Aspects on Modeling of Hydro-Turbine Speed Governor

Gordana Janevska, Sotir Panovski

Abstract— The liberalization of the electricity market enforces the use of more productive and energy efficient technologies. Hence, the revitalization of some parts of the equipment in the existing power systems was required. Such a need is imposed on hydro-turbine speed governors. Governor play an important role in hydraulic turbine. It maintains the stability of the system frequency by controlling the speed of the system. The paper analyzes the standard control algorithm for turbine governors, the PID controller. The fundamental basics of PID controllers are illustrated, methods of tuning are considered in order to demonstrate the adaptation of these devices to the system, but also their limitations are highlighted. Finally, alternative control systems are also considered.

Index Terms— Hydro-turbine governor, Intelligent systems, PID control, System modeling.

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1 INTRODUCTION

Turbine governor in hydropower plants are equipment for control and as soon as possible adjust the turbine output power, as well as the output deviations between the power and the load in the network. The turbine governor should fulfill two main objectives:

1. To maintain the stable and constant rotational speed of the turbine generator unit at any load in the grid and to overcome the conditions in the hydraulic inlet circuit.
2. In case of load rejection or emergency stops, the inlet of the turbine shall be closed according to certain acceptable limitations between the increment of the rotational speed of the turbine generator unit and the pressure rise in the hydraulic inlet circuit.

The fundamental function of a hydro-turbine governor is to control the speed and/or load through the feedback signal of the speed error and /or power variation to control the gate position, which regulates the water flow through the penstock. In this way, the active power balance in the system is ensured, and also the grid frequency is maintained within nominal value under electrical load variations.

A governor regulates the speed and power output of a prime mover as a control system. The governor includes mainly a controller function, and one or more control actuators.

Turbine controllers are usually of the PID type, and their implementation can include a wide range of configurations: from purely mechanical or electro-mechanical controlers to fully electronic devices. Around 40 years ago, mechanical-hydraulic turbine governors were predominant. Then, due to the growing demands regarding the possibilities and characteristics of the control system, analogue electronic controlers were introduced. Twenty years ago, the digital turbine governors were introduced. Nowadays, the control system of turbine generator unit, which includes the turbine governor, is manufacture in digital computer technology.

2 PID CONTROLLER AS A TURBINE GOVERNOR

One of the most widely applied control laws in hydropower plant governing systems is the PID control. The name comes from the three functions (Proportional, Integral and Derivative) included in the calculation of corrections. In the case of pure proportional control, the control action is simply proportional to the control error, i.e. $u(t)=K_p e(t)$. The lower values of the controller gain K_p lead to a greater steady-state error, and the higher values give better steady-state performance, but worse transient response. The usual way to reduce the steady-state error is by integrating the integral action. The integral term I gives a control action that is proportional to the time integral of the error, i.e. $u(t)=K_i \int e(t)dt$. Although the steady-state error may be reduced to zero, such performance is achieved at the expense of stability. A third term can be added to reduce the oscilation. The purpose of the derivative action is to improve the closed-loop stability. The derivative term D is proportional to the time derivative of the control error, i.e. $u(t)=K_d\ [e(t)/dt]$. The derivative action increases the system damping, which allows larger values for K_p and K_i to be used.

The overall transfer function of the PID controller is:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s\ . \tag{1}$$

Often, the controller transfer function is presented as

$$G_c(s) = K_p\left[1 + \frac{1}{sT_i} + sT_d\right], \tag{2}$$

where:

$Ti = K_p/K_i$ is integral action time (reset time),
$Td = K_d/K_p$ is derivative action time (rate time).

Block diagram of PID governor for hydraulic turbines is given in fig.1. As it is showen, the three terms of the controller treat the present control error (proportional), past control error (integral), and predicted control error (derivative). The derivative term in the control action is important in the case of iso-

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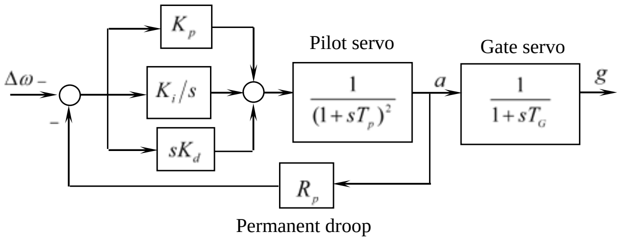

Fig. 1. Block diagram of PID governor for hydraulic turbines.

2.1 Governor Tuning

Within the limited structure of a PID controller, the processes used to find the values of the proportional gain K_p, the integral constant T_i, and the derivative constant T_d are known as tuning methods.

The governor tuning, i.e. adjustment of the PID gains, can be examined in terms of plant stability and dynamic performance. There are different methods of governor tuning, which not only indicate stability, but also provide information on the adjustments needed to meet a given performance specification. Manual tuning methods depend on ability to test the system response manually, and then adjust the PID values until a satisfactory response has been found. Modern industial facilities use PID tuning software to ensure consistent results. Here the same methods as in manual tuning are used, but the processes are automated to reduce the required time and to help improve standardization.

The most critical condition for governor tuning would be with the unit supplayingan isolated load at maximum output. Here, the stability of a hydraulic turbine generating unit configured to supply an isolated load is analysed using the Routh-Hurwitz criterion. The effect of the derivative gain is analyzed using the root locus method [2]. In the case of a small isolated network, the unit must act to maintain the system frequency. Most units at some time may be required to supply isolated loads either deliberately or by accident. For example, a black-start operation may be required or the power system may split into smaller networks. Even when isolated, the dynamic load characteristics will vary and must be taken into account in control design.

Using the solid mass approximation for short / medium head penstok, the linearized model is used to represent the dynamics of the hydraulic plant, i.e. the classical transfer function of a hydraulic turbine. Since we are interested in the frequency variation with power, the load dynamics are modelled by the constant power. The model of the plant used for steady state analysis is presented by the block diagram given in fig. 2.

The system transfer function can be written as:

$$G(s) = \frac{(K_p s + K_i + K_d s^2)(1 - T_w s)}{s(1 + 0{,}5T_w s)(T_m s + D_p)}, \tag{3}$$

where T_w is water starting time, T_m is mechanical starting time, and D_p is the load damping, which is proportional to the connected load and the load's frequency sensitivity.

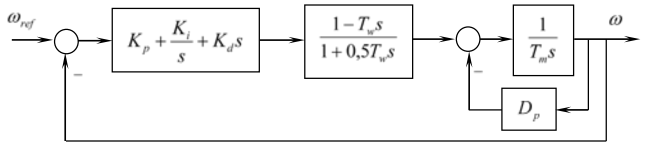

Fig. 2. Block diagram of a hydraulic turbine generating system.

The well-known Ruth-Hurwitz stability criterion is used to obtain an analytical expression for the system's stability boundaries depending on the values of hydropower plant and controller parameters.

Combining the transfer function of the governor with that of the controlled system shown in fig. 2, the system characteristic equation can be derived in the form:

$$\begin{aligned} &s^3(0{,}5 - X_3) + s^2(X_3 - X_1 + 1 + 0{,}5X_4) + \\ &+ s(X_1 - X_1X_2 + X_4) + X_1X_2 = 0 \end{aligned}, \tag{4}$$

where:

$X_1 = K_pT_w/T_m$; $X_2 = K_iT_w/K_p$; $X_3 = K_d/T_m$;

and the system regulation is

$X_4 = D_pT_w/T_m$.

Applying the Routh test, it is obtained that in order to ensure a stable system response the following criteria must be fulfilled:

- $0{,}5 - X_3 > 0$, i.e. $0{,}5 > X_3$, which means that the derivative gain must be set to $K_d < 0{,}5T_m$;
- $1 - X_1 + X_3 + 0{,}5X_4 > 0$, which results in $X_1 < 1 + X_3 + 0{,}5X_4$;
- $X_1 - X_1X_2 + X_4 > 0$, which results in $1 + X_4/X_1 > X_2$;
- $X_1X_2 > 0$;
- $A_1A_2 - A_0A_3 > 0$, which results in

$$\begin{aligned} &(1 - X_1 + X_3 + 0{,}5X_4)(X_1 - X_1X_2 + X_4) - \\ &- (0{,}5 - X_3)(X_1X_2) > 0 \end{aligned}. \tag{5}$$

If all the above conditions are satisfied, the system stability boundaries can be established by setting (5) to be equal to zero, which results in:

$$\begin{aligned} &X_1^2(X_2 - 1) + X_1(1 - 1{,}5X_2 + X_3 - 0{,}5X_4 - 0{,}5X_4X_2) + \\ &+ (X_4 + X_3X_4 + 0{,}5X_4^2) = 0 \end{aligned}. \tag{6}$$

The benefit of defining the stability boundaries in terms of X_1 and X_2 is apparent from their definition, where it is seen that they are universal parameters and not related to any specific system parameters [5]. Hovey [3] has considered the stability boundaries for a system governed by a PI-type controller and operating with regulation X_4 set to zero. In Hovey, the operating point for optimum transient response was chosen as $X_1 = 0{,}5$ and $X_2 = 0{,}25$. The self-regulation of the turbine and connected loads acts to reduce the speed transient and to increase the stability of the unit. It can be seen that the governor setting chosen by Hovey is conservative and does not utilize the maximum capability of the generating system. Similarly, Paynter [2] has recommended an operating point for optimum transient response at $X_1 = 0{,}4$ and $X_2 = 0{,}169$.

The effect of governor parameters on the system dynamic behavior of a unit supplying an isolated load is analyzed using the root locus method. The system representation shown in fig. 2 is used. The open loop system transfer function as represented by (3), relating to the parameters X_1, X_2, X_3 and X_4, can be rewritten as:

$$G(s) = \frac{-X_3 s^3 + s^2(X_3 - X_1) + s(X_1 - X_1 X_2) + X_1 X_2}{s(1+0.5s)(s+X_4)} . \qquad (7)$$

In their investigations, Hagihara et al [2] predict changes in the pattern of root loci that limites the derivative gain to $K_d \le K_p T_w / 3$. However, it has been shown that the root loci pattern changes appear at a higher value $X_3 = 0{,}45$ and yields an extension of the K_d stability limits [5].

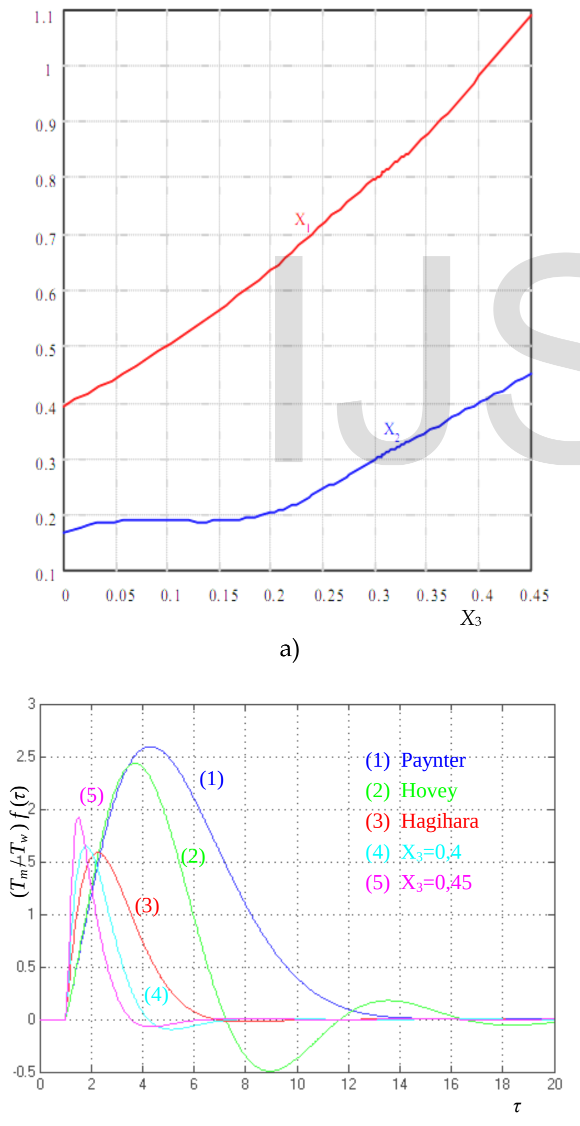

Fig. 3. a) Optimum values of X_1 and X_2 for different values of X_3.
b) Optimum transient responses for X_4=0.

The optimum system settings change for each value of X_3; consequently, X_1 and X_2 should be adjusted accordingly as shown in fig.3.a, where higher X_3 values result in increased values of X_1 and X_2. The effect of X_3 on the transient response of the system for a step load change has been obtained using the model built in SIMULINK. Fig. 3b illustrates the effect of adding the derivative term as it confirms that the system will stabilize rapidly with less overshoot compared to the cases where it is omitted. When the system operates with $X_3 = 0{,}45$, it will be very active and may cause an extra overshoot due to the fast response caused by the high integral gain setting. The results imply that increasing the derivative gain will couse the enlargement of the stability boundaries to a predetermined value of $X_3 = 0{,}5$ where the final limits are reached according to the Routh test. The generating unit is required to deliver a fast response to load changes and selecting $X_3 = 0{,}4$ will achieve that aim. In this case, the optimum PID gains are adjusted to:

$$K_p = 0{,}97\frac{T_m}{T_w}, \qquad K_i = 0{,}39\frac{T_m}{T_w^2}, \qquad K_d = 0{,}4T_m .$$

The optimum response is based on a prototype ITAE response. i.e. prototype set of transient responses to minimize the Integral of the Time multiplied by Absolute value of Error.

2.2 Limitations of PID Controllers

The PID controller is by far the most common control algorithm. The general empirical observation is that most industrial processes can be controlled reasonably well with PID control. Althow it is widespread and popular application in many industries, PID controller is not without its limitations.

It is an interesting observation that many industrial controllers only have PI action and that in others the derivative action can be switched off. PI control is adequate for all proceses where the dynamics are essentially of the first order.

Similarly, PID control is sufficient for processes where the dominant dynamics are of the second order. For such processes there are no benefits gained by using a more complex controller. When the system is of a higher order than two, the control can be improved by using a more complex controller than the PID controller.

For example, systems with dominant time delays are candidates for more sophisticated control. Namely, there seems to be general agreement that derivative action does not help much for proceses with dominant time delays. For open loop stable processes, the response to command signals can be improved by introducing dead-time compensation. The load disturbance rejection can also be improved, because a dead-time compensator allows a higher loop gain than a PID controller.

One of the problems with PID controllers is the so-called "integrator wind-up". In this case, the actuator "saturates", i.e. it is working at its maximum level, which is actually less than what was required of it by the controller. In fact, the system will effectively be running in an open loop, and the error will be continuously integrated, leading to a multiple increase of the integral term. If the actuator saturates at a response level that does not actually decrease the error, the system may become unstable.

Another problem is one of mechanical wear of the device. In a system that continuously performs small adjustments in a limited range, "dead-band" may appear. In addition, the problem with PID controllers is that they can not be adjusted to changes over time, and the system it controls will be constantly changing due to aging and mechanical wear. Thus, the PID controller decreases its efficiency over time (if there is no human intervention), which will eventually reach a stage where it can no longer control the system.

The problem with tuning process should also be mentioned. Most tuning methods for PID controllers are not 100% accurate for all cases. It is usual practice to use the calculated values as a starting point and then adjust the PID controller to better suite the overall system immediately after its installation.

3 INTELLIGENT SYSTEMS – POTENTIAL APPLICATION

Intelligent systems apply the principles of human intelligence, such as the ability to learn and the decision-making process. These systems can be used for different needs. As control systems, three types of intelligent systems are practically applied: Fuzzy Logic, Artificial Neural Networks (ANN) and Adaptive Neuro Fuzzy Inference Systems (ANFIS).

Fuzzy logic system uses human decision making processes and presents them in a mathematical form. People are imprecise by nature, using descriptors as "fast" or "slow" for turbine speed. Fuzzy logic represents such terms in a numerical way, using fuzzy sets. This approach avoids the clear nature of the conventional Boolean logic, which can cause step impulses when transitioning from one to another state. The use of human descriptors also ensures easy implementation of expert rules.

Artificial neural networks imitate the ability of the human brain to learn. ANNs mimic the human brain to a limited extent using artificial neurons, which behave approximately as organic neurons. The signals passed between the neurons are subject to a multiplier known as a weight. Neurons will "fire", which generates a signal when the inputs that receive satisfy a present condition. By adjusting the weights in the network of neurons according to the current error, ANN can "learn", as the weights being adjusted to a point where the error is zero. In this way, ANN can be trained to complete a task without the need for an external human tuning. In addition, ANN can self-adjust over time through retraining with operational data. Hence, ANN can change over time as the system is involved in changes.

Intelligent systems are becoming increasingly used to tune the parameters of a conventional control systems such as PI controller. This has its advantages because the intelligent system can tune the controller rapidly, without the need for human intervention. Ideal results are achieved when the tuning system is used continuously, so that the controller parameters are continuously adjusted to compensate for changes in the parameters of the plant itself. However, the lack of this approach is that it may be incompatible with the standards in the field of electricity, which require the response to a set of predetermined inputs be constant value over time.

Intelligent systems in control systems can also be used as controllers. This avoids the complexity of the system - instead of configuring an existing controller, the intelligent system is the controller itself. An ANN applied in this way would be capable of self-tuning to suit the controlled plant. A fuzzy logic system would have the benefit of smoother response than the responses of conventional controllers. The ANFIS system combines the best of both components, implementing a fuzzy logic system with an ANN. This leads to a system that can use fuzzy logic and learn.

To develop a controller that uses intelligent systems, data from existing hydroelectric power plant is needed. This includes data on: penstock pressure, guide vane position, output mechanical power, speed, system frequency, circuit breaker position, stop and start commands, system reference point and previous error.

4 CONCLUSION

Speed governor play an important role in hydraulic turbine. It maintains the stability of the system frequency by controlling the speed of the system. The paper analyzes the standard control algorithm for turbine governors, the PID controller.

The essence of the PID controller as a hydro-turbine governor is illustrated and a tuning method are considered in order to demonstrate the process of its adaptation to the system.

Tuning the speed governor is a very important issue. The paper examined governor tuning, i.e. adjustment of the PID gains, in terms of plant stability and dynamic performance. The most critical condition for governor tuning would be with the unit supplaying an isolated load at maximum output. Here, a general guide for optimum adjustment of the gains of the governor for a unit supplaying an isolated load, or a small power system, has been provided. The stability of a hydraulic turbine generating unit configured to supply an isolated load is analysed using the Routh-Hurwitz criterion. The performance of the governor and hence the plant response can be improved by appropriate derivative gain. The effect of the derivative gain is analyzed using the root locus method.

It should be noted that the PID controllers are not without their limitations. They are inadequate to control complex systems. Also, they are unable to adapt to changes that occur in the system over time, may prove to be unstable by inadequate equipment, and there are difficulties in their standardization.

Intelligent systems offer an alternative approach to control of hydraulic turbines. These systems offer a way of either automatically tuning PID controllers without the need for manual fine-tuning, or they can be used as a control system by themselves.

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