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Determination of the optimal PID control law for RPM of hydroelectric power plant units

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ABSTRACT: *This article examines the solutions and the typical mistakes in solving the problem that became evident during the blackout of the Georgia's power system on July 27, 2014. One of the problems turned out to be the inability of hydroelectric power plants (HPP) connected to the grid to operate autonomously and ensure energy consumption for their own needs and for priority consumers. The main problem was that, in order to restore the disconnected part of the power system from a zero state, these HPPs did not have at least one unit capable of quickly starting up after receiving the corresponding instruction from the dispatching licensee. This unit was needed to connect to the grid and provide the reference frequency and voltage for synchronizing the units of the stopped HPPs, all in the absence of voltage in the grid. Undoubtedly, the fulfillment of all these requirements depends on the control systems of the units, in particular, on the quality of the control of the RPM of the units.*
KEYWORDS: *Digital control systems, Hydraulic unit, PID control law, Steel pressure pipeline, Water Hammer.*

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I. Introduction

On July 24, 2014, the double-circuit 500 kV power transmission line "Imereti" which connects the western part of Georgia with the eastern part, failed due to overload. The entire power flow consumed by the eastern part, amounting to approximately 1277 MW, was redistributed to two double-circuit 220 kV lines, which also failed. As a result, two major HPPs "Inguri HPP", with an installed capacity of 1300 MW, and "Vardnili HPP 1", with an installed capacity of 220 MW, were completely disconnected from the eastern part of Georgia. Consequently, a system-wide failure occurred in the remaining HPPs in eastern Georgia, leaving the entire eastern region, and then the western region of Georgia completely without electricity. It became necessary to supply electricity to strategic facilities and priority consumers (Hospitals, Air traffic control services, Railways, and others).

Significant problems arose, and an investigation into their causes revealed the inability of the HPPs connected to the grid to operate autonomously. Furthermore, none of these plants had at least one unit capable of quickly starting up after receiving the corresponding instruction from the dispatching licensee. Such a unit was essential to provide the reference frequency and voltage for synchronizing the units of the stopped HPPs, facilitating the restoration of the power system from a zero state. The cause of this was the control system, specifically the low speed and rigid algorithm PID control for regulating the RPM of the units. Attempts to restore the power system lasted more than 24 hours and were successful only after importing electricity from neighboring countries. After this incident, the Georgian State Electric System made changes to regulatory documents, according to which HPPs of type "C" and "D" (with an installed capacity of more than 10 MW and 30 MW, respectively) are required to have the capability to restart the power system from a zero state and ensure its operation in an isolated mode [1].

To meet the new regulatory requirements, it became necessary to modernize the hydropower unit's control systems. With the availability of modern digital tools, such as single-board devices based on microcontrollers and PLCs, the process of upgrading control systems is not a problem. However, the real challenge lies in the fundamental knowledge of automatic control theory principles and the specifics of controlling interdependent (inter-acting) processes in HPPs. Knowledge of programming methods and languages for controllers alone is not sufficient for developing control systems for control objects with high risk levels, which include first- and second-category capitalization objects. According to the regulatory documents in force in Georgia, such objects include hydraulic structures (The hydroelectric power plant's headworks, pressure pipeline, and hydropower unit hall in the power station building), whose proper operation is crucial for the safety of public health, human life, and environmental safety.

II. Interdependent (inter-acting) processes in hydroelectric power plants

When developing control systems for HPP units, it is essential to consider the interdependence (interaction) of processes occurring in different parts of the hydraulic structures. This is especially important when the power plant needs to operate under emergency conditions, such as: participating in the restart of the power system from zero state and/or functioning in an isolated mode within a specific part of the grid. Let's consider the processes that are interdependent (interacting):

a. Acceleration of the hydraulic unit in case of emergency disconnection from the load.

The maximum acceleration coefficient of modern HPP units (hydropower units) depends on the type of turbine and generator design. The acceleration coefficient (ratio of maximum speed to nominal speed) typically falls within the following ranges [2]:

- For Francis turbines: 1.4 – 1.8;
- For Pelton turbines: 1.8 – 2.5;
- For Kaplan turbines (radial-axial turbines): 1.6 – 2.0;
- For modern high-efficiency crossflow turbines: 2.5 – 4.5.

In emergency conditions (e.g., load rejection scenarios), short-term acceleration coefficients may exceed 2.5, however, inexperienced developers of modern control systems usually prevent excessive overspeed to avoid equipment damage and try to reduce the water flow to the runner as quickly as possible. Such a decision is incorrect and may lead to highly undesirable consequences. Why? You will see below.

For Francis, Crossflow, and Kaplan-type turbines, the water flow to the runner is regulated by the guide mechanism (Water Guiding Device), while for the Pelton-type turbine, it is controlled by a needle valve located inside the nozzle, which can move in and out to regulate the water jet. For the normal operating mode of the HPP (during scheduled startup, increase or decrease in power, and planned shutdown of the hydro unit), the water flow regulation occurs gradually over several minutes. Consequently, the water flow velocity in the pressure pipeline (penstock) of the HPP changes smoothly over a relatively long period of time. In this mode, the unit does not change its rotational speed (RPM, voltage frequency), which is not regulated, as it is rigidly tied to the grid and operates in accordance with its voltage frequency.

In extreme operating modes of a HPP (participation in the restart of the power system from a zero state and/or operation in an isolated mode in a specific part of the grid), the time delay in the hydraulic unit control system does not ensure stable grid voltage frequency and power. Excessively rapid regulation of the water flow to the runner (generator output voltage frequency) or the rapid reduction of the water flow during the emergency disconnection of the hydraulic unit from the load (load rejection) sharply increases/decreases the water flow velocity in the pressure pipeline (penstock), which increases the risk of water hammer occurrence.

b. Water Hammer

Water hammer is a hydraulic transient phenomenon that occurs when there is a sudden change in water flow velocity within a pipeline. In HPPs, this typically happens when: Turbine wicket gates close or open rapidly; Main penstock valves operate suddenly; Load rejection occurs in the turbine. These sudden changes generate pressure waves that travel through the water column, potentially causing severe damage to the pipeline, valves, and other components of the HPP. The Joukowsky equation provides an estimate of the pressure surge (maximum value) due to water hammer [3]:

$$\Delta P = \rho \cdot a \cdot \Delta V$$

where: ΔP - pressure surge (Pa); ρ - water density (kg/m³); a – water hammer wave velocity (m/s); $\cdot\, \Delta V$ - change in water flow velocity (m/s).

For a steel pipeline, the value of the water hammer wave velocity can be determined by the equation [3]:

$$a = \sqrt{\frac{K}{\rho \cdot \left(1 + \frac{K \cdot D}{E \cdot t}\right)}}$$

where: K – bulk modulus of water (~ 2.2×10^9 Pa for water at 20°C); ρ – density of water (~ 1000 kg/m^3); D – internal diameter of the pipe (m); t – wall thickness of the pipe (m); E – Young's modulus of steel (~ 2.1×10^{11} Pa).

According to the Joukowsky equation, the greater the change in the water flow velocity, the greater the pressure change in the pressure pipeline, and accordingly, the higher the risk of damage to the pipeline, valves, and other components of the HPP. The critical time of a HPP pressure pipeline is the time it takes for a pressure wave to travel from one end of the pipeline to the other and return. Practically, this is the damping time of the pressure wave of the Water Hammer and this parameter is crucial for analyzing hydraulic transients and ensuring the stability of the system. The value of the critical time (the wave reflection period) in seconds can be determined by the equation [3]:

$$T_{CR} = \frac{2 \cdot L}{a}$$

where: L - length of the pressure pipeline (meters).

The critical time determines whether a hydraulic transient will lead to severe pressure surges. When the flow rate is changed in a time (the closure time of the valve or gate) greater than zero but less or equal to T_{CR} seconds, the magnitude of the pressure rise is the same as with instantaneous closure. This can result in a strong water hammer effect, potentially damaging the pipeline. However, the duration of the maximum value of pressure decreases as the time of closure approaches T_{CR} seconds. Under these conditions, the pressure distribution along the pipeline varies as the time of closure varies. The pressure decreases uniformly along the line if closure is in T_{CR} seconds. The maximum pressure at the control valve exists along the full length of the line with instantaneous closure and for slower rates the pressure travels up the pipe a distance equal to $L\text{-}a\cdot T_{CR}/2$, then decreases uniformly. For valve closing times greater than $2\cdot L/a$ seconds, the maximum pressure rise will be the maximum rate of change in flow with respect to time, $\Delta V/\Delta t$. Nonlinear closure rates of a valve can be investigated and the proper valve closing time determined to hold the maximum pressure rise to a desired limiting value. This is very important to prevent the damaging of the pressure pipeline.

Modern Pelton-type turbines, unlike other types of turbines, have a water jet deflector. When the deflector is raised during normal operation, the water flow from the nozzle will not be affected. The turbine runs normally When the deflector is raised during normal operation, the water flow from the nozzle will not be affected. The turbine runs normally. In the event of an emergency shutdown of the hydraulic unit, the deflector is in action, the nozzle will spray the water flow is blocked by the deflector and turned to the lower outlet, and the turbine stops running. At the same time, the flow velocity of water in the pressure pipeline does not change. It is possible to choose a valve or gate closure time whose value can be much greater than $2\cdot L/a$, thereby avoiding significant impact of hydraulic hammer on the pressure pipeline.

III. Participation of HPPs in the grid restart from a zero state and the operation in an isolated grid

Participation of a HPP in the restart and operation of an isolated grid involves a set of processes that ensure the stability and reliability of the grid when it is disconnected from the main power system, such as in the case of a blackout or major failure. During grid restart, it is important to maintain stable voltage frequency and voltage, so HPPs can be involved in this process, which can provide rapid regulate these parameters, especially with fast-acting turbines such as Pelton or Francis turbines. The grid restart process requires careful coordination and the step-by-step execution of a series of actions by the participants in this process, which are listed below.

Step 1 – Generation of initial power supply required to provide energy to the main auxiliary systems of the HPP and the network, such as: auxiliary loads, relay protection devices, and communication systems.

Step 2 – Connecting to the grid and supplying initial power supply to the grid to provide the reference voltage frequency and voltage, as well as energy to the main auxiliary systems of other HPPs involved in the network restart process.

Step 3 – Once the reference voltage frequency and voltage are established in the grid, the other HPPs start and synchronize their units, connect them to the grid sequentially only upon the dispatch service's instructions, and participate in voltage frequency and voltage regulation. The units of hydroelectric power plants with relatively low installed capacity are started first.

Step 4 – After connecting the units with sufficient total capacity to the isolated grid (determined by the dispatching service), the dispatching service begins the gradual connection of the load to the grid. Priority consumers are connected first. This process may take several hours, after which part of the grid begins to operate in isolated mode until the entire power system is restored.

A feature of the operation of part of the grid in isolated mode is that changes in load cause changes in voltage frequency (voltage amplitude), which must be promptly regulated and maintained within specific limits set by the requirements of regulatory documents.

IV. Optimal PID control law for voltage frequency (RPM) control of HPP units

According to regulatory requirements, when the station operates in isolated mode within part of the grid, it must ensure operation within the following voltage frequency ranges: From 47.0 to 47.5 Hz – for no more than 20 seconds; From 47.5 to 48.5 Hz – for no more than 30 minutes; From 48.5 to 49.0 Hz – for no more than 60 minutes; From 49.0 to 51.0 Hz – for an unlimited duration; From 51.0 to 51.5 Hz – for no more than 30 minutes; From 51.5 to 52.5 Hz – for no more than 30 seconds; From 52.5 to 53.0 Hz – for no more than 10 seconds [1]. Therefore, the frequency control system must ensure stability, fast response, and high-quality regulation – meaning that transient processes must occur without overshoot or oscillations, as these may cause frequency sweep in the isolated part of the grid and trigger the relay protection system by frequency. On the other hand, maintaining the frequency within a narrower range, i.e., responding quickly to small deviations from the reference frequency (50 Hz), does not require a significant increase in the water flow to the turbine's runner. The change in the water flow

velocity in the pressure pipeline (ΔV) will remain negligible, and consequently, the risks of water hammer will also remain low. To achieve this, it is necessary to choose the optimal control law for turbine RPM regulation.
The transfer function of the turbine can be approximated by the equation [4]:

$$W_T(s) = \frac{1}{T_T \cdot s + 1}$$

where T_T is the turbine time constant, which depends on the mass of the flywheel on the turbine shaft.
The transfer function of the PID controller has the following form [4]:

$$W_C(s) = k_P + k_I \cdot \frac{1}{s} + k_D \cdot s = \frac{k_D \cdot s^2 + k_p \cdot s + k_I}{s}$$

Where: k_P is the proportional gain; k_I is the integral gain; k_D is the derivative gain.
In this case, the transfer function of the open-loop system (characteristic equation) has the following form:

$$W_{OS}(s) = W_C(s) \cdot W_T(s) = \frac{k_D \cdot s^2 + k_p \cdot s + k_I}{s} \cdot \frac{1}{T_T \cdot s + 1}$$

The transient processes of the system without overshoot, oscillations, and with zero steady-state error (astatic control) are achieved if the characteristic equation of the control system has a single zero root, i.e., the transfer function of the open-loop control system will have the following form [4]:

$$W_{OS}(s) = \frac{k}{T_T \cdot s}$$

Thus, the optimal PID control law can be determined from the following equation:

$$W_{OS}(s) = \frac{k_D \cdot s^2 + k_p \cdot s + k_I}{s} \cdot \frac{1}{T_T \cdot s + 1} = \frac{k}{T_T \cdot s}$$

It is evident that for the transfer function to assume the required form, it is necessary that $k_D = 0$, i.e., the control law must be proportional-integral (PI). For proper tuning of the PI controller, let us introduce the condition, assume that:

$$\frac{k_P}{k_I} = T_T \implies k_I = \frac{1}{T_T} \cdot k_P$$

Taking this into account, the open-loop transfer function of the PI control system will have the following form:

$$W_{OS}(s) = \frac{(T_T \cdot s + 1) \cdot k_P}{T_T \cdot s} \cdot \frac{1}{T_T \cdot s + 1} = \frac{k_P}{T_T \cdot s}$$

and this means that the characteristic equation of the control system has one zero root.
In order to simplify the dynamic retuning of the PI controller for adjusting (increasing/decreasing) the control speed, a modification of the PI controller was made. For this modified PI controller, it is assumed that $k_I = 1$; accordingly, $k_P = T_T$ and an overall gain coefficient k is introduced. Consequently, the transfer function of the PI controller takes the following form:

$$W_{MC} = k \cdot \left(k_P + \frac{1}{s}\right)$$

For digital control systems the practical implementation of the modified PI controller is very simple, it can be represented as a series connection of a PI controller with proportional block, the gain coefficient *k* of which can be adjusted programmatically. Fig. 1 shows the transient process graphs during the startup of HPP units when the power grid or part of it operates in isolated mode. If the above tuning principles for PI controller are not followed, then the graph of the transient control process will appear as represented by curve I in Fig. 1. If the above tuning principles for PI controller are followed, then the graph of the transient control process will appear as represented by curves II and III in Fig. 1. Curve II of the transient response corresponds to a lower overall gain coefficient, while curve III corresponds to a higher one. For the safe startup of units, it is recommended to choose the value of the overall gain coefficient (k) in such a way that the duration of the transient process exceeds the critical time of the pressure pipeline of the hydroelectric power station (T_{CR}) by 3-4 times.

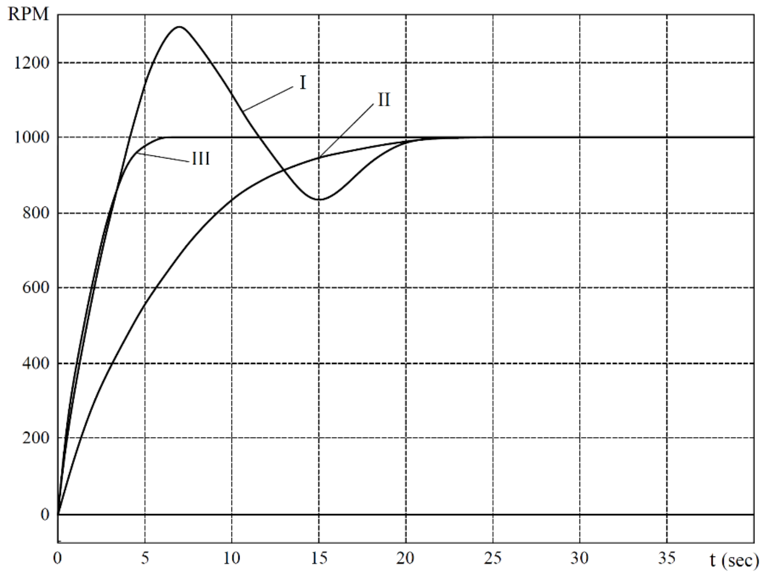

Fig.1. Examples of transient processes in turbine RPM control during the startup of HPP units

Fig. 2 shows examples of transient processes of the PI control law for the RPM regulation of an already started turbine during load connection/disconnection.

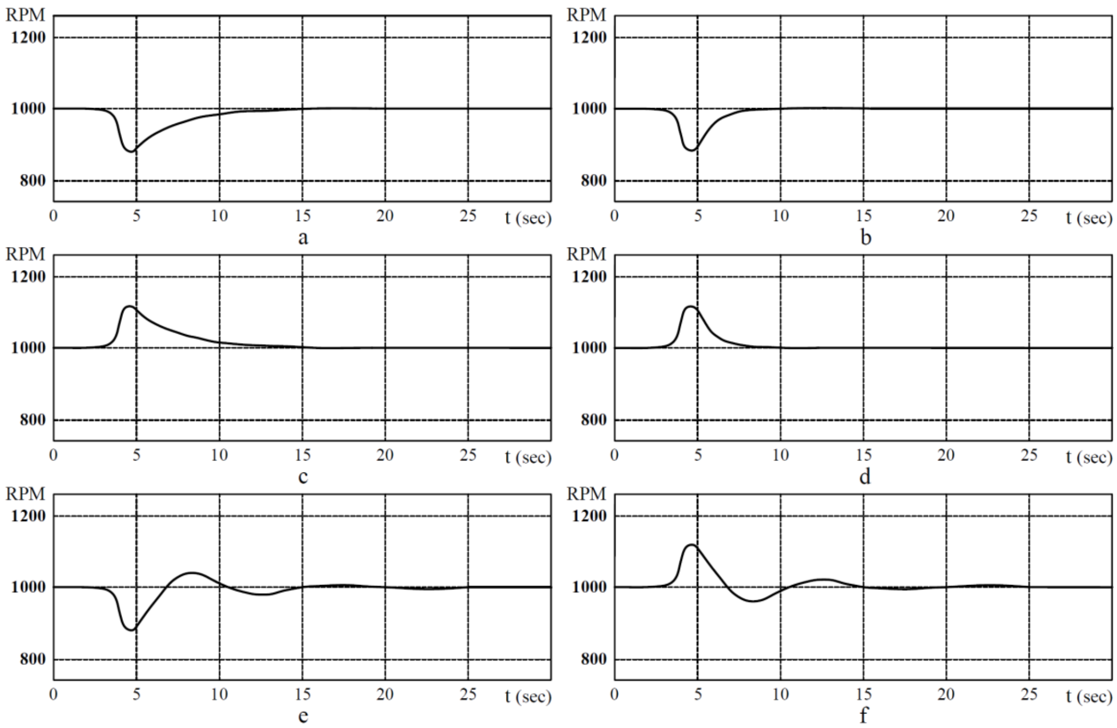

Fig. 2. Examples of transient processes in turbine RPM control during load connection/disconnection

Graphs a and b of Fig. 2 show the transient processes of RPM regulation during load connection using a properly tuned modified PI controller. Graph a corresponds to a lower value of the gain coefficient k, while Graph b corresponds to a relatively higher value. The same is shown in Graphs c and d for load disconnection. Graphs e and f show the transient processes of frequency regulation by improperly tuned PI controllers during load connection and disconnection, respectively.

V. Conclusion

Since 2007, the modified PI controller has been implemented at several hydroelectric power plants, taking into account their operation in synchronous mode with the grid. The installed capacity of these HPPs ranged from 3 MW to 12 MW, and the rated water flow varied from 1.5 m^3/s to 5 m^3/s. After 2015, the control systems were updated, and a new operating mode was added for the HPPs, allowing them to operate in an isolated mode within a specific part of the grid. Tests of the control system were conducted for all possible extreme scenarios for both operating modes of the HPPs. For the isolated operating mode of HPP in a part of the grid, the load varied within 10-15% of the installed capacity of HPP, the voltage frequency was maintained within 50 ± 1.5 Hz, and the transient processes lasted no more than 10-15 seconds, which is fully acceptable according to regulatory requirements. During the extended operational period of the implemented control systems at the HPPs, no incidents occurred. During local accidents, the HPPs operated without interruption in autonomous mode and successfully met their own energy consumption needs.

The modified PI controller has the following advantages:

- The simplicity and ease of tuning the controller compared to other tuning methods, such as: Ziegler–Nichols Tuning Method; Ultimate Gain Method; Cohen-Coon Method and Trial-and-Error Method (Manual Tuning).
- The flexibility of the controller – the ability to automatically change the control speed (modify settings and/or the magnitude of the control discretization).
- Guaranteed stability of the control system (absence of overshooting and oscillations).

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