AUTOMATIC CONTROL FOR HYDROELECTRIC POWER PLANTS

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Contents

Summary

Water and energy are essential elements of humanity's life and civilization, and hydropower relates to both. It contributes to harnessing waterflow in hydrological or river systems, thus alleviating floods and droughts, and it allows sustainable and clean power production and distribution, which is easily adaptable to changing demand. It has ecological effects to be considered as well.

This article discusses first the operational similarities and differences of hydropower production when compared with generation by thermal-power prime movers. Today's industry standards in control systems design and implementation are then outlined, with respect to safety systems, control algorithms, and hardware implementation. Here the rapid growth in computer technologies for process control has had a major impact. Recently, options or add-on functions to standards have been developed and tested for the specific needs of particular classes of hydropower system. They are now available for routine use, and are described here as "advanced control features." An outlook on the perspectives and driving forces for hydropower control concludes the article.

1. Introduction

The aim of the article is to show the similarities and differences in the operational characteristics of hydropower plants when compared with power generation by other widely used prime movers, such as steam or gas turbines and diesel engines. This will clarify the need for particular hydropower control functions.

From the power system perspective, the following configurations must be distinguished:

- Operations connected to a very large ("infinite") bus. The unit delivers to the grid a given power flow, which is set by a central load dispatch with no direct concern for frequency stabilization. This is typical of normal operation in Europe, for example.
- Operating in an isolated mode, that is in a single machine grid. Here the speed regulator continues to be active when the generator switch is closed. It balances unit power output to current power demand, using the local grid frequency as measure of the imbalance. In other words, the actual power output of the unit is a derived quantity and not freely selectable as with interconnected operations. This mode is widely used in rural areas with so called microhydro plants, and is also

often specified for local emergency power supply, if the tie line should fail.

- Operations connected to a small grid (of typically 10 machines or less), where each machine has a significant influence on the grid frequency, and thus each machine has to contribute to frequency control by manipulating its power output. This is typical of small regional grids when tie lines fail.

The “normal” operation sequence and the associated control tasks for units with synchronous generators also apply to hydropower units:

- standstill
- run-up
- stabilization at grid frequency (speed control at no load)
- synchronization and switch-in to interconnected operation mode
- power output control, load swings with constraints (see below)
- unloading and switch-out to speed/no-load mode
- or, as a frequent case of “non-nominal” operation, trip (switch-out under load, speed increase and stabilization at nominal speed for re-synchronization); and
- shutdown: speed coast-down and final braking to standstill.

In one unit grid operation, the generator is switched to the local grid at standstill and runs up to the grid frequency during its run-up (“black-start”). There is no transfer to delivered power control mode; the unit will stay in speed control mode. Synchronization may be required at a large local load, if the connection to the interconnected grid becomes available again. (Note that there is no operational difference from the situation where the prime mover is, for example, a diesel engine.)

However hydropower exhibits a number of peculiarities, which lead to particular control tasks. The following presents an overview.

Hydropowerplants and inertia: A first significant difference from thermal plants is that the *inertia of the driving water column* is not negligible. The kinetic energy stored in the water column is comparable to the kinetic energy of the turbine/generator rotor. The main parameter is the water-column time constant T_w defined (in IEC standard 61362) as the ratio of twice the kinetic energy of the water column at rated flow and rated hydraulic power. Typical values of T_w are given for two plant types, which are shown in Figures 1 and 2.

High-head plant:

- conduit length L = 1000m
- area A = 1 m^2
- water speed w = 5 m/s, U_{kin} = 12.5 MWs
- head H = 500 m
- P = 25 MW
- T_w = 0.5s

Low-head plant:

- conduit length L = 20 m
- area A = 4 m^2
- water speed w = 5 m/s, U_{kin} = 1 MWs
- head H = 5 m
- P = 1 MW
- T_w = 1.0s

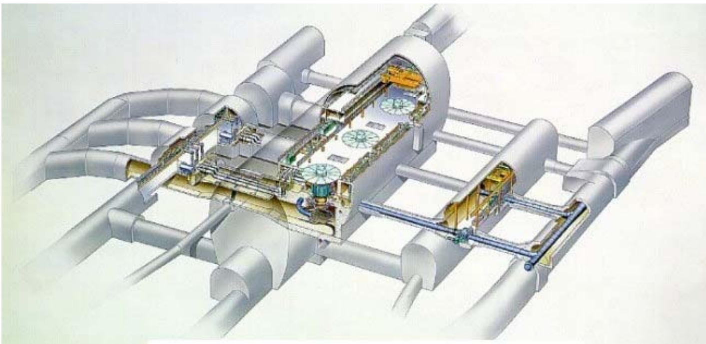

Figure 1. Typical high-head storage hydropower plant (schematic)

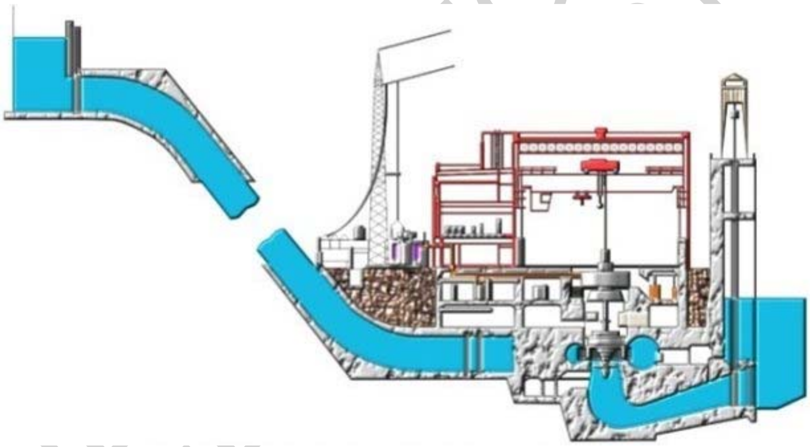

Figure 2. Typical low-head run-of-river hydropower plant (schematic)

This can be compared with the rotor time constant T_a, the ratio of the rated angular momentum of the rotor to the rated torque, with typical values of 1 … 5 s.

The water column inertia leads to so-called water hammer effects, which limit the admissible rate of flow changes, normally to about ±100% per minute.

Similar but much stronger constraints arise in thermal power plants, due to differential expansions and thermoshock, the limited load-following capability of steam generators, and similar factors, which normally impose constraints of the typical form: instantaneous load swing ≤ ±5%, long-term loading rate ≤ ±5% per minute.

Specific hydropower constraints: Hydropower plants are on the interface to a supply system with particular constraints (the fuel reservoir in thermal power plants is so large compared with rated fuel consumption, that it does not interfere with daily operations).

Hydroenergy storage, which is mass storage, is always bounded. It may be large in high-head storage plants in the mountains, but is small in low-head run-of-river plants, especially if level or flow variations are strongly constrained by fluvial navigation or for ecological reasons.

There are many cases where the flow is fully dictated by the hydrological system. Hydropower production must be less than, or at most equal to, what is offered from upstream, and any water that does not pass through the system has to be shed through weirs, compensators, outfalls, or other escape routes.

In any case the geographic site of the hydropower station is bound to the hydrological system, whereas thermal power stations can be more conveniently placed close to main consumption centers. Thus long transmission lines are often necessary, which may have adverse effects on grid stability, and need additional control equipment.

Reverse operation: A third unique feature is "reverse operation," which uses surplus electric power from the grid to refill the reservoir with large pumps or pump turbines.

Design differences: Depending on the head and flow offered by the hydrological system, water turbines and pumps vary widely in design and thus also in available control actuators (see Figures 1 and 2). The difference is much larger than for steam or gas turbines, which tend to be of standard sizes.

Actuating power: Hydraulic machines also require large actuating forces. Therefore high actuating power must be available during startup and load swings. For synchronization, isolated grid operation, and frequency control participation, the actuators must be positioned precisely in relation to large stiction and friction forces. However during steady-state operation of the unit, actuating power consumption tends to drop to a very small percentage. Finally, sufficient actuating energy must be stored for multiple black-starts. Therefore pressurized oil servo systems are used almost everywhere (see Section 4 for more details). Note that this may not apply in special cases, and for microhydropower, where control by ballast resistors on the electrical side is commonly used.

However, hydro power systems also have similarities to thermal power plants. For instance when the flow from the hydrological system is large, then several identical units are arranged for parallel operation within a power station. This generates many "joint control" tasks, such as unit scheduling, bumpless start and stop of units, total power or flow control, and best efficiency load distribution.

Another similarity is in control system structuring methods on the functional level. Two main approaches are used. The first is to distinguish separate subsystems within the hydropower plant, such as—for each unit—the main shutdown valve, the turbine, the generator, and the transformer, all with their associated auxiliary systems (lubrication, cooling, pressurized air supply, etc.) and their control systems (sensors, actuators, control algorithms, and both pressurized oil and DC power supplies). Thus one may consider all such "controlled subsystems" to be as autonomous as possible. They are linked by mass and energy flows on the plant level, and a restricted number of command and control signals, which coordinate the interaction of the subsystems from the next higher level. Note that in such cases the subsystems with their control systems become "objects" in the software/programming sense, which is very advantageous.

Experience has shown that this is a key factor for efficient and high-quality engineering. The second main approach is to distinguish common layers within each subsystem control unit and attribute each control function to one such layer. The common layers on the unit level are:

- the plant layer, with locally distributed sensors and actual flow modulating elements such as needles, wicket gate, and the like, and all cabling for supply and signals;
- the actuator drive layer: that is, the servomotors;
- the safety system layer, with flow-limiting orifices, closing weights, closing springs, emergency stop relays and oil valves, and so on (see Sections 2 and 4);
- the control system layer, containing the positioning control loops on the lowest sublayer, then speed and power or flow regulators with their associated logic functions on the second sublayer, and local sequence of unit operating states on the third sublayer (see Sections 3 and 5); and
- the communications layer, both to the local operating panel and to the next higher level at power station control (see Section 4).

Such structuring in layers is a key factor for control function standardization, good fit of add-on functions, reliable software, good management procedures for project implementation, transparent documentation, and serviceability.

The main ideas were developed for thermal power plants, and are also the basis of the standard "Power Station Designation System," which is a crucial element for efficient maintenance with minimum downtime.

2. Safety Systems for Hydropower Units

Hydropower plants traditionally have a well-established safety system (protection system). Its objective is to protect human beings, the plant equipment, and the environment from damage due to failure or malfunction. It also has to minimize production losses by avoiding secondary damage to equipment.

Faults may occur on the basic plant level (building, mechanical, and electric equipment), in the auxiliary equipment (e.g. lubrication oil system, cooling water system) or in the automation system (sensors, computers, electro-hydraulic converters, pressurized oil supply, etc.).

Safety systems will be activated to avoid or reduce damage. Barrages are monitored by separate systems for the regulatory agency. If the penstock should burst, for example from low cycle fatigue, then the automatic closing of the inlet gates at the reservoir outlet prevents flooding of the environment and limits secondary damage. (See Figure 3; note that there are two independent inlet gate systems in series.)

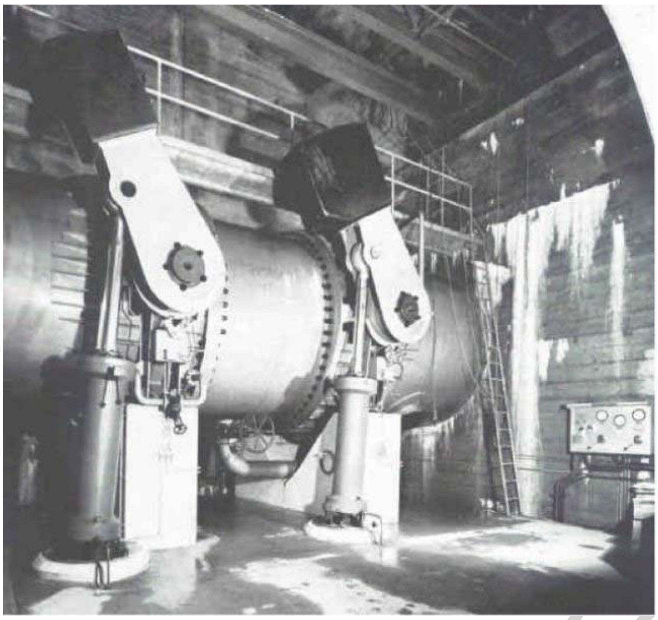

Figure 3. Two consecutive safety butterfly valves with closing weight at Biasca (Switzerland, 1956), diameter 3200 mm, design head 54m

The next subsystem along the waterflow is the hydroelectric unit. The main objective of the safety system is to shut it down, that is to shut down water flow (the power input to the unit) and reduce speed to a standstill.

In case this should fail, and to keep the rotor from failing, both turbine and generator rotors are traditionally designed to withstand prolonged runaway speed; for Pelton units this is 1.8 times nominal speed, for Francis units 2.0 times and for Kaplan units 2.8 times nominal speed.

This makes for a very heavy design. (Note that this is not a design criterion for steam or gas turbine rotors; they will normally fail at 1.2 times nominal speed, so a reliable system is even more important for them.)

To keep the rotor from runaway action and to stop the unit automatically, quickly, and safely, it is standard practice to use two fully independent systems: namely the turbine regulating mechanism (wicket gate, deflector/needle) and the safety shut-off valve (spherical valve, butterfly valve).

They have to be capable of blocking the maximum possible water flow through the turbine. They must also close as fast as possible in view of the maximum permissible water hammer in the penstock. This is implemented by passive means: orifices in the oil outlet of the servomotors.

For economic reasons, low-pressure turbines are not usually equipped with a safety shut-off valve, and the principle of two independent shut-off devices is not applied. In such cases specific additional devices are necessary, which are independent of the governor oil supply system, such as closing weights (see Figure 4), or an additional emergency pressure oil supply.

Figure 4. Modernized turbine control system (1986) at Burglauenen (Jungfraujoch-Bahn, Switzerland, four two jet Pelton units 1 MW each), left hand foreground: pressure oil subsystem, center: servomotor supporting the closing weight, actuating the two needles by the lever arrangement, right background: closing weight for the shutdown valve

In case of faults, the unit will be shut down automatically, initiated by two separate safety circuits.

Rapid shut-down: This is used when faults in the mechanical or electrical system of the unit occur. In case of mechanical failures, the tripping of the generator switch will be delayed until the system reaches a no-load condition so as to avoid a speed increase. Faults in the electrical subsystems will immediately trip the generator switch.

Emergency shut-down: This is activated if faults in the turbine control system occur, or in case of extreme overspeed or other major faults within the power station. The safety circuit acts directly on the separate emergency shut-down devices.

Operating experience over decades on a very large number of hydropower plants has demonstrated that they run for many years without being interrupted by turbine faults. Stoppages due to electrical causes (e.g. lightning) are more frequent. Major accidents are very rare, but have grave consequences.

Recently, when hydropower plants have been built or refurbished, they have usually been equipped not only for fully automatic, but also for unmanned and remotely controlled operation. Consequently, faults such as increased vibrations of the turbine-generator unit can no longer be detected and acted upon by on-site staff. It is therefore necessary to install monitoring and diagnosis systems that allow analysis of trends and early failure detection (see Section 5.4).

The basic prerequisites for undisturbed operation are and will always be professional maintenance of the plant equipment and periodic tests of the safety equipment, as specified by the supplier's instructions and based on strict quality-assurance management within the ISO 9000 framework.

3. Standard Control Algorithms

3.1. Basic Concepts

Generally, good control concepts are based on mathematical models for the dynamic response of the process to be controlled. To derive such models in form of differential equations, it is most helpful to structure the process into elementary subsystems of finite dimensions, each with a "content variable" (evenly distributed within the subsystem) and both "inflow(s)" and "outflow(s)." Typical content variables would be mass, momentum, and energy, and corresponding flows would be mass flow(s), torque(s) or force(s), and power, all being functions of time.

Then the basic "dynamic balance" for the elementary system is

$$\frac{d}{dt}(content) = \sum_k (flow\_in) - \sum_i (flow\_out)$$

It is also useful to eliminate dimensions and to scale variables appropriately by using rated values

$$\frac{rated\ content}{rated\ flow}\frac{d}{dt}\left(\frac{content}{rated\ content}\right) = \sum_k\left(\frac{flow\_in}{rated\ \ flow}\right) - \sum_i\left(\frac{flow\_out}{rated\ \ flow}\right);$$

$$\text{with}\ \ \tau = \frac{rated\ content}{rated\ flow}$$

where τ is the characteristic time parameter of this elementary dynamic balance, such as a "run-up time," "fill time," and so on; in other words τ indicates its relative storage capacity.

Inflows and outflows are either functions of external "forces" (manipulated variables or disturbances) or are internal flows driven by potential differences to adjacent elementary systems, that is, algebraic relations. "Potential" variables (such as pressure, speed, etc.) are also derived from content variables by algebraic relations. Also internal inflows to one elementary subsystem are outflows to adjacent elementary subsystems, and vice versa. Finally, the focus is on the "largest storage" subsystems, yielding low-order approximate models. Typical examples in hydropower systems are rotor speed at no load, frequency in isolated grids at low loads, level in "deep" reservoirs, servomotor position (if oil compressibility is neglected), and so on. Then the mathematical model consists of a first-order lag for the dominant storage dynamics with time constant τ_1 and a small delay τ_t to approximate all the other small time constants. A suitable control algorithm for this type of plant is the standard PI regulator with the transfer function

$$G_R(s) = \frac{u(s)}{e(s)} = k_p\left(1 + \frac{1}{sT_i}\right)$$

with *u(s)* as the manipulated variable (actuator input) and *e(s)* as the control error $e = r - y$ with r as the reference value and y as the measured variable (sensor output). Its parameter values k_p and T_i can be designed using the well-known rules of Ziegler–Nichols or Chien–Hrones–Reswick, or other procedures. Note that the delay τ_t always limits the attainable closed loop bandwidth. Also input constraints (control saturations) are always present, so anti-windup features are mandatory. "Windup" occurs in control loops with integral action, when the controller output variable *u(t)* transiently exceeds the saturation values on the actuator. It causes large overshooting of the controlled variable *y(t)* at reentry to the linear range. To avoid this effect, a nonlinear "anti-windup" feedback has to be added to the PID algorithm. However the plant response is not always that simple. Hydropower systems frequently exhibit weakly damped resonances within the frequency range relevant for control loops. Then simple PID control is not able to cope, and must be replaced by more advanced control concepts. Note however that they require much more precise models, and must be more carefully designed, using extended simulations, in order to succeed. "Trial and error" methods so popular in standard PID technology are bound to fail for such complex control systems. Another basic concept is a multi-cascade structure (Figures 5 and 6). There are individual position control loops for each actuator—for needles, gate or runner blades, weir or overfall, and so on—and there is a master regulator for the main controlled variable, such as speed, frequency, or level. Note that the manipulated variable in the dynamic balance discussed above is an inflow or outflow, whereas the physically manipulated variable is a position. This is taken into account by inserting a flow control loop to compensate for the effects on flow of variable head, speed, and the like.

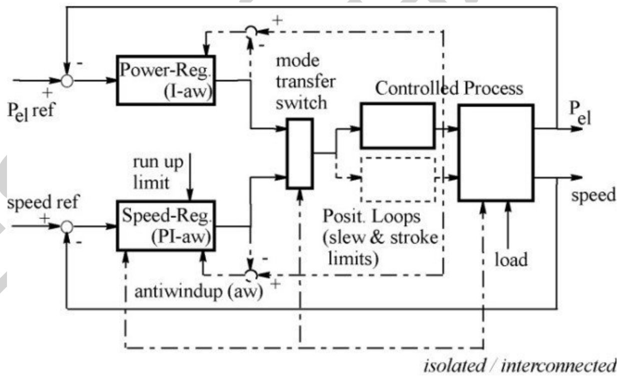

Figure 5. Speed and power control loops for run-up and interconnected operation modes

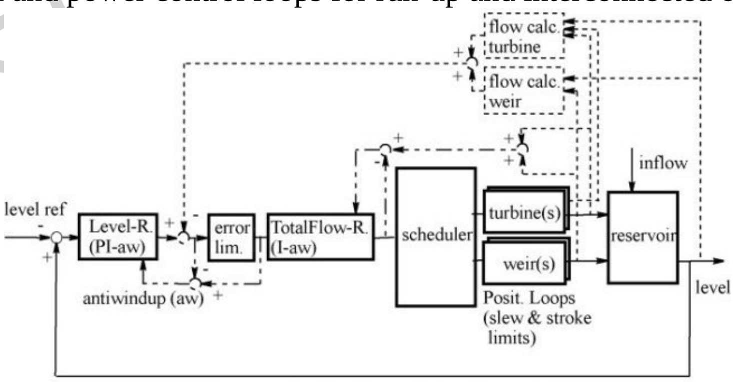

Figure 6. Standard level and outflow control cascade

Frequently, the main regulator output *u(t)* has to be split up to several parallel actuator loops. Typical examples are power control with several needles in parallel on a Pelton turbine, and level control with parallel operation of turbines and weirs in a river power station. Then a scheduler function block has to be inserted (see Section 3.4 and Section 5 for more details).

Note that dynamic responses for flow and power have no dominant time constant τ_t unlike the others given above (apart from the severe nonlinear servomotor slew rate limitations, which however appear only for large input deviations). They should thus be modeled by a series of lags with small time constants or approximated by a pure delay τ_t. Then the most suitable control algorithm is dominant I-action. A weak P-action may improve performance. Anti-windup is again mandatory.

The next subsections will discuss the application of these basic concepts to the actual control loops.

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Biographical Sketches

A.H. Glattfelder was born in 1940, and received his diploma degree in mechanical engineering from ETH Zurich, Switzerland, in 1964. After working with Brown Boveri, Baden, he joined the Measurement and Control Lab (Prof. Dr. P. Profos) and received his degree of Dr. sc. techn. in 1969, and his Habilitation in 1973.

He has been working with EscherWyss and Sulzer Winterhur for 15 years in management positions. From 1982 to 1984 he was responsible for Turbine Control Systems design.

In 1991 he joined the Automatic Control Laboratory at ETH Zurich. He teaches courses in Control Systems Design, and does some industry consulting. His research interests are the design and analysis of control systems with input ant output constraints (antiwindup and overrides), and modelling techniques for control. He is responsible for research cooperation with the University Hospital in Berne/Switzerland: Automatic Control in Anesthesia.

L. Huser was born in 1953 and graduated in Mechanical Engineering from Swiss Federal Institute of Technology, Zurich (Switzerland), in 1977. He joined the research department of Escher Wyss, where he specialized in system dynamics and control engineering. From 1983 to 1986 he worked for the governor department on the development of digital governors. Since 1986 he has been responsible for the development of digital governors, monitoring and process control systems at Escher Wyss (now VA TECH Hydro AG).

Peter Dörfler was born in 1942 in Vienna, Austria. He received his education and degree (1965) as a Mechanical Engineer at the Vienna Technical University. From 1966 to 1978 he has been working on different development projects in the area of supercharging and exhaust gas control of internal combustion engines, mostly at Brown Boveri Ltd., Baden (CH). In 1978 he joined the hydraulic laboratory of Escher Wyss. For several years he has been developing methods to understand and improve fluid-excited vibration in hydropower equipment, some of which have been published. With one of these studies, on the notorious half-load pulsation of the Francis turbines, he achieved his doctoral degree at Vienna Technical University (1982). Since 1988 he has also been responsible for the domain of water hammer and stability problems of turbine control. Recently he became head of the Transients and Safety Engineering group of VA TECH Hydro AG, Zurich.

Johann Steinbach was born in 1947 in Schärding, Austria. In 1975 he obtained his B.Sc. degree in Mechanical engineering from Zürcher Hochschule Winterthur, Switzerland, specializing in Process and Energy Technologies. He then joined Escher Wyss in Zürich, Switzerland, as a design engineer for hydroturbine control systems. From 1979 to 1984 he was project manager in the same department, where he was responsible for the control design and commissioning of seven major plants. Since 1984 he has been manager of the same governor and control engineering department, now with VA TECH Hydro AG, in Kriens, Switzerland, and has managed the control projects of about 30 major hydropower installations worldwide.