Overview of DFIG-Based Wind Turbine Systems in Europe

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Doubly-Fed Induction Generators (DFIGs) when used in Wind Turbine Systems (WTS), are typically sized within the 1.5 to 6 MW power range. Currently, DFIG-based systems hold a significant position in the global market, and they are expected to experience substantial growth by 2030.

DOI
https://doi.org/10.18690/um.feri.4.2025.20

ISBN
978-961-286-986-1

Keywords:
wind turbine systems (WTSs), WTS developments, doubly-fed induction, generators (DFIGs), DFIG-based WTSs, DFIG characteristics

University of Maribor Press

I Introduction

According to Eurostat's 2023 electricity production, consumption, and market overview [1], the shares of net electrical energy generation for the EU in 2021 were: Combustible fuels 41.9 %, nuclear 25 %, wind 13.7 %, hydro 13.3 %, solar 5.8 %, and others 0.3 %. Comparing these statistics with those of 2011 reveals that Renewable Energy Sources (RESs) have experienced significant growth from 2011 to 2021, rising from 19.5 % to 33 %. Furthermore, the Ten-Year Network Development Plan (TYNDP) 2020 [2], a joint scenario report by ENTSO-E and ENTSOG, predicts that wind will cover 29 % of the electricity generation by 2030, and this number is expected to increase to 41 % by 2040. However, RESs generally have variable and uncertain natures. They also pose challenges to the stability and reliability of the grids [3]. Therefore, wind and pumped-hydro power plants mostly use variable speed generators (VSGs) that are connected to the grid mainly through Power Converters (PCs) to allow for voltage and frequency control. This abstract focuses on the most commonly used and commercially available features of DFIG-based systems when used as VSGs in WTSs.

II Wind Turbine system developments

European Wind Industry: Europe has always been a pioneer in moving towards clean energy. According to a report, the Wind Energy in Europe, published in 2023 [4], a total of 255 GW of wind power capacity was installed in Europe by 2022, 88 % of this is onshore and 12 % is offshore. Germany maintains Europe's largest installed wind power fleet, with over 66 GW of installed capacity. Alongside Germany, Spain (30 GW), the UK (29 GW), France (21 GW), Sweden (15 GW), and Turkey (12 GW) collectively contribute to two-thirds of the total installed capacity in Europe. Exact statistics on the contribution of different generator types may not be available, but clearly, DFIGs hold a market share of approximately 50 % for electricity production within WTSs. The most important European manufacturers that supply DFIG products are ABB, VEM Motors, and Vestas. Additionally, some non-European companies support the European market, such as CRRC, GE, Shandong Huali Motor, and TD Power Systems [5].

Manufacturing Evolution: Until around 1998, most manufacturers constructed Constant-Speed Systems (CSSs) with a power range below 1.5 MW. They utilized a three-stage gearbox and a standard squirrel-cage induction generator directly connected to the grid. After 1998, many manufacturers began producing Variable-Speed Systems (VSSs) with DFIGs to meet the new grid requirements. Around 2005, several alternative VSSs were proposed. In these systems, BrushLess (BL) generators come with a gearbox and a fully rated PC [6]. In the meantime, due to the decreasing costs of power electronics components and permanent magnet materials, Direct-Drive (DD) systems have been developed [7]. In these systems, permanent magnet or electrically-excited synchronous generators are combined with a fully rated PC on the stator side, and the gearbox is eliminated to reduce the likelihood of failures and maintenance problems.

Comparison of Different Wind Turbine Systems: Table I, as presented in [6] and further amended here, provides an overview of the strengths and weaknesses of the DFIG-based systems compared to other WTSs. VSSs enable operation across a wider range of wind speeds to capture greater kinetic energy from the wind. Generally, the high-speed generators are slightly more efficient than the low-speed DD generators, although gearbox losses cannot be ignored. Additionally, the partially rated PC used in DFIG-based systems has lower losses than the fully rated PC used in DD and BL systems.

Table 1: Comparison of different wind turbine systems Strengths (+), Neutral (0), Weaknesses (-)

		Wind Turbine Systems			
		CS	DFIG	BL	DD
Energy Yield	Generator Type	+	+	+/-	-
	Mechanical Components	-	-	-	+
	Power Converter	+	0	-	-
Reliability and Maintenance	Complexity	+	-	-	-
	Mechanical Loads	-	+	+	+
	Brushes	+	-	+	+/-
	Gearbox	-	-	-	+
Voltage & Frequency Control		-	0	+	+
Operation at Different Frequencies		-	-	+	+
Grid Faults	Fault Detection	+	-	-	-
	Fault Ride-Through	+	0	+	+
	Post-Fault Recovery	-	0	+	+
Cost, Size and Weight		+	0	-	-

The reliability and maintenance of a WTS are affected by different factors such as complexity, mechanical loads, brushes, and gearbox. VSSs with more components are generally less reliable than simpler CSSs. On the other hand, VSSs primarily use pitch control [8], which involves adjusting the blades' angle to regulate the mechanical load on their components during high-speed winds. Brushes in DFIG-based systems require regular replacement, and gearbox failures may occur. These drawbacks have limited their offshore applications, where maintenance costs are considerably high.

Considerations regarding grid faults include fault detection, fault ride-through, and post-fault recovery. Traditionally, a WTS could be disconnected during a fault and reconnected after the fault has been cleared. However, as per new grid requirements, it must remain connected during faults [9]. Grid faults are typically identified by large fault currents. PCs used in VSSs do not permit currents larger than 10 to 20 % of their rating, which affects fault detection. A standard DFIG-based system with a partially rated PC may not fulfil the grid fault ride-through requirements. Additional equipment is required to ensure compliance. Potential solutions include advanced control strategies, implementing a crowbar short-circuiting the rotor windings, and sometimes utilizing additional resistances [6]. The contribution of the DFIG-based system to supply active and reactive power for frequency and voltage recovery after the fault depends on the solution chosen.

Generally, DFIG-based systems have simple and robust constructions and smaller sizes, weights, and costs compared to other categories with fully rated PCs.

III DFIG-based system characteristics

In a DFIG, the stator winding is directly connected to the grid and operates at nearly constant voltage and frequency. The rotor winding is supplied by a partially rated PC, which provides the machine with variable voltage and frequency. Control over the torque, active power, and reactive power through the rotor and stator is achieved by adjusting the amplitude, frequency, and phase of the voltage applied to the rotor. Most manufacturers adjust the synchronous speed to be in the middle of the variable speed range. This allows the DFIG to operate at sub-synchronous speeds, where the generator receives power through the rotor, as well as super-synchronous speeds, where the generator delivers power through the rotor.

Power Range: For WTS applications, DFIGs have been developed for a wide power range, spanning from several kW to over 10 MW. However, below 1.5 MW, the use of DFIGs is often not justifiable in terms of cost versus performance compared to other categories [10]. Additionally, manufacturers typically do not employ DFIGs in power greater than 6 MW [11]. Some of the most commonly installed DFIGs include Acciona AW-100/3000 (3 MW), Gamesa G83-2.0 (2 MW), and Vestas V80-2.0 (2 MW). In 2023, DFIG systems with power capacities of 2.2, 3.2, and 3.6 MW dominated the market share [5]. In the concept of DFIG-based systems, the rated power corresponds to the total power that can be generated by both the stator and the rotor. This occurs at the maximum allowable slip s at super-synchronism, typically equal to -0.25 or -0.3. When neglecting losses, the rotor power equals the stator power multiplied by this maximum slip ($P_r = -s_{max} P_s$).

Power Converter: DFIG-based systems commonly employ standard back-to-back PCs consisting of a Grid-Side Converter (GSC) and a Rotor-Side Converter (RSC) that share the DC bus. Most manufacturers use two-level converters with standard IGBTs to reduce costs for the 1.5 to 3 MW power range. However, for higher power ranges, three-level converters are expected to be the preferred option [11]. The sizing of both converters differs depending on the strategy chosen for magnetizing the machine. If the machine is magnetized from the rotor (over-excitation), the RSC must be sized to deliver the quadrature torque component and the direct magnetizing current, which is typically around 30 % of the nominal current of the machine. The GSC only needs to deliver the active current component. This strategy is primarily selected when the stator needs to operate at the unity power factor. If the machine is magnetized from the stator (under-excitation), the RSC must be sized to deliver the quadrature torque component. The GSC only needs to deliver the active current and the reactive current components [8].

Voltage level: For DFIGs with typical power capacities, low voltage (such as 400, 690, or 900 V) stator windings can be used. The typical ratio between the rotor and the stator-rated voltages, denoted as k, is within the range of 2.6 to 3.3. Therefore, the rotor winding should be designed for a medium voltage. The rotor-rated voltage is reached at a standstill ($s = 1$). However, DFIGs typically operate near synchronous speed; hence, the maximum rotor voltage at s_{max} is typically less than a third of its rated voltage ($U_{r\text{-}max} = s_{max} U_{r\text{-}rated}$). Thus, the rotor-side PC can be scaled down. For instance, with the most common stator-rated voltage, 690 V, and $k = 2.6$, the rotor-rated voltage would be 1794 V. With s_{max} = -0.3, the maximum rotor voltage would be 598 V, which is the maximum available voltage for the RSC. Furthermore, the GSC would require a transformer to be connected to the 690 V grid. It is worth mentioning that for the power range from 1.5 to 4 MW, the same voltage as the stator-rated voltage may be chosen for the maximum rotor voltage at s_{max}. Then, no transformer is needed to match the GSC to the power grid voltage. For this purpose, k can be chosen as $1/s_{max}$. However, for higher powers, it may be more practical to use a transformer on the grid side [10].

Acknowledgements

This work has been supported by the Austrian Science Fund (FWF) under Grant-DOI 10.55776/I6250 and by the Slovenian Research and Innovation Agency (ARIS) under project no. J2-4475.

[12] has been used to enhance the grammar and editing of the text. However, it has not been used to generate content.

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