niza, okvaro razsmernika ali pa samo napako v komunikaciji. Tak sistem pa odpove v primeru, ko gre za odstopanja le nekaj odstotkov ali pa v primeru, ko je celotno polje modulov pod vplivom umazanije, nadzorni sistem pa vrši javljanje okvar samo na podlagi medsebojnih primerjav (na nivoju posameznega niza ali na nivoju posameznega MPPT vhoda razsmernika).

Naprednejši nadzorni sistemi vključujejo tudi senzor direktnega obsevanja na ravnino modulov, na podlagi katerega se izvede primerjava med trenutno močjo, odčitano iz razsmernika, ter napovedano močjo, izračunano na podlagi obsevanja. Tudi tukaj se pojavljajo težave pri računanju, saj so v določenih primerih odstopanja prevelika, kljub temu da elektrarna obratuje normalno brez okvar ali umazanije na modulih. V takšnih primerih prihaja do lažnega javljanja odstopanj, česar pa si ne želimo.

3.1 Analitični izračun napovedane moči fn polja

Večina komercialno dostopnih nadzornih sistemov vrši kontrolo izhodne moči elektrarne na podlagi izmerjenega obsevanja in temperature celice, le-ta pa je v veliko primerih izračunana. Na podlagi parametrov o modulih, ki jih poda proizvajalec, lahko izračunamo trenutno moč [3] z linearnim preračunom trenutnega obsevanja na STC, potem pa dobljeno vrednost korigiramo še s temperaturnim koeficientom moči. Za izračun moči z izmerjeno temperaturo uporabimo izraz (1), z izračunano temperaturo [4] pa (2).

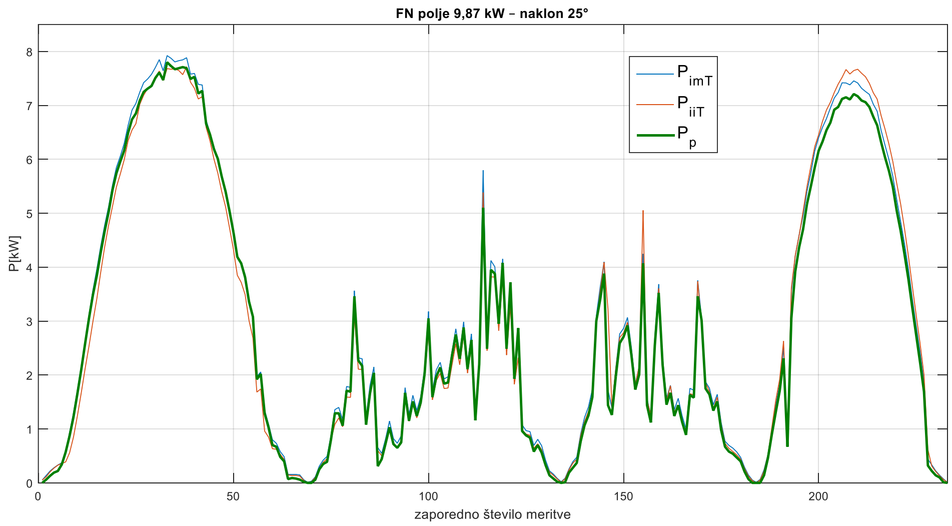
$$P_{imT} = \frac{G_a}{1000} \cdot P_{inst} \cdot \left(1 - \gamma(T_{mT} - T_{STC})\right) \qquad (1)$$

$$P_{iiT} = \frac{G_a}{1000} \cdot P_{inst} \cdot \left(1 - \gamma(T_{iT} - T_{STC})\right) \qquad (2)$$

pri tem so:

P_{imT} izračunana trenutna moč elektrarne na osnovi izmerjene temperature celice [kW],
P_{iiT} izračunana trenutna moč elektrarne na osnovi izračunane temperature celice [kW],
G_a trenutno obsevanje [W/m^2],
P_{inst} inštalirana moč elektrarne [kW],
γ temperaturni koeficient moči [1/°C],
T_{mT} izmerjena temperatura modula oz. celice [°C],
T_{iT} izračunana temperatura modula oz. celice [°C],
T_{STC} temperatura modula oz. celice pri STC [°C].

Na podlagi tabelaričnih podatkov smo preverili točnost opisanega algoritma za različna FN polja. Rezultate smo preverili na podlagi meritev v štirih dneh – dveh sončnih in dveh delno oblačnih, enkrat v poletnem in drugič v zimskem času. Ker so uporabljeni razsmerniki enakega tipa, imajo enak t.i. euro izkoristek [2], kar je bil tudi pogoj o enakih lastnostih primerjanih FN testnih polj.



Slika 23.1: Prikaz napovedane in izračunane moči za FN polje 25°

Rezultati za FN polje z naklonom modulov 25° so prikazani na sliki 1. Z rdečo črto je prikazana izračunana moč na osnovi izračunane temperature celice (P_{iiT}), z modro pa na osnovi dejansko izmerjene temperature celice (P_{imT}). Z zeleno je prikazana pričakovana (napovedana) moč (P_P), ki je dejansko izmerjena trenutna moč. Izračunana vrednost temperature celice daje v določenih dnevih precej slab rezultat, nekoliko bolje pa se obnese izračun z merjeno temperaturo. Podobno obnašanje opazimo na FN poljih z drugimi nakloni, in če povzamemo rezultate iz prakse ugotovimo, da so takšne meritve za diagnosticiranje manjših odstopanj napovedane moči manj uporabne, saj je rezultat preveč odvisen od drugih dejavnikov, kot so način montaže modulov, hitrost vetra, konstrukcijska zasnova modulov itd. Glede na to, da imamo na voljo velik arhiv meritev, bomo poizkusili poiskati natančnejši algoritem za izračun napovedane moči elektrarne, s katerim bomo lahko diagnosticirali tudi manjša odstopanja v moči oz. proizvodnji električne energije sončne elektrarne.

3.2 Algoritem za napoved moči sončne elektrarne na osnovi umetnega nevronskega omrežja

Ugotovili smo, da metoda računanja pričakovane moči oziroma napoved moči na podlagi sončnega obsevanja in temperature celice z analitičnim modelom ne daje dovolj dobrega rezultata za različne konfiguracije sončnih elektrarn skozi celo leto, ne glede na to, ali smo temperaturo celice merili ali izračunali. V kolikor imamo na voljo dovolj veliko bazo izmerjenih vrednosti obratovalnih parametrov sončnih elektrarn, lahko algoritem za izračun napovedane moči izvedemo s pomočjo umetnega nevronskega omrežja, kot je prikazano v nadaljevanju. Arhiv teh podatkov, ki so izmerjeni med normalnim delovanjem elektrarne, ko na njej ni okvar ali drugih dejavnikov, ki bi vplivali na njeno izhodno moč, lahko uporabimo za iskanje funkcije za izračun napovedane moči oziroma napovedi proizvodnje v realnem času.

Osnove delovanja umetnih nevronskih omrežij izhajajo iz modela aktivnosti človeških možganov. Človekova obdelava informacij poteka preko vzbujanj med nevroni (živčnimi celicami). Človekov osrednji živčni sistem je sestavljen iz več milijard nevronov. S stališča obdelave informacij lahko obravnavamo vsak nevron kot enostaven procesor [5].

Učenje in testiranje sta praktično najpomembnejša dela ustvarjanja nevronskega omrežja. Prvi korak učenja je vnos vprašanj z znanimi odgovori. Sledi primerjava odgovora omrežja z znanimi pravilnimi odgovori (testiranje). Nato se prilagajajo uteži povezav med posameznimi nevroni, dokler omrežje ne da pravega odgovora. Postopek se ponavlja tako dolgo, dokler omrežje ni ustrezno naučeno. Cikel učenja se izvaja, dokler niso zadoščene zahteve določenega kriterija (maksimalni čas učenja, maksimalni pogrešek, maksimalno število ciklov …). Pričakovani rezultat je umetno nevronsko omrežje, ki lahko odgovarja tudi na vprašanja z neznanimi odgovori. Za preizkušanje pravilnosti sledijo testi z drugimi vprašanji, na katera so odgovori že znani.

Za izračun napovedane moči elektrarne s pomočjo nevronskega omrežja bomo za fazo učenja omrežja uporabili nabor polletnih meritev za vseh šest FN testnih polj s fiksnimi nakloni modulov in tako poiskali povezavo – funkcijo med vhodnimi podatki ter napovedano močjo, ki jo bomo potem preizkusili na posameznih FN testnih poljih. Najprej je potrebno pripraviti bazo podatkov, imenovano učni vzorci.

To so vhodni podatki za določitev nevronskega omrežja. V našem primeru smo kot razpoložljive učne podatke izbrali:

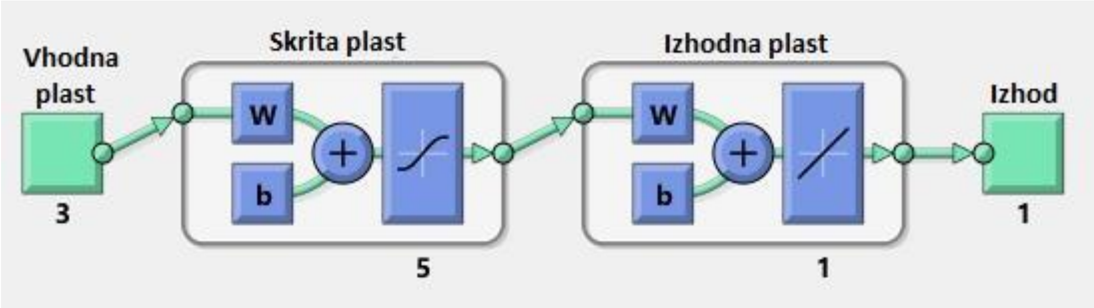
- temperaturo celice [°C],
- direktno obsevanje [W/m^2],
- globalno obsevanje [W/m^2].

Ciljne vrednosti so bile izmerjene vrednosti izhodne moči:

- moč elektrarne [kW].

Kreiranje in konfiguracija omrežja

Po tem, ko je bilo nevronsko omrežje kreirano (slika 23.2), mora biti konfigurirano in naučeno. V našem primeru vsebuje nevronsko omrežje tri vstopne nevrone, 5 skritih nevronov ter en izstopni nevron.

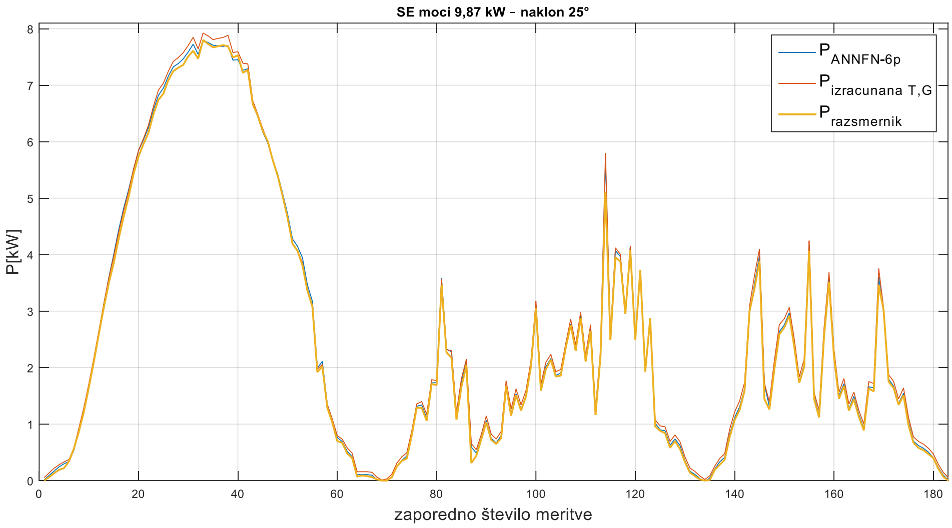


Slika 23.2: Model nevronskega omrežja v Matlab-u

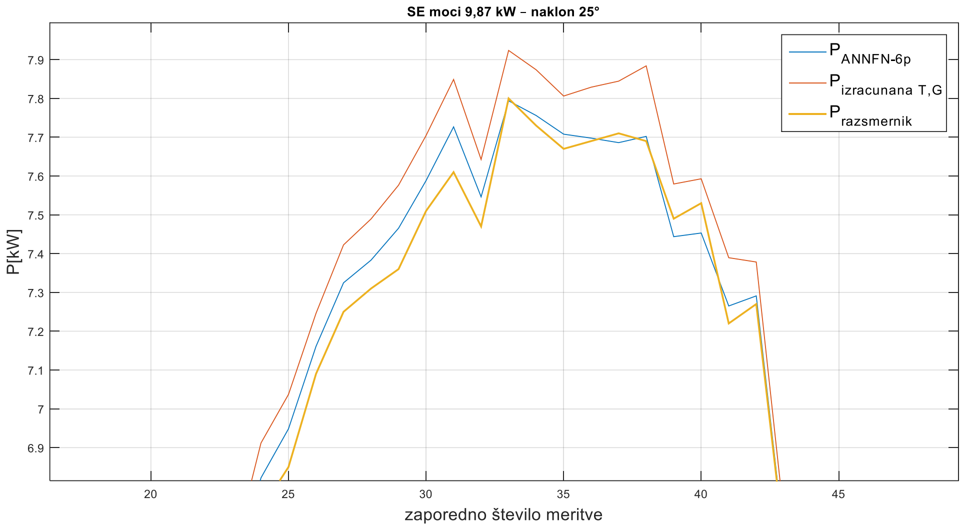
Vstopni nevroni predstavljajo izbrane izmerjene vrednosti: direktno in globalno obsevanje, temperaturo celice. Srednja raven je t. i. skrita raven, katere velikost je bila s preizkušanjem optimizirana na pet nevronov. Zadnji ali izstopni nevron pa je izhodna moč sončne elektrarne – ciljna vrednost. Vsi ti podatki so izmerjeni takrat, ko elektrarna deluje brez okvar, na modulih oz. referenčni celici za merjenje obsevanja pa ni umazanij. Konfiguracija vključuje takšno zasnovo omrežja, ki je združljiva s problemom, kot je opredeljeno v vzorčnih podatkih.

3.3 Preizkus napovedovanja trenutne moči s pomočjo nevronskih omrežij na različnih fn testnih poljih

Na slikah 23.3 in 23.4 je prikazan potek moči za FN polje 25°, in sicer za tri naključne dni. Z rumeno ($P_{razsmernik}$) je prikazan potek izmerjene moči razsmernika – ciljne vrednosti, z rdečo ($P_{izracunana\ T,G}$) potek moči, izračunane analitično na podlagi obsevanja in temperature celice, ter z modro ($P_{ANNFN\text{-}6p}$) potek moči, izračunane s pomočjo nevronskega omrežja. Medtem ko v delno oblačnih dneh opazimo manjša odstopanja v vrednostih, pa je v območju večjih moči (sončen dan) z nevronskim omrežjem določena moč zelo blizu izmerjeni.



Slika 23.3: Prikaz izračunanih in izmerjenih vrednosti moči za FN polje 25°

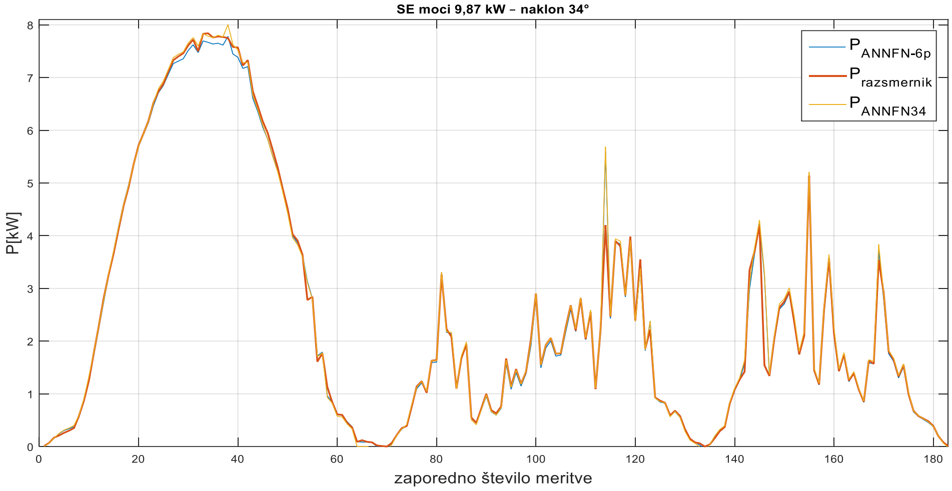


Slika 23.4: Prikaz izračunanih in izmerjenih vrednosti moči za FN polje 25° – detajl

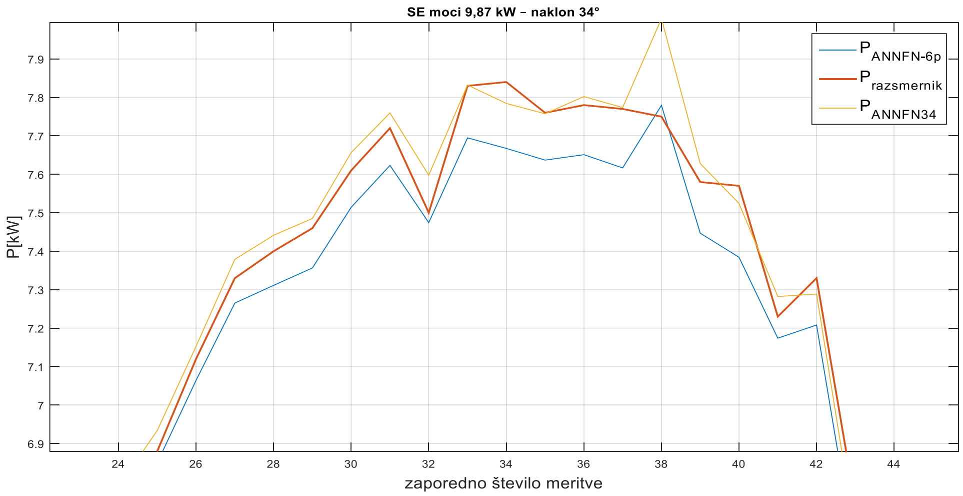
Na podlagi obsevanja in temperature celice analitično izračunana izhodna moč daje v območju večjih moči prevelike vrednosti. To ima za posledico nepotrebno javljanje sistema za spremljanje delovanja elektrarne (monitoring) o prevelikih odstopanjih med napovedano (izračunano) in izmerjeno izhodno močjo elektrarne.

Obravnavali smo izračun napovedane moči elektrarne na osnovi prenosne funkcije, ki je bila izračunana s pomočjo nevronskih omrežij na bazi polletnih podatkov za FN polja z različnimi nakloni. Takšno nevronsko omrežje je do neke mere univerzalno, saj ga lahko uporabimo na sončnih elektrarnah z različnimi nakloni. V nadaljevanju si bomo ogledali še nekaj primerov, ko je funkcija za izračun napovedane moči dobljena s pomočjo nevronskih omrežij, učni podatki nevronskega omrežja pa so z meritvami pridobljeni samo za opazovano FN polje in ne za več polj.

Tokrat opazujemo, kateri izračun napovedane moči s pomočjo nevronskega omrežja bolje opravi svoje delo: tisti, ki ima učne vzorce na osnovi podatkov za več FN polj ($P_{ANNFN-6p}$), ali tisti, katerega osnova so podatki samo opazovanega polja ($P_{ANNFN34}$). V nadaljevanju so na slikah poteki moči $P_{ANNFN-6p}$ prikazani z modro, $P_{ANNFN34}$ z rumeno in $P_{razsmernik}$ (ciljna vrednost) z rdečo barvo.



Slika 23.5: Prikaz izračunanih in izmerjenih vrednosti moči za FN polje 34°



Slika 23.6: Prikaz izračunanih in izmerjenih vrednosti moči za FN polje 34° – detajl

Primerjavo (slika 23.5) pogledamo za polje z naklonom 34° za iste tri opazovane dni kot v prejšnjem primeru. Pregled detajla na sliki 6 nam pokaže boljše ujemanje napovedane moči s ciljno v primeru izračuna z nevronskim omrežjem z učnimi podatki polja modulov z naklonom 34°.

4 Sklep

V delu smo predstavili medsebojno primerjavo delovanja elektrarn z dvema omenjenima vrstama razsmernikov, tako v normalnih pogojih obratovanja, kot tudi v primeru delno senčenih modulov. Ugotovili smo, da lahko v delovanju prihaja do manjših, komaj zaznavnih razlik ali pa večjih, lažje opaznih. Te ugotovitve, izoblikovane na podlagi analize izmerjenih obratovalnih parametrov dejanske elektrarne, so bile podlaga za nadaljnje korake, ko smo iskali algoritem za izračunavanje napovedi pričakovane izhodne moči elektrarne v danem trenutku, na podlagi meritev okoljskih parametrov.

Na podlagi meritev obsevanja in temperature celice nadzorni sistemi napovedujejo izhodno moč elektrarne, ki bi jo glede na inštalirano moč modulov morala v tistem trenutku dosegati. V praksi pa se izkaže, da takšna napoved pogosto ni dovolj natančna, zaradi česar prihaja do nepotrebnega javljanja nadzornega sistema o nepričakovanem zmanjšanju izhodne moči elektrarne, kar predstavlja nenormalno obratovalno stanje.

Če se z dodatnimi meritvami prepričamo, da elektrarna v nekem obdobju obratuje brez okvar, lahko takšno bazo izmerjenih podatkov uporabimo v algoritmu za napovedovanje izhodne moči fotonapetostnega polja, ki temelji na uporabi umetnih nevronskih omrežij. Pri tem so vhodni podatki pri učenju nevronskega omrežja informacije o pogojih obratovanja, ciljna vrednost pa je izmerjena izhodna moč fotonapetostnega polja elektrarne. Naučeno umetno nevronsko omrežje lahko v nadaljevanju uporabljamo za napovedovanje izhodne moči posameznega fotonapetostnega polja ali celotne sončne elektrarne, ob upoštevanju trenutnih pogojev obratovanja. Slednji so pogosto podani v obliki merjenega obsevanja in temperature celic fotonapetostnih modulov.

Umetna nevronska omrežja za različna fotonapetostna testna polja so bila učena z različnimi nabori učnih podatkov. Pri tem smo enkrat uporabili nabor merjenih podatkov s fotonapetostnih testnih polj z različnimi nakloni, drugič pa samo podatke merjene na opazovanem testnem polju. Predlagan način napovedi izhodne moči posameznih polj sončne elektrarne z ustrezno naučenimi umetnimi nevronskimi omrežji omogoča uporabo podatkov preteklega obratovanja elektrarne za učenje umetnega nevronskega omrežja, ki omogoča bolj točno napovedovanje izhodne moči elektrarne. Slednje je s pridom mogoče uporabiti v sistemu za nadzor delovanja elektrarne. Pri tem se lahko nevronsko omrežje tudi sproti uči in se tako dinamično prilagaja spreminjanju obratovalnih pogojev in staranju posameznih elementov elektrarne.

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Električna poljska jakost srednjenapetostnega podpornega izolatorja z različnim številom reber

MIRZA SARAJLIĆ, PETER KITAK, NERMIN SARAJLIĆ & JOŽE PIHLER

Povzetek Članek obravnava modeliranje srednjenapetostnega podpornega izolatorja. V programskem orodju Matlab je izdelan model izolatorja, nato je izveden izračun električnega polja v programskem orodju Elefant. Poudarek je namenjen zunanji obliki izolatorja. V članku so prikazani primeri izolatorja z različnim številom reber in njihov vpliv na električno polje izolatorja.

Ključne besede: • električna poljska jakost • srednja napetost • podporni izolator • elefant • matlab •

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Electric Field Strength of the Medium Voltage Post Insulator with Different Number of Ribs

MIRZA SARAJLIĆ, PETER KITAK, NERMIN SARAJLIĆ & JOŽE PIHLER

Abstract The paper describes the designing of a medium voltage post insulator. The insulator model was designed in Matlab software and calculations of the electric field were in Elefant software. The emphasis is on the external shape of the insulator. The paper presents examples of the insulator with different number of ribs and their influence on the insulator's electric field strength.

Keywords: • electric field strength • medium voltage • post insulator • Elefant • Matlab •

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1 Uvod

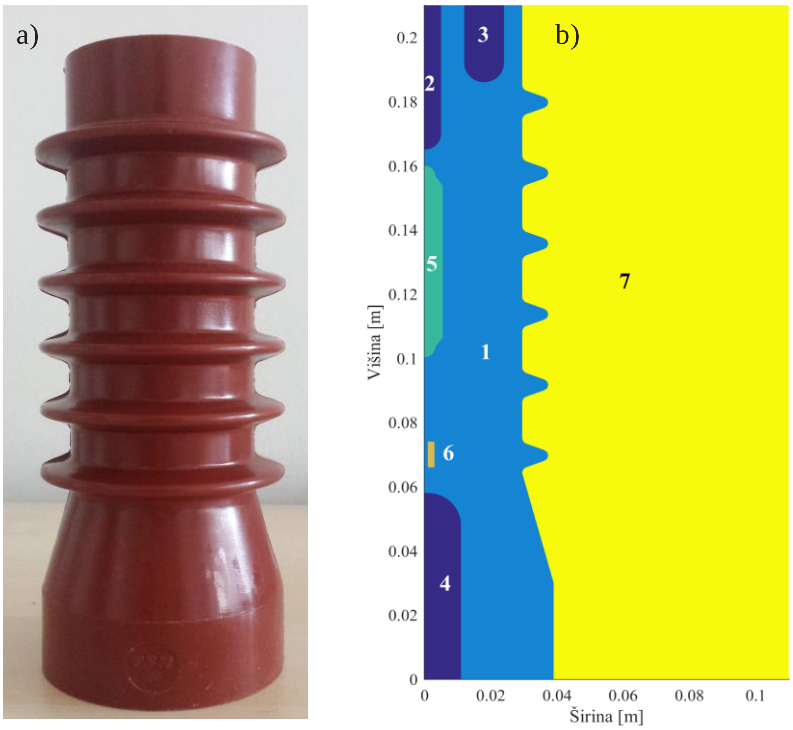
Izolatorji so najštevilnejši elementi, uporabljeni v vsaki stikalni napravi [1]. Osnovna naloga izolatorjev je električno izoliranje prevodnih delov od ozemljenih delov in mehansko pritrjevanje opreme ali vodnikov, ki so na različnih potencialih. Uporabljajo se za zunanjo in notranjo montažo. Danes se uporabljajo epoksidni izolatorji za notranjo montažo (slika 24.1a). Izolatorji iz epoksidnih smol imajo zelo dobre izolacijske, mehanske in termične lastnosti, ter veliko odpornost na različne kemikalije. Odlikujejo se tudi po malih dimenzijah, zahtevnih oblikah in dolgi življenjski dobi [2]. Za notranjemontažne naprave so najštevilnejši podporni izolatorji, zato jih bomo v članku natančneje obravnavali.

Model izolatorja bo zgrajen v programskem orodju Matlab. Obstoječ izolator vsebuje 6 reber (slika 24.1 a). Raziskali bomo vpliv števila reber na električno polje izolatorja.

2 Model izolatorja

Na sliki 1b je prikazan model izolatorja v Matlabu. Izolator je sestavljen iz 7 področij:

1. Izolacijski material iz araldita in je na plavajočem potencialu;
2. Zgornja elektroda iz kovinskega materiala in je na potencialu 125 kV;
3. Zgornji desni priključek iz kovinskega materiala in je na potencialu 125 kV;
4. Spodnja elektroda iz kovinskega materiala in je na potencialu 0 V;
5. Kondenzator iz keramike in je na plavajočem potencialu;
6. Upor iz kovinskega materiala in je na plavajočem potencialu;
7. Zrak (plavajoči potencial).

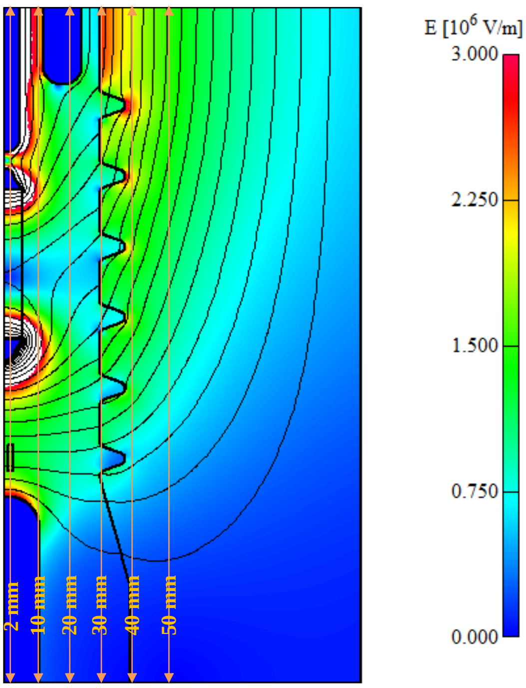


Slika 24.1: a) Obstoječ izolator in b) Model izolatorja v Matlabu

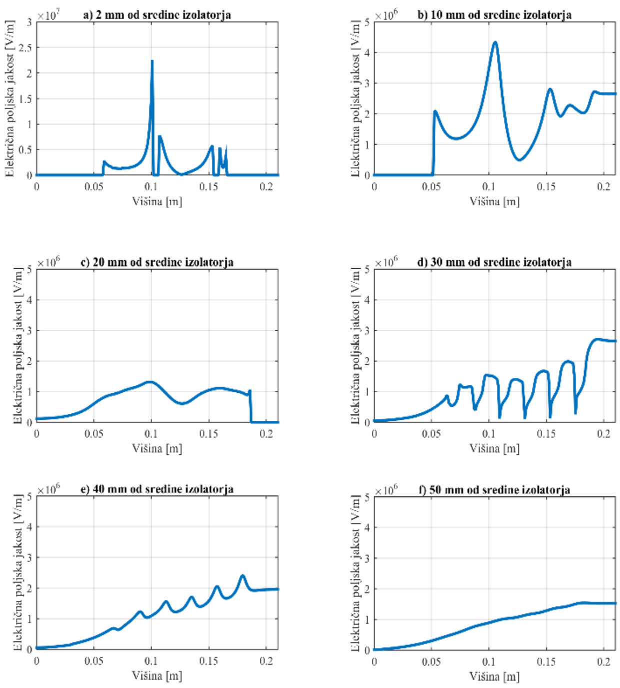
Na zgornjo elektrodo in zgornji desni priključek je priključena visoka napetost (najvišja preskusna napetost, ki jo mora 20 kV izolator vzdržati). Spodnja elektroda je ozemljena. Električno polje v okolici in na zunanji površini izolatorja mora biti manjše od 3 MV/m, znotraj izolatorja pa manjše od 30 MV/m [4, 5].

Načrtovanje izolatorja zahteva vhodne podatke, kot so geometrija izolatorja, materiali in robni pogoji. Matlab predstavlja predprocesor, v katerem je parametrično zapisan model izolatorja. Po vnosu vhodnih podatkov, predprocesor ustvari datoteke v katerih so zapisani material, geometrija in robni pogoji. Te datoteke služijo kot vhodni podatki za izračun električne poljske jakosti v Elefantu.

Slika 24.2 prikazuje izris električne poljske jakosti obstoječega izolatorja. Slika 24.3 prikazuje električno poljsko jakost na različnih oddaljenosti od sredine izolatorja. Kot je razvidno iz slike 24.3, v notranjosti izolatorja (pri 2 mm, 10 mm in 20 mm) ni presežena prebojna trdnost 30 MV/m. Tudi v zraku (pri 30 mm, 40 mm in 50 mm) ni prišlo do presega električne poljske jakosti (3 MV/m).



Slika 24.2: Električna poljska jakost obstoječega modela izolatorja



Slika 24.3: Diagram električnih poljskih jakosti obstoječega modela izolatorja na različnih oddaljenosti od sredine izolatorja

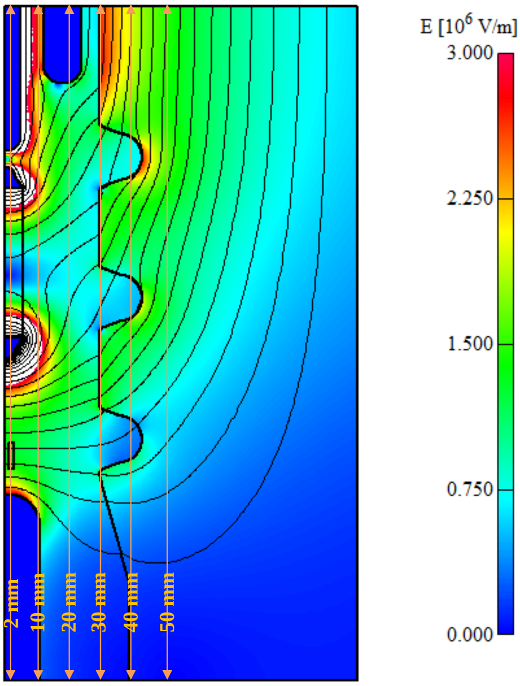
3 Model izolatorja z različnim številom reber

V nadaljevanju je obravnavano modeliranje zunanjosti izolatorja. Narejeni so primeri izolatorja z manjšim številom reber in z večjim številom reber ter primerjava z obstoječim izolatorjem.

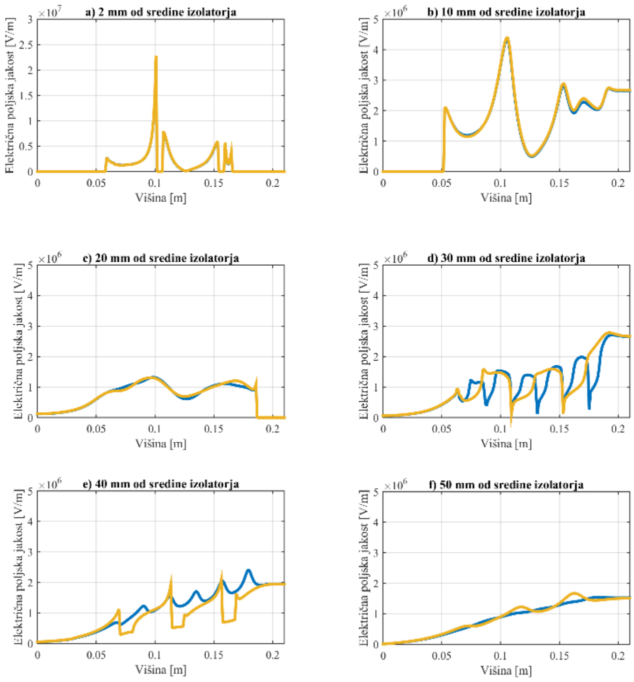
3.1 Model izolatorja z manjšim številom reber

Prikazali bomo izolator s tremi in štirimi rebri ter preverili kako ta sprememba vpliva na porazdelitev električnega polja. Izris električne poljske jakosti izolatorja s tremi rebri je prikazan na sliki 24.4. Slika 24.5 prikazuje primerjavo električne poljske jakosti obstoječega izolatorja in izolatorja s tremi rebri na različnih oddaljenosti od sredine izolatorja.

Na sliki 24.5 je z rumeno barvo označena vrednost električne poljske jakosti izolatorja s tremi rebri, a z modro barvo električna poljska jakost obstoječega izolatorja. V notranjosti izolatorja ni velikih razlik (slike 24.5a, 5b in 5c). Na slikah 24.5d in 24.5e so vrednosti električnega polja približno enake s to razliko, da je električno polje boljše porazdeljeno pri obstoječem izolatorju. Na sliki 24.5f so male razlike v vrednosti električnega polja.



Slika 24.4: Električna poljska jakost izolatorja s tremi rebri

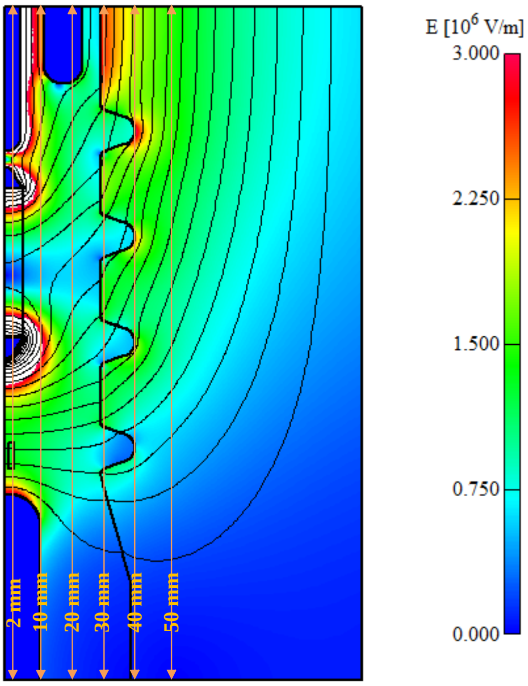


Slika 24.5: Primerjava vrednosti električne poljske jakosti obstoječega izolatorja (modra linija) in izolatorja s tremi rebri (rumena linija) na različnih oddaljenosti od sredine izolatorja

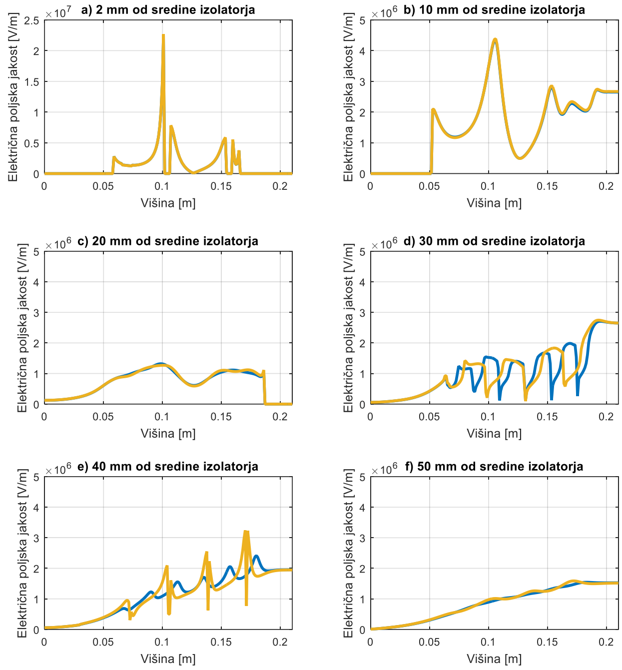
Slika 24.6 prikazuje izris električne poljske jakosti izolatorja s štirimi rebri. Slika 24.7 prikazuje primerjavo električne poljske jakosti obstoječega izolatorja in izolatorja s štirimi rebri na različnih oddaljenosti od sredine izolatorja. Podobno kot pri primeru izolatorja s tremi rebri niso prisotne velike razlike v notranjosti izolatorja (slike 24.7a, 24.7b in 24.7c). Tudi v tem primeru je električno polje boljše porazdeljeno pri obstoječem izolatorju (sliki 24.7d in 24.7e).

3.2 Model izolatorja z večjim številom reber

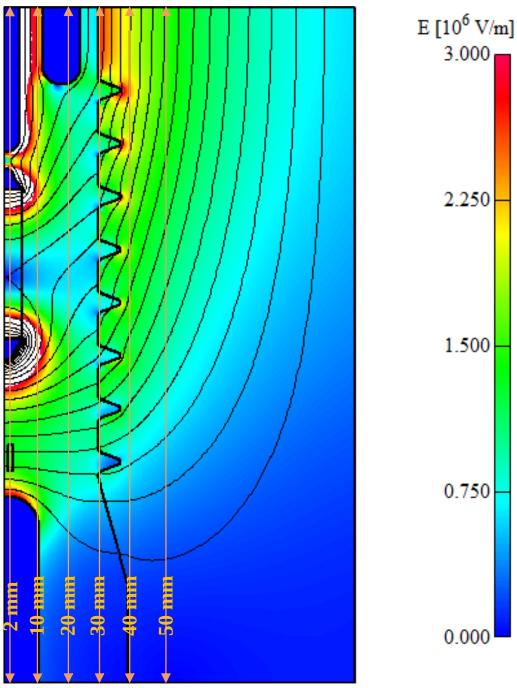
Prikazali bomo izolator z osmimi rebri in desetimi rebri, ter preverili kako ta sprememba vpliva na porazdelitev električnega polja. Izris električne poljske jakosti izolatorja z osmimi rebri je prikazan na sliki 24.8, a izolatorja z desetimi rebri na sliki 24.9. Slika 24.10 prikazuje primerjavo električne poljske jakosti izolatorja z osmimi rebri in obstoječega izolatorja. Slika 24.11 prikazuje primerjavo električne poljske jakosti izolatorja z desetimi rebri in obstoječega izolatorja.



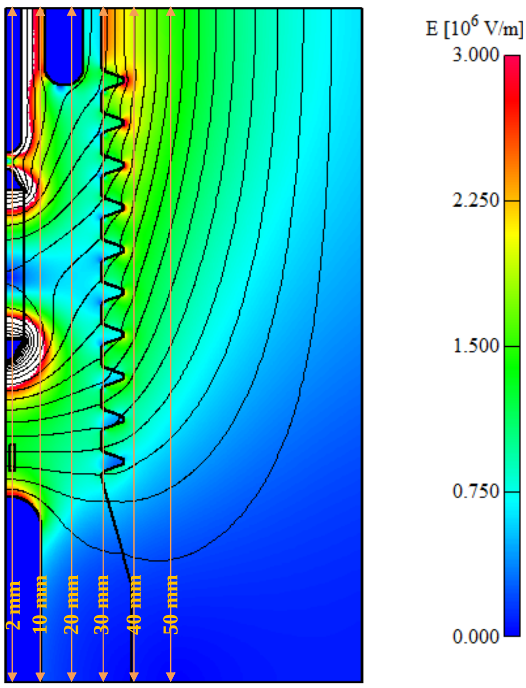
Slika 24.6: Električna poljska jakost izolatorja s štirimi rebri



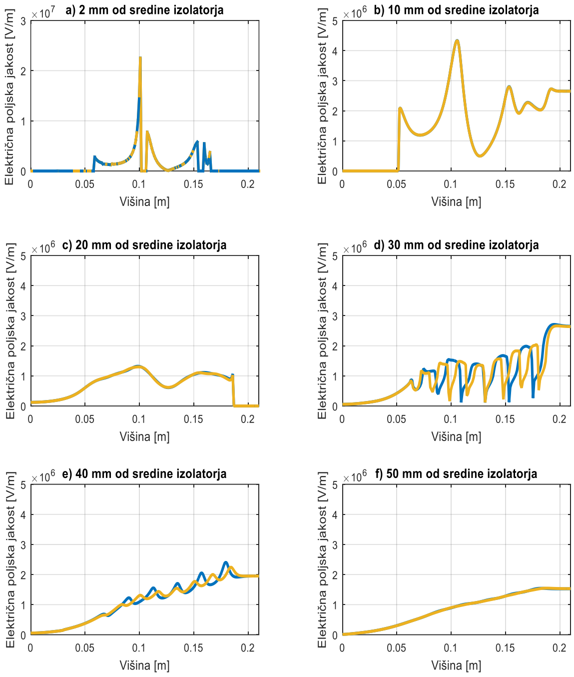
Slika 24.7: Primerjava vrednosti električne poljske jakosti obstoječega izolatorja (modra linija) in izolatorja s štirimi rebri (rumena linija) na različnih oddaljenosti od sredine izolatorja



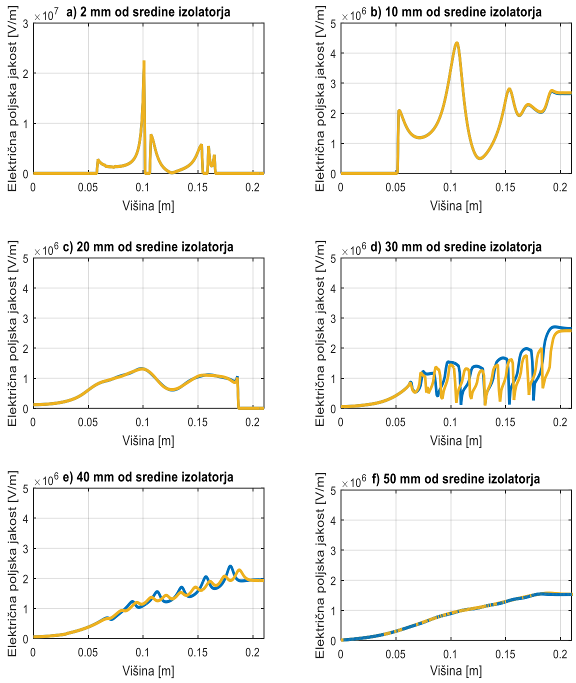
Slika 24.8: Električna poljska jakost izolatorja z osmimi rebri



Slika 24.9: Električna poljska jakost izolatorja z desetimi rebri



Slika 24.10: Primerjava vrednosti električne poljske jakosti obstoječega izolatorja (modra linija) in izolatorja z osmimi rebri (rumena linija) na različnih oddaljenosti od sredine izolatorja



Slika 24.11: Primerjava vrednosti električne poljske jakosti obstoječega izolatorja (modra linija) in izolatorja z desetimi (rumena linija) na različnih oddaljenosti od sredine izolatorja

Pri izolatorju z osmimi rebri niso prisotne velike razlike v notranjosti izolatorja (slike 24.10a, 24.10b in 24.10c). V primerjavi z obstoječim izolatorja je električna poljska jakost boljše porazdeljena pri izolatorju z osmimi rebri (slika 24.10d). Pri izolatorju z desetimi rebri niso prisotne razlike znotraj izolatorja (slike 24.11a, 24.11b in 24.11c). V najbolj obremenjenem področju (slika11d) so vrednosti električne poljske jakosti nekoliko manjše in je električno polje boljše razporejeno kot je to pri obstoječem izolatorju.

4 Sklep

V članku je opisan srednjenapetostni podporni izolator za notranjo montažo z obstoječim številom reber ter vpliv števila reber na električno poljsko jakost izolatorja.

Narejeni so primeri izolatorja z manjšim številom reber in z večjim številom reber ter so vrednosti električne poljske jakosti primerjane z obstoječim izolatorjem.

Po dobljenih rezultatih lahko zaključimo, da so razlike v vrednosti električnega polja pri izolatorju z manjšim ali večji številom reber male ali zanemarljive v primerjavi z obstoječim izolatorjem. Porazdelitev električne poljske jakosti je boljša pri izolatorjih z večjim številom reber v primerjavi z obstoječim izolatorjem. Pri izdelavi izolatorja z manjšim številom reber lahko poenostavimo proizvodnjo in zmanjšamo izmet. Pri izolatorjih z večjim številom reber, zaradi boljše porazdelitve električnega polja zmanjšamo naprezanje okolice izolatorja, kar ugodno vpliva na porazdelitev električne poljske jakosti v stikalni celici.

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