Water Turbine Hydraulic Regulating System and Modifications To Meet Grid Stability Requirements

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Over the past three decades, the hydropower sector has seen major technological advancements, driven by rising global electricity demand, increasing energy prices, and growing awareness of the environmental impacts of conventional power generation. These factors have strengthened the role of renewable energy sources-particularly hydropower-in building sustainable energy systems with lower ecological footprints. Current research focuses on retrofitting and digitalizing existing hydropower infrastructure, developing next-generation hydro and aero-hydrodynamic technologies, and deploying hybrid systems integrated with advanced energy storage solutions. Given the inherent variability of renewable sources, high-capacity storage technologies are essential for enhancing grid stability, frequency regulation, and overall resilience. Furthermore, the development of advanced smart grid architectures is crucial to enable distributed, multi-nodal power generation, improve demand–supply balancing algorithms, and support the seamless integration of small and medium-scale energy producers. Together, these innovations aim to optimize energy efficiency, support decarbonization goals, and ensure a reliable and flexible power supply in the face of evolving energy needs and climate challenges.

Keywords:
water turbine,
hydraulic power unit,
design and operation,
design modifications,
grid stability

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1 Introduction

The beginning of utilization of hydro power for electricity production dates back almost 150 years. In this time, many types of water turbines in a very wide range of sizes were developed. Hydro power generating unit consist of water turbine, which converts energy of the water into rotation and generator, which converts rotation into electricity. Main parts of water turbine are runner (rotated by the flow of water), shaft (connecting the runner to generator) and distributor (carefully regulates the flow of water on to the runner from closed position to maximum discharge). These assemblies include all components necessary to run the units – load bearing structures, bearings, seals, mechanisms for power transmission, etc.

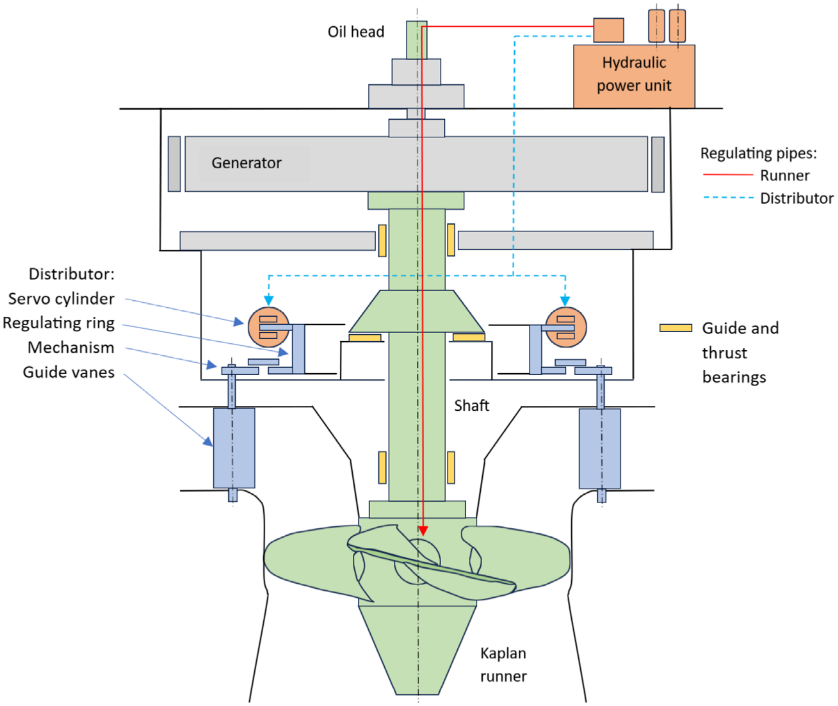

Figure 1: Typical Kaplan generating unit.

Source: own

Water turbines can achieve impressive efficiency. Up to 96 % of water energy can be converted into rotation of the unit (various mechanical and electrical losses decrease effacing of the whole unit). To reach such values, each water turbine and generator must be carefully adopted to specific hydraulic conditions. Available head and flow of the river are the most contributing factors.

Main classification of hydraulic units is based on the type of runner installed:

- Kaplan runner is designed to be regulated together with distributor which is suitable for low head and large discharge hydropower plants (HPP). Double regulation allows high efficiency in a wider operation range which is necessary to utilize all water level fluctuations at low head.
- Francis runner is designed with fixed blades, compete regulation is performed only with distributor. These units can cover the largest range of heads and discharges. Such runners are less expansive to manufacture and do not need a regulating system. Narrower operating range is acceptable due to lesser influence of the head fluctuation.
- Pelton type of water turbine is fundamentally different to Kaplan and Francis in mechanical design and physical principles that govern energy transformation. Open water jet is used to power the runner (impulse turbine). Such units are suitable for the highest heads and small discharges. In comparison, Kaplan and Francis are a reaction type turbines, where runner is encased into sealed water passage connecting upstream and downstream water level. Pressure, kinetic and potential energy of the water are being transformed inside the passage to achieve optimal conditions to power the runner.

Figure 2: Kaplan, Francis and Pelton runners.
Source: own

Main design variations of the units, in addition to runner selection, include vertical or horizontal main shaft, main shaft bearing arrangement (1 thrust and typically 2 or 3 guide bearings with different locations in relation to generator), distributor type (cylindrical or spherical), water passage design (steel liner or concrete, bulb, open pit, etc.). Design influencing factors are natural conditions of HPP location, quality vs. cost, maintenance requirements, limitation of transportation to HPP locations, etc.

Generating units are equipped with auxiliary systems which enable their operation and typically include hydraulic regulation, lubrication, cooling and drainage systems.

2 Turbine regulating system

Turbine regulating system has a function of starting, regulating and stopping the unit. It also performs a safety function (shut down or "speed no load" operation) in case of turbine and generator faults. Kaplan and Francis turbine regulating systems have similar basic design. Major difference is that a complete section for runner regulation is not necessary for Francis turbine. Regulating system is divided into mechanical assemblies (distributor and runner) and hydraulic power unit which are discussed in the next chapters and various electrical control systems.

HPP are, in addition to the generating units, equipped with other systems which are also typically operated by hydraulic power units (HPU) such as turbine inlet valves, water passage gate mechanisms, trash rack cleaning machines, etc.

2.1 Distributor

Main parts of distributor are hydraulically shaped guide vanes arranged in circumference around the runner (typically 16, 20 or 24 pieces). Their purposes are:

- Close the water passage, stop the flow of water on to the runner and stop the unit (normal stop or emergency)
- Regulate and assure optimal water flow to the runner while unit is operating

Each guide vane is connected through a linkage mechanism to a common regulating ring which is rotated by hydraulic servo cylinders. Depending on the size and type of units 1 or 2 cylinders are installed. Varus layouts are possible (parallel on each side of the unit, rotated by 180°, located on inner or outer diameter of regulating ring) which influence the oil requirement for movement, regulating force and dimensions.

Distributor is equipped with locks for closed position (automatic) and open position (typically mechanical) for safety and maintenance reasons. Locks can also be installed to servo cylinders which can simplify regulating ring design.

For specific units with horizontal shaft a closing weight can be installed to assure closing in case of HPU failure (larger size turbines with no possibility of safety turbine inlet valve). Most units have vertical shaft where weight cannot be installed (direction of gravitational force is perpendicular to regulating ring movement).

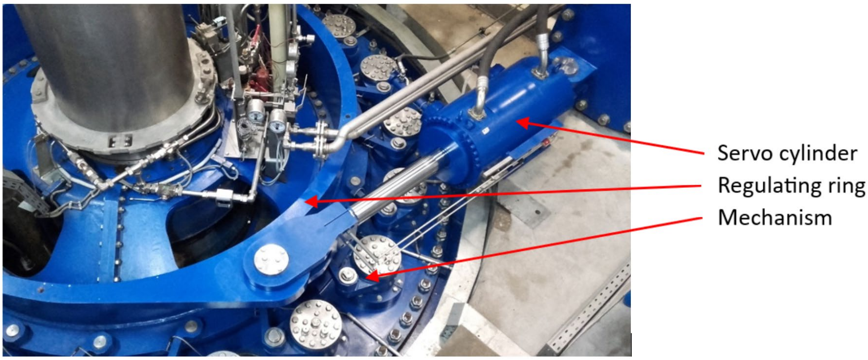

Figure 3: Distributor.
Source: own

2.2 Kaplan runner, oil head and pipes in shaft

Kaplan runner blades are regulated by servo cylinder integrated into the runner hub. Cylinder and blades are connected through a linkage mechanism. Complete assembly is carefully designed to fit inside a narrow hub where access and maintenance possibilities are very limited and operate in harsh conditions completely submerged into water passage. Operational life is typically minimum 40 years.

Regulation of blades is arranged with hydraulic power unit located in the powerhouse (15+ meters above runner), through oil head (special assembly connecting stationary pipes and rotating shaft) and special pipes in shaft (connecting oil head and runner).

Oil head is located on the top of the generator and unit main shaft. It has many design challenges:

- It must maintain high regulating pressure with minimum leakage losses;
- It must sustain constant blade position for a long operating periods where oil flow is very low (only compensation of losses) and handle large flows in case of emergency where fast movement are required;
- Sealing between stationary and rotating parts is contact free. Minimum clearances are achieved by fitting one part to another which prevents repairs. Complete assembly must be replaced in case of damage.
- It must handle vibrations.

Pipes in shaft are specially designed section of hydraulic piping. Two pipes are installed, one into another, and both together inside a central hole of unit main shaft. Diameter of shaft hole varies depending on the size of the unit and is typically between 160 mm and 250 mm. Due to length of main shaft and site assembly limitation both pipes must be splitted into sections (up to 6 m long) with flange or thread connections. These connections are very critical:

- They must conform to tight space inside main shaft hole;
- Bolted flange connections cannot block the flow of oil (especially in emergency – large flows);
- Assembly is performed under difficult condition;
- They must maintain good sealing properties during the operational life time.

Inner pipe is connected to the moving part of the servo cylinder inside the runner (depending on design a piston or cylinder housing can move). Complete piping assembly must be straight over the complete length and allow free movement which enables runner blade position feedback. Position is monitored at the oil head.

Shaft hole and two pipes form three channels. Two are used for runner regulation, third one is used to fill (or drain) the runner hub with oil or water (ECO runners). Top of the rotating shaft is designed to allow drainage of fluid away from the shaft and generator.

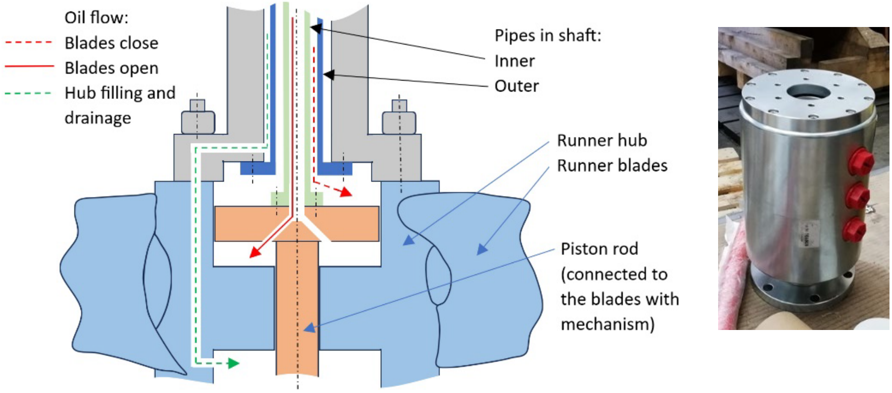

Figure 4: Kaplan runner with integrated servo cylinder and pipes in shaft, oil head (right).
Source: own

Runner, oil head and pipes in shaft have in recent decades undergone significant design changes driven by increasing oil regulating pressure. Level was slowly raised from 20 bar to 40 bar and 60 bar and recently quickly to 130 bar and even 160 bar which has downsized the equipment, allowed for cylinder placement change inside runner hub (from top to bottom), influenced oil head leakage, etc.

2.3 Hydraulic power unit (HPU)

Hydraulic power unit has a function of suppling pressurized oil for turbine regulation. All operational regimes, especially safety functions, must be considered in design (they are presented in the next section). Basic design and operational requirements are always similar but final solution can be significantly adjusted for each Customer. Main driving factors are price, working pressure level and safety requirements.

HPU is a complex assembly. Typical main pars are:

- Oil sump tank
- Variable displacement piston pump with electric motor – 2x
  - Main pumps for pressurizing accumulator station, which then supplies the oil for regulation.

  - Primary pump is working permanently, second is stand by, priority changed periodically for reliability and equal wear.
  - Pumps are activated in predetermined sequence to compensate consumed oil (at first low pressure point main pump is regulated to increase discharge, at second low point stand by pump is activated).
- Accumulator station
  - Source of pressurized oil for the system.
  - Size determined based on safety requirements – number of cylinders strokes in case of system fail (typically 3 strokes before minimum pressure is reached).
  - Typical arrangement with piston and nitrogen bottles or bladder type.
- Main regulation valves used during normal turbine operation
  - Servo proportional directional valve – 2x
  - One valve for runner, second for distributor regulation
  - Pilot operated for larger units
- Emergency shut down valve system
  - Fault signal triggers a sequence which isolates both main proportional valves and opens cartage valves which allow higher oil flow to distributor and quick stopping of the unit
  - Solenoid directional control valves activated by fault signal – 2x
  - Hydraulically actuated cartridge valves for isolation of both main proportional valves – 2+2x
  - Hydraulically actuated cartridge valves for oil supply during emergency shut down – high flow – 2x
  - During emergency shut down distributor is closed and runner remains in the current position
- Manual control for maintenance purposes
  - Guide vane and runner blade position is manually set to required opening and blocked to prevent unvented movement during maintenance works
  - Main proportional valves are isolated with cartage valves (the same as used for emergency stop)
  - Solenoid directional control valves, separate for distributor and runner – 2x
  - Manual isolation valves with lock – 2+2x

- Filtration loop unit – continues operation
- Cooling loop unit
- Oil head minimum pressure requirement
    - Modern oil head solutions suitable for high pressures are designed with minimal clearances between rotating and stationary parts. Constant minimal pressure (typically 5 bar) is mandatory to prevent seizure.
    - Pressure regulating valve with check valves for each flow direction
    - Isolation valve for unit standstill

HPU is equipped with all necessary parts for safe operation inside designed parameters, continues system monitoring and alarm or emergency shut down signaling (safety valves – for each pump and accumulator station section, temperature, pressure, flow and level transmitters and switches, shut off valves for maintenance, additional high pressure filters after each main pump, oil heater arrangement, etc.).

HPU is designed to be operated automatically. Electrical signals for valve actuation are received from digital turbine regulator. Runner and distributor opening feedback signals are continually monitored by independent linear transmitters and compared to the input signals to assure correct position.

Figure 5: Hydraulic power unit.

Source: own

3 Hydro generating unit operating regimes

Hydro generating unit has three basic operating regimes – normal operation, emergency shut down and load rejection.

3.1 Normal operation (start up, power regulation and shut down)

Starting procedure can begin when turbine, generator and all auxiliary systems are ready which is confirmed by a number of signals (pumps on; oil, pressure, temperature levels OK, filters not clogged, safety element OK, distributor lock OFF, hydrostatic bearing lubrication ON, water passage gates removed, etc.).

HPU begins opening of runner and distributor proportional valves which releases water flow on to runner blades at which point the unit starts rotating. At approx. 15 % opening "speed no load" point is reached and unit is ready for synchronization with the electrical grid. This is the most critical sequence during which the unit must quickly increase the power output to desired value inside the operational limits while all the time maintaining nominal speed and grid frequency. Maximum output can typically be reached in approx. 15 sek.

During normal operation the unit power output can be regulated. These actions are also performed by actuation of both proportional valves. Runner and distributor positions are carefully matched across the entire opening range to assure optimal hydraulic conditions at any point. This is referred as on-CAM operation.

Normal shut down procedure is as well carried out by proportional valves. During this sequence the distributor will close and stop the water flow and power generation. Runner typically remains submerged in the trapped standing water inside the water passage (depending on the height difference between runner centerline and level of the water at the HPP outlet – tail water level). Due to high weight and inertia of rotating parts the runner is moved into open position where turbulent mixing of trapped water creates braking effect which significantly reduces the time until unit reaches stand still.

Distributor servo cylinder is designed to dampen the last ~20% of the stroke to prevent water hammer effect in the power plant water passage. Fast initial closing time is approx. 4 sek, complete closing time is approx. 15 sek.

3.2 Emergency shut down

Emergency shut down can be triggered by a number of different faults on the unit, its systems or even inside complete HPP and results in the unit being stopped. Main proportional valves are immediately isolated which leaves the runner in its current position while pressurized oil for distributor closing is supplied trough two separate high flow cartridge valves.

3.3 Load rejection

Load rejection is triggered by a sudden loss of generator load and results in unit rotating at nominal speed with no load (speed no load). Runner and distributor are both closed trough main proportional valves until they reach "speed no load" point. If no other faults are signalled the unit can be quickly restarted. Load rejection can occur during start up (unsuccessful synchronization with grid) or during normal operation.

4 Electric grid regulation requirements

Hydro generating units are typically connected to country's electric grid to which it must strictly conform during operation. The main challenge of ensuring stable grid is to continually and very accurately balance the power demand with production from various sources with very different characteristics while all the time maintaining grid frequency inside a narrow tolerance.

Demand for electricity is constantly changing but the general daily trends are predictable. Traditional power generation sources are also very predictable and provide good balance between stable base production (nuclear, coal) and required flexibility (hydro, gas). All these power plants have an additional advantage of large inertia which provides resistance against rapid power balance changes and aids in grid stability efforts.

Solar and wind power plants are in comparison unpredictable both in time and amount of electricity generation. In addition, the inertia of these systems is extremely low. As a result, these power plants are causing disturbances in the grid and make them more unstable. With very fast implementation of such projects and decommissioning of nuclear and coal plants their share in energy mix is increasing and so are the challenges.

Hydro power plants positively address many of these topics. Electricity produced is green without emissions and renewable, operation can be regulated and they have good inertia. Their impact on the installed location is however large which has in recent times stopped or delayed many new projects. Despite some of the impacts, like flood prevention, being very positive. In more developed countries majority of the river potential is already utilized and the focus is on the modernization of existing equipment which is between 40 and 60 years old.

Since hydro equipment is built for long service life the requirements for more flexible operation first started affecting existing units which were not designed for such load cycles. As a result, equipment started failing. New and newly modernized existing turbines are designed considering new load cases, but due to the nature of equipment which can only be tested when fully assembled at site, and many new additional design upgrades (self-lubricating bearings in mechanism linkages, oil free ECO Kaplan runners, etc.) the development path exposed new unexpected technical challenges.

5 Turbine design considerations to meet grid stability requirements

Due to large verity of turbine types and sizes and locations of installation with specific local needs the operation was always diverse. But typical low head Kaplan double regulating units were operated in a steady regime with few starts and stops and small number of adjustments to power output. It was common to set it to current river flow conditions and operate in best efficiency point for longer durations. During such operation the hydraulic loads are uniform and changes are gradual with small impact.

5.1 Load cycles

Higher flexibility requirements significantly increased the number of start-stop cycles and power adjustments necessary to respond to larger power fluctuations and even more importantly, highly increased the number of micro adjustments for maintaining grid stability (commonly referred as primary frequency control – PFC).

Older units which were first subjected to such loads without any modifications started experiencing mechanical failures. This was due to not being designed for such cases, lower quality materials (general purpose castings), not developed non-destructive testing (NDT) methods to check material quality and looser tolerances. The most common fault was braking of the linkage parts of runner blade mechanism where design compromises must be made due to tight space.

In modern turbines all these areas were already improved due to natural engineering and manufacturing advances. The biggest challenge remained due to micro position adjustments – how to determine and evaluate their actual load cycles and effect on bearings and seals. Finite element method (FEM) analysis has greatly improved, moving from individual parts to full assembly evaluation with more accurate loads and boundary conditions specification and including prediction of equipment lifetime.

Runner hub sizes have also reduced allowing higher water discharges and increased power outputs. This has additionally compacted and complicated mechanism design.

5.2 Bearings

Bearing (and partly seal) behaviour was significantly impacted by new strict environmental regulations. Runner hubs with complete mechanism were traditionally filled with oil which ensured optimal lubrication. Since this creates risk for river water pollution (protected only by one set of seals which are very difficult to maintain and replace) a modern oil free ECO runner was developed. Hub is in this case empty (dry) or water filled, which has a negative effect on the friction during mechanism movement.

In ECO runners, traditional bronze bearings were replaced by self-lubricating bearings (solid lubricant forms part of the base material) of different designs – sintered bronze with graphite of PTFE (approx. 10 %) or complete composite design (filament wound of casted). For some designs it was determined only after the turbine was put in operation that bearings are not suitable and need to be redesigned and replaced which created extreme costs and long unit shut down periods. The most critical example are PTFE bearings where it was established that damp environment significantly raises the friction, in many cases beyond the capacity of regulating system.

Despite great improvements and some clear advantages (example: reduced edge pressure) the self-lubricating bearings result in higher friction compared to oil filled runner design. For PFC regulation it was established that micro movements suffer from stick slip effect since solid embedded lubricant need certain minimum movement lengths to be fully effective.

Interestingly some Customers have recently started switching back to bronze bearings lubricated by oil for the new runners. This is another example of diversification of the hydro industry and that individual Customer experiences and good practices are the main driver for their decisions.

5.3 Deadband

Deadband represents the length of servo cylinder stroke before movement is observed on runner blade or guide vane when direction of travel is changed. Because of the requirements for precise positioning and frequent micro movements for adjustment the deadband must be minimized. Typical target specified in recent technical specifications is 0.1 % of servo cylinder stroke which amounts to 0.6 mm at average stroke of 600 mm.

This value is low considering the number of parts and bearings in runner and especially distributor mechanism. Distributor with 24 guide vanes is equipped with 120 bearings (3x for each guide vane and 2x for each link connection) ranging from 50 mm to 220 mm with fit tolerance H8/f7, where individual clearances can reach up to 0.1 mm. Regulating ring radial bearing diameter typically ranges between 3 m and 6 m and has a clearance between 0.3 mm and 1 mm.

When complete assembly is evened out the dead band value typical slightly exceeds the new requirements. The issue is also that standard bearing tolerances in worst case allow for higher unacceptable deviation and that the actual value can only be confirmed once the unit is assembled on site. Modifications at that point are extremely difficult, costly and will result in long project delays.

Since the requirement for lower deadband is relatively new the modifications are not yet matured and are not part of the standard design principles. It is however certain that the target will not be achieved without bigger changes.

One known and proven solution used in hydro industry is to replace the standard fit tolerance with final machining of one part, based on exact measured diameter of counterpart. Diameter of bearing counterpart would be determined based on minimum technically allowed clearance. This process is used occasionally and for smaller parts which are easy to handle. Due to the high number and large size of the parts and the difficulty of positioning them on the machines to perform additional final step, such technological procedure will significantly raise project costs and extend the timelines.

6 Conclusions

Ensuring grid stability will continue to be a challenge. Modern electric control systems are capable of processing large amount of information and quickly respond with adjustment signals. Hydraulic power units and especially main servo proportional valves have also developed and offer high frequency response.

The main issue remains to be runner and especial distributor assemblies. Big number of large and heavy parts crate deadband regardless of very tight machining tolerances (example: 1 ton guide vane bearing surfaces run-out is inside 0.02 mm). Further reduction of bearing clearances is technically possible but in practice difficult and expensive to achieve. Additional consideration is the negative effect of new load cycles on the turbine equipment and especially bearings.

Therefore, it is worth reviewing if water turbines should be utilized for primary frequency control operation or at least limit the required micro adjustments to the technically acceptable level. Rapidly developing battery storage systems offer an elegant solution which could solve the issue electronically instead of mechanically.