Robust Control Analysis of Hydraulic Turbine Speed

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Abstract—An effective control strategy for the hydro-turbine governor in time scenario is
adjective for this paper. Considering the complex dynamic characteristic and the
uncertainty of the hydro-turbine governor model and taking the static and dynamic
performance of the governing system as the ultimate goal, the designed logic combined
the classical PID control theory with artificial intelligence used to obtain the desired
output. The used controller will be a variable control techniques, therefore, its
parameters can be adaptively adjusted according to the information about the control
error signal.

I. INTRODUCTION

The theory is to build a dam on a river that has a maximum drop in elevation. Eventually, the dam
stores lots of water behind it in the reservoir. Around the bottom of the dam wall there is the water
opening. Gravity causes it to fall through the penstock inside the dam. At the end of the penstock there
is a turbine propeller, which is turned by the moving water. The shaft from the turbine goes up into the
generator, which produces the power.

In this project, we are focusing more on control system rather than mechanical design. Therefore,
instead of gravity pressure in the flow of water, we prefer to use pump to obtain required pressure to
rotate the turbine.

We are designing an algorithm through artificial intelligence technique in controller to obtain the
desired output. The output of the system should be stable, fast response time and produce constant
voltage.

II. GOVERNING SYSTEM

The important part of a hydraulic power unit is a turbine governor that helps in the efficient
conversion to electrical energy of hydraulic mechanical energy.

![Fig 1. Generalized diagram of Speed Control of hydro-turbine.](image)

The different governing have different impacts on the hydraulic system. The P mode gives an
immediate action to the error, in the input by calculating the size of the error.

In fact, the P mode produces a control action which is proportional to the input error. The D mode
reacts to the input error and produces a control signal to the rate of change and extends the
proportionality constant to maintain the stability limits. This mechanism can be accelerated in PID
controller where an addition I made which trims the error signal and tries to bring the value to zero.

And the transient droop compensator acts as a D mode here, which is required for a stable operation
when power is affected by the rate of flow. Moreover, in Fuzzy PID, the implementation of fuzzy
logic provides a certain level of artificial intelligence to the conventional controllers. Since fuzzy logic
provides fast response times with virtually no overshoot. Loops with noisy process signals have better stability and tighter control when the fuzzy logic control is applied.

Fig 2. Block Diagram for P Controller

Above diagram includes P-controller in which the value of Kp= 6; it has been derived from transfer equation of turbine.

Fig 3. Block Diagram for PI Controller

Above diagram includes PI-controller in which the value of Kp = 6 and Ki = 10; it has been derived from transfer equation of the turbine.

Fig 4. Block diagram for PID Controller

Above diagram includes P-controller in which the value of Kp= 6, Ki= 10 and Kd= 0.01; it has been derived from transfer equation of turbine.

Fig 5. Block Diagram for Fuzzy Logic
The main advantage of the fuzzy control method is to control the processes that are too complex to be mathematically modelled. The membership functions must be optimally determined to design an efficient FLC for a problem. Many factors related to Run-off River or hydro power are subjective and difficult to quantify in this type of process such as Water Level or Depth is at “Below Danger Level-Danger Level-Above Danger Level”. Similarly, the water flow rate is “Slow-Normal-Fast” etc. Still fuzzy logic enables the evaluator or the decision maker to incorporate this information in the environmental performance evaluation system which is imprecise, vague and subjective. Therefore, the FLC method is a very suitable method for small hydroelectric power generation problem. The rule base and membership functions have a great influence on the performance of FLC. The fuzzy linguistic variable performance can be easily characterized by common terms as: “Good – Moderate – Bad; Strong – Average – Weak; High, Medium-Low” etc. Each term is called a linguistic modifier. Hence a fuzzy set is formed when a linguistic variable is combined with a linguistic modifier.

Application of Fuzzy Logic in hydro power comprised in three stages:

a. Fuzzification (Assigning input and output variables; Converts the Classical or Crisp Values to Fuzzy Sets)

b. Fuzzy Logic Rules and Fuzzy Inference Methods (Mamdani Inference Method)

c. Defuzzification (Converts the Fuzzy Set to Classical or Crisp Values) Fuzzification: Usually, a fuzzification of mathematical concepts is based on the generalization of these concepts from characteristic functions to membership functions. Let us assume M and N be two fuzzy subsets of X. Intersection (M∩N) and union (M∪N) are defined as follows: (M∩N)(x)= min(M(x),N(x)), (M∪N)(x)= max(M(x),N(x)). A simple falsification is usually based on the min and max operations.

Fuzzy Rules and Fuzzy Inference Methods: Mamdani inference method, as defined for solving either manually or in MATLAB Software, expects the output membership functions to be fuzzy sets. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required. There are several ways to define the result of a rule, but one of the most common and simplest is the "max-min" inference method, in which the output membership function is given as the truth value generated by the premise.

![Fig 6. The Input FIS Variables](image-url)
Defuzzification: It is the process of producing a crisp or quantifiable result or output in fuzzy logic, from obtaining fuzzy output sets and corresponding membership degrees. Most common and useful defuzzification technique is “Centre of Gravity Method”. In “Centre of Gravity Method”, the first step of defuzzification typically is to "cut off" parts of the triangular graphs to form trapezoids (or other shapes). Then, “The Centroid” of this shape, called the fuzzy centroid, is evaluated. The x coordinate of “The Centroid” is the defuzzified value. The “Centre of Gravity Method” is very popular and is used widely for calculation.

III. SERVOSYSTEM

Servomechanism is an automatic device that uses error sensing negative feedback to correct the action of the mechanism. It usually includes an inbuilt encoder or other position feedback mechanism to ensure the output is achieving the desired effect. To implement the control system in reality, we are considering 12V DC pump instead of penstock whose flow rate is controlled through PWM signal given by governing system. According to the input from governing system, it changes its pressure of water flowing into the turbine.
The step down transformer is used to reduce the voltage into 5V. LM7805 voltage regulator used to maintain a constant voltage level. LED to indicate the circuit is functioning. The Capacitor acts like a filter to reduce noise disturbances in the circuit.

**Fig 9. Circuit Diagram**

**Fig 10. Pelton turbine**

**Fig 11. Circuit Diagram of Control System**
1. PIC Controller: The raw output voltage is given to the controller, which proceed according to the provided embedded logic and gives a signal to the relay for further operation.
2. LCD: The analog signal is digitized and displayed on the LCD screen.
3. Crystal Oscillator: To give pulse to the PIC Controller.
4. Transistor: It is used to amplify the electrical signal.
5. Relay: It gives a signal to the pump according to the designed logics.
6. Transformer: It is used to step down the main line voltage.
7. Turbine: Pelton turbine is used to operate at low discharge and overall efficiency is high.

IV. MATHEMATICAL EQUATION HYDRAULIC TURBINE

In the pursuit of a mathematical model of the hydro turbine, generation of a differential equation was required. In order to find a fitting equation while avoiding excess complexities, the interaction between the water and the blade was modelled as water particles colliding with the blade, creating an impulse on the blade, causing it to move. Because of this, certain assumptions had to be made about the behavior of water. Due to the very slow movement of the turbine, drag and turbulence were excluded, as they weren’t the primary focus. Also, it was assumed that each water molecule transferred one-hundred percent of its energy to the blade.

Nomenclature:

\( V_{rel} \) = velocity of water relative to the moving prop
\( V_w \) = velocity of water
\( V_{xprop} \) = apparent velocity of blade in x direction
\( V_t \) = tangential velocity of prop
\( \theta \) = pitch of prop blade \( \omega \) = angular velocity of prop
\( r \) = length of prop blade \( h \) = height of prop blade
\( F_{w/p} \) = force of water on prop
\( P \) = impulse
\( \rho \) = density of water = 1000kg/m\(^3\)
\( d\text{Vol} \) = volume of water colliding with prop at an instant
\( \tau \) = torque on prop
\( I \) = Moment of Inertia
\( t \) = time

The tangential velocity of the blade is written as-

\[ V_t = \omega r \]

Due to the angle of the prop blade (pitch), it is given an apparent velocity in the x direction as seen by the moving water. This is accounted for as -

\[ V_{xprop} = \frac{V_t}{\tan \theta} = \frac{r\omega}{\tan \theta} \quad (1) \]

Because of this apparent velocity of the blade, the relative velocity between the water and blade is given as

\[ V_{rel} = V_w - V_{xprop} \quad (2) \]

Substituting (1) into (2) we get -

\[ V_{rel} = V_w - \frac{r\omega}{\tan \theta} \quad (3) \]

We know that force multiplied by time equals impulse;
\[ \frac{F_w}{pt} = \frac{P}{t} \]

Dividing both sides of the equation by the time we get

\[ \frac{F_w}{P} = \frac{t}{t} \]

From impulse-momentum,

\[ dF_{wp} = dmV_{rel}/dt \]

The mass of water colliding with the blade at an instant is defined as-

\[ dm = \rho w dV \text{o}l \]

The instantaneous volume is-

\[ dV \text{o}l = hV_w dtdr \]

Substituting (6) into (5), we get-

\[ dm = \rho w hV_w dtdr \]

Substituting (7) into (4), we get-

\[ dF_{wp} = \rho w hV_w \frac{dV_{rel}dtdr}{dt} \]

Substituting (3) into (8), we get-

\[ dF_{wp} = \rho w hV_w (V_w - r\omega \tan \theta) d\theta \]

In order to account for 18 blades, the force must be multiplied by the numbers of blades-

\[ \frac{18dF_w}{\rho} = 18\rho w hV_w (V_w - r\omega \tan \theta) d\theta \]

Multiplying both sides by \( r \) and integrating

\[ \int r dF = \int 18\rho w hV_w (V_w - r\omega \tan \theta) r d\theta \]

\[ F \cdot r = 18\rho w hV_w \left( \frac{V_w r^2}{2} - \frac{r^2 \omega \tan \theta}{3} \right) \]

From the definition of torque -

\[ F \cdot r = \tau = \int \frac{d\omega}{dt} \]

Substituting (10) into (9) results in the differential equation,

\[ \int \frac{d\omega}{dt} = 16\rho w hV_w \left( \frac{V_w r^2}{2} - \frac{r^2 \omega}{3 \tan \theta} \right) \]

This is the differential equation we will be using to model the torque. Furthermore, one can find an equation for the maximum omega by setting \( d\omega \) equal to zero.
Dynamic modeling of hydraulic turbine and governor for small perturbations about a steady state condition the turbine may be represented by following linearized equation.

\[ q = a_{11} h + a_{12} n + a_{13} g \]

\[ m = a_{21} h + a_{22} n + a_{23} g \]

The above equation gives the formulae for the flow \( q \) of the water to the turbine and the torque \( m \) of the turbine rotation. These two are measured for the per unit deviation with respect to the head \( h \), speed \( n \) and gate position \( g \).

Hydro Turbine Modelling

\[ 1 - \frac{sT_w}{1 + 0.5sT_w} \]  

\( T_w \) is the water time constant of the hydro-turbine.

\[ a_{11} = \frac{\partial q}{\partial h}; \quad a_{12} = \frac{\partial q}{\partial n}; \quad a_{13} = \frac{\partial q}{\partial g}; \quad a_{21} = \frac{\partial m}{\partial h}; \quad a_{22} = \frac{\partial m}{\partial n}; \quad a_{23} = \frac{\partial m}{\partial g} \]

For ideal turbine at rated speed and head:

\[ a_{11} = 0.5 \quad a_{12} = 0 \quad a_{13} = 1 \quad a_{21} = 1.5 \quad a_{22} = -1 \quad a_{23} = 1 \]

\[ T_w = \frac{0.366P_l}{H_{r2}AE} \]  

(15)
This water time constant is in terms of power($P_l$), height of the feet($H_t$), average penstock area($A$) and combined efficient turbine:

\[ 1 - \frac{T_{ws}}{1 + 0.5T_{ws}} \]

So, for the model of the hydro-turbine is concerned the hydro turbine transfer function has some special characteristic and we will discuss the specific characteristic of this hydro turbine transfer function.

V. RESULTS AND DISCUSSION

![Fig 12. Speed vs Time graph for the P Controller](image1)

![Fig 13. Speed vs Time graph for the PI Controller](image2)

Fig. 3 and fig. 4 shows P and PI controller output respectively. The first controller shows steady state error and also a long response time. In the second figure the steady state error is solved and reached the set point. But it takes more time to get the set point. Both the graph has a drawback of high oscillation and long response time.
In fig. 5 and fig. 6 we get the graph with reduced response time and also there is no oscillations. In fig 5 the set point is obtained, but the time response is still high. Therefore, in fig.6 using fuzzy logic the time response is reduced and the set point output is achieved.

Thus, these graphs show that the fuzzy logic gives the better result than the other 3 controllers (P controller, PI controller and PID controller). It gives reduced response time and a prominent output for the linear system.

VI. CONCLUSION

In this paper, we automatically control the speed of the turbine rotation with different control system methods. The pump input is being controlled by the controller according to the output achieved initially. The output from the turbine is given to the pump to be controlled through the controller. Here we are trying with some controllers. Already P Mode, PI Mode and PID Mode are all implemented. But in this the problem is there is some time delay and overshoot too. To reduce this factor, Fuzzy logic is implemented which cancels out the time delay and oscillation to some extend. This logic is implemented in the working protocol.

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