Hydro Power Plant Voltage Enhancement via BWO-tuned PI Controller

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Abstract: PI control has been the most common way to control the parameters because it is easy to set up and works well for controlling many different processes. However, the vast majority of conventional PI tuning approaches depend on trial and error for complicated processes with limited system knowledge, which may not give the ideal PI settings. In a number of situations, the tuning of PI controllers has been accomplished with excellent results by using optimization techniques. In this research, a simulation model of a hydropower plant was developed via MATLAB/Simulink software and the connection of models for the various power plant components. The objective is to determine how it performs and how it reacts to an unstable environment. By implementing a BWO (Black Widow Optimization) tuned PI controller, model voltage fluctuations have been reduced, while the voltage has been stabilized and errors have been minimized (MSE, MAE, MAPE, and RMSE).

Keywords: Hydropower plant, PI controller, BWO (Black Widow Optimization), Optimization Techniques.

1. Introduction

Coal, natural gas, and oil were the top three most popular fuels used in power generation in 2009 [1]. These resources are quickly running out and causing damaging emissions to the environment. That's why it's important to look into alternative energy sources. Hydroelectric power is a method of harnessing flowing water using a turbine, which converts the kinetic energy of water into mechanical energy. In developing countries, rural electrification through small-scale hydropower is one of the most cost-effective energy options. Hydropower is a renewable form of energy. They do not deplete resources like air, land, or sun like other types of power plants do to produce electricity. Hydroelectricity is generated in the winter and spring from the mountain streams and clean lakes. Using the types of heads often found in irrigation-based Small Hydro plants results in relatively stable electrical production. It is clear, however, that while the available head remains somewhat constant, the available discharge changes considerably. Depending on the regional crop trends, electricity generation is the sole source of power for the hydroelectric discharges used for irrigation.

1.1. PI in Hydro

PI (Proportional-Integral) controllers are commonly used in the control of hydraulic power plants, including hydroelectric power plants. The purpose of the PI controller is to govern the system output by modifying the input depending on the difference between a desired setpoint and an actual output. This aim is accomplished by the PI controller.

In the context of hydro plants, PI controllers are used to regulate water flow and the speed of turbine. This can be achieved by adjusting the turbine gates opening, which controls amount of water that enters the turbine. The PI controller receives feedback from sensors that measure the turbine speed and water flow rate, and adjusts the opening of the wicket gates accordingly.

The proportional gain (K_p) and integral gain (K_i) are the two main parameters that need to be tuned in a PI controller as shown in Equation 1. The proportionate gain influences the controller's reaction to variations in the error output, whereas the integral gain influences the steady-state error. The tuning of these parameters is critical for achieving the desired control performance. Proportional control alone may not be sufficient for controlling a hydro plant, as it can result in overshoot and instability. The addition of integral control helps to eliminate steady-state error and improve response time. However, the excessive integral gain can lead to oscillations and instability. The correct balance of proportional and integral gain is essential for achieving optimal control performance.

$$u(t) = k_p \, e(t) + k_i \int_0^t e(t) \, d(t) \quad (1)$$

1.2. Need for PI tuning

The need for PI tuning in a hydro plant arises from the fact that hydraulic power generation involves complex and dynamic processes that require precise control. The goal of PI tuning is to optimize the performance of the control system by adjusting the values of the controller parameters to achieve the desired response characteristics.

Here are some specific reasons why PI tuning is necessary for a hydro plant:

a) Improved efficiency: The correct tuning of PI controllers can improve the efficiency of the hydro plant by regulating the water flow and the speed of the turbine. This helps to minimize losses and ensure that the plant is operating at maximum efficiency.
b) Stability and safety: The proper tuning of PI controllers ensures that the control system is stable and able to respond quickly to changes in the system. This is important for maintaining the safety of the plant and preventing damage to the equipment.
c) Adaptability: Hydro plants are subject to a wide range of operating conditions and external factors such as changes in the weather or the water level. Properly tuned PI controllers can adapt to these changes and help to maintain the stable operation of the plant.
d) Reduced maintenance costs: An optimally tuned PI controller can reduce wear and tear on the plant equipment by minimizing unnecessary or excessive movements of the turbine wicket gates. This can result in lower maintenance costs and longer equipment life.

Overall, PI tuning is an important aspect of the control system design and maintenance in a hydro plant and is essential for ensuring efficient, safe, and reliable operation of the plant. Traditional PID tuning approaches [2] may be divided into three distinct categories: rule-based tuning, heuristic tuning, and optimization-based (or model-based) tuning. Even if intuitive tuning may be achieved by trial and error with an accurate grasp of the role of each PI parameter, this is almost often the case. This approach is straightforward to implement, but it is time-consuming and may not provide reliable results [2]. Rule-based tuning, which includes Ziegler-Nichols, Cohen-Coon, Kappa-Tau, and Lambda tuning [3,] involves using basic models to estimate the process based on the step test (often first-order plus dead-time models) usually first-order plus dead-time models. These methods are sensitive to changes in the actual process and the approximation model notwithstanding their widespread use. If a precise process model and a detailed technical specification are available, optimization-based approaches may be used to determine the ideal PID values. Nonetheless, such tactics need a sufficiently detailed model [4], which may be difficult to develop in practice. The unique PI tuning technique described in this work was based on the solution of an optimization problem. This strategy has a lot of potential and is far more dependable and flexible than its rivals. It also does not impose any limitations on the chosen PID controller or process model. In [5], propose a robust IMC-based PID controller for hydropower plants with the water hammer effect. The stability of the hydraulic unit was found to be enhanced by the suggested tuning method. This study provides a thorough analysis of metaheuristic algorithms and how PID controller tuning uses them [6]. A description of the most sophisticated metaheuristic techniques for PID controller parameter tuning is provided, in [7]. It has been shown that novel optimization strategies for the optimal tuning of PID controllers generate better results than the old way by using simulation findings based on transient response characteristics. In the paper [8-9] FLC and other optimization techniques are discussed for PID tuning, and frequency control using optimization techniques via PI tuning in the paper [10].

1.3. Techniques used for PID tunning

Automatic Generation Control (AGC) of a multi-source, multi-area connected power system was effectively handled using PID & I-PD controllers, which were suggested & successfully implemented in a publication [11]. These controllers' gains were accomplished using the Fitness Dependent Optimizer (FDO) algorithm. A two-area reheat thermal, gas, and hydropower system is used to assess the performance of FDO-based controllers, in particular FDO-PID and FDO-I-PD. This investigation's main objectives are FDO-PID and FDO-I-PD. The FDO-PID and FDO-I-PD controllers are unquestionably the best when it comes to thermal reheat, gas, hydro, and multi-source power output in terms of the time of settling (Ts), overshoot, and undershoot. This is the case when comparing the results. A design method for selecting PID controller parameters to stabilize an electrohydraulic servo control system was provided in [12] using BFA, PSO, GA, and ACO. Stability was discovered by reducing step response uncertainty. In contrast to GA, modern desktop or workstation PCs with high-end specifications are required for obtaining a higher-quality solution with a faster response time when using this algorithm. Additionally, a suggested BFA approach is capable of avoiding the issue of the PSO method's premature convergence and obtaining a solution of a higher quality while simultaneously improving computing efficiency.

PID controllers used in the artificial regulation of insulin are tuned using optimization algorithms like BSOA, CTOA, GA, GSA, GWOA, PSO, and SRA [13]. It has been found that the GWOA technique is more suitable for the process of simulating using MATLAB-Simulink and then doing online analysis in real-time, where a decision is made based on performance data that was obtained after the simulation was performed. PID controller parameters for two different processes are tuned using two different optimization algorithms in a paper [14], and it is concluded that in CSTR (Continuous Stirred-Tank Reactor), the PSO-based tuned values outperform the GA. The responses are essentially the same for both optimization procedures in the QTP process (Quick Test Professional), notwithstanding a little variance in peak overshoot values. In [15], the system parameter value is optimized using GA, FA, & PSO algorithms, and a PI controller is implemented to regulate it. To evaluate controller settings, each of these approaches employs a different cost function, which includes Integral Time Square Error (ITSE) or Integral Time Absolute Error (ITAE). From the foregoing replies, it can be seen that PSO has an optimum response in terms of Ts and overshooting. These three optimization techniques were all employed to obtain the ideal PI controller parameters comparison to the PI and PID topologies used in this experiment, PID configuration, according to the paper [16], was much more effective. Optimization strategies were more successful than analytical or traditional tuning methods for controllers.

1.4. BWO (Black Widow Optimization)

Black Widow Optimization (BWO) is a recently developed optimization algorithm inspired by hunting behaviour of black widow spiders. BWO is a meta-heuristic algorithm that can be used for global optimization problems, including the tuning of PI controllers in hydro plants. The BWO algorithm simulates the hunting behavior of black widow spiders, which involves searching for prey in a complex environment. The spiders use a combination of exploration and exploitation strategies to find best prey. These techniques are used in the BWO algorithm to traverse the search space and reach the global optimum.

The BWO algorithm can be applied to PI tuning in hydro plants by treating the controller parameters as the decision variables to be optimized. The algorithm employs a fitness function that evaluates the performance of a control system using metrics including rise time, settling time, overshoot, and steady-state error. Fitness function is used to performance evaluate of each candidate solution and guide the search toward the global optimum. Compared to other optimization algorithms, BWO has several advantages for PI tuning in hydro plants, including its ability to handle non-linear and non-convex optimization problems, and its ability to converge quickly to the global optimum. BWO is also less likely to get trapped in local optima, which can be a problem for other optimization methods.

The grey wolf algorithm is only one example of an optimization approach that was developed after being inspired by the beauty of the natural world. Packs of 5-12 wolves are ideal for these gregarious animals. Wolf pack hierarchy was divided into four distinct levels:

alpha (a), beta (b), omega (x), and delta (d). In a pack, the alpha has ultimate authority and always gets his or her way. Level 2 is where beta will find, while level 3 is where find Omega. Delta follows Alpha's and Beta's directives but has the upper hand while battling Omega. This algorithm is modelled like a pack of wolves that goes out to hunt. Following, encircling, and attacking the victim are the three stages of GWOA. Black Widow Optimization (BWO) is presented in this research as a unique metaheuristic optimization method with motivation drawn from the unusual courtship behaviours of black widow spiders. There are essential differences between the proposed method and its predecessors. Due to its rapid convergence speed and avoidance of local optimization difficulties, the BWO algorithm is an excellent option for both the exploitation and exploration phases. It is also important to note that BWO may find a balance between exploitation and exploration. Numerous optimization problems can have multiple local optimum solutions, but because BWO can investigate a vast region, it is a viable option. The suggested BWO approach is evaluated on 51 benchmark functions and 3 practical engineering optimization issues to determine its efficiency. Compared to existing meta-heuristic algorithms such as GA, PSO, BBO, ALO [17], MFO [18], GWO [19], WOA [20], SHO [21], MVO [22], and HS [23], the gathered data shows that the suggested method provides better results. Figure 1 illustrates the BWO process flowchart.

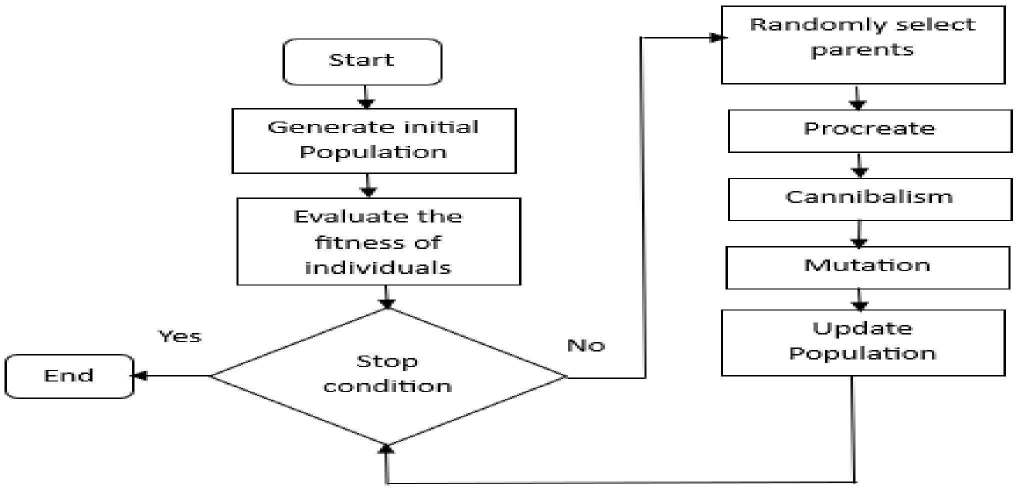

Fig. 1. Flow chart of BWO

Section 2. shows the mathematical modelling of the Hydropower plant.

Section 3. shows the Governing system and Hydraulic turbine modelling.

Section 4. The materialistic Approach for PI tunning is discussed.

Section 5. The simulation model Hydropower Plant is explained briefly.

Section 6. Result and conclusion included.

2. Mathematical Modeling

Mathematical modeling of hydro plants involves the development of mathematical equations that describe the dynamic behavior of the plant. These models are used for a wide range of purposes, including design, control, optimization, and analysis of the plant's performance.

The mathematical modeling of hydro plants typically involves the following steps:

a) System identification: This involves the collection of data from the plant, such as flow rates, pressure, and temperature, to identify the key variables and parameters that influence the behavior of the plant.
b) Model formulation: Based on the system identification, a set of mathematical equations are developed that describe the dynamic behavior of the plant. These equations may include mass and energy balances, conservation equations, and empirical correlations.
c) Model validation: The model is validated by comparing its predictions with experimental data obtained from the plant. This helps to ensure that the model accurately represents the plant's behavior under different operation conditions.
d) The validated model may then be utilized in simulation studies to provide predictions about the plant's behavior in a variety of operating situations. Simulation studies can help to identify potential problems, optimize the design and operation of the plant, and improve the efficiency and performance of the plant.

Differential equations are commonly used to describe relationships between the many parts of a power system. Studying a system's behavior requires the use of differential equations, which are useful due to their varying nature [24]. For a small system, linear system analysis methods are used to explore dynamic behavior in the context of linear system equations. Each part of the system under study is a transfer function block connected to illustrate the system. For systems on a large scale, a state-space model will be employed to study the system using linear differential equations. To examine temporary stability, however, nonlinear differential equations are used [25].

2.1. Modeling Techniques for a Small Hydroelectric Plant

There are several methods for modeling a small hydropower plant, depending on the level of detail required and the purpose of the model [26]. Some common methods include:

a) Empirical models: Empirical models are based on statistical correlations between input and output variables. These models are relatively simple and easy to develop, but they may not capture the system’s underlying physics. Empirical models are often used for preliminary design studies or feasibility studies.
b) Mathematical models: Mathematical models are based on laws of physics and describe the behavior of the system using mathematical equations. These models can be quite detailed and accurate, but they require a significant amount of data and computational resources to develop and run. Mathematical models are often used for detailed design studies or performance analysis.
c) System identification: System identification involves collecting data from the hydropower plant and using statistical techniques to identify the underlying system dynamics. This method can be used to develop both empirical and mathematical models and can be particularly useful when data is limited or the system is complex.
d) Simulation models: Simulation models use mathematical models to simulate behavior of hydropower plants under different operating conditions. These models can be used to optimize the design and operation of the plant, and to evaluate the impact of changes in the system.

3. Governing System and Hydraulic Turbine Modeling

3.1. Hydraulic Turbine Modelling [28]

Hydraulic turbines are the key components in hydropower plants, and their modeling is critical for design, operation, and control of these plants. Modeling hydraulic turbines involves developing mathematical equations that describe their dynamic behavior under different operating conditions [27]. This section covers the equations that describe the fluctuations in flow and mechanical power that were derived regarding turbine speed, gate opening, & runner blade movement of a hydro turbine. Because Francis operates more efficiently than others, it is employed in a variety of hydraulic applications. The Francis turbine is therefore utilized in this modeling; as a result, the fluid's pressure will fall as the water flows through the turbine. Falling pressure across the turbine causes a reduction in output power. Since turbine's power production is proportional to water velocity, system starts to work or reaches a steady state when the penstock's flow rate is constant. The following assumption [28] underpins the equations that characterize the transient performance of hydraulic turbines. As may be seen in Figure 2, the Hydraulic power plant is laid out in a block design.

i. The frictional resistance of a hydraulic turbine's blade is disregarded since it is thought to be smooth.

ii. Penstock water hammer is ignored.

iii. Fluid is thought to be incompressible.

iv. The water's velocity in the penstock changes instantly when the gate opens.

v. The output power of a turbine is a function of the head and flow velocity product.

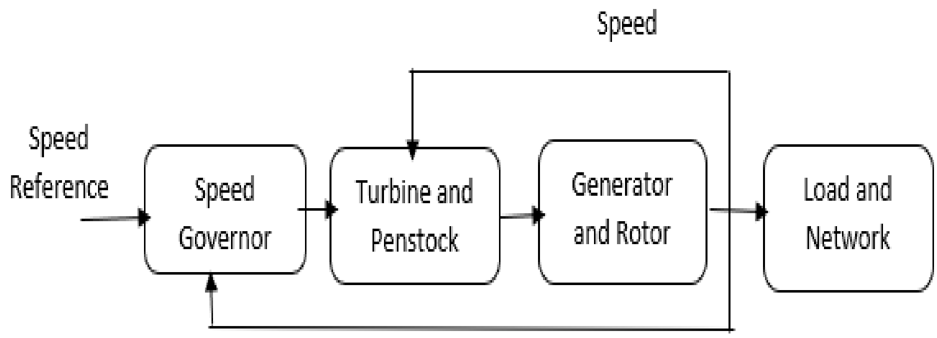

Fig. 2. Simplified functional block of a Hydraulic power plant

3.1. Governor Modelling

Governors are critical components in hydropower plants as they control the power output of the turbines by regulating the water flow to the turbines. The modeling of governors involves developing mathematical equations that describe their dynamic behavior under different operating conditions.

The most commonly used approach for modeling governors is the transfer function method, which involves deriving a transfer function that relates the output of the governor (e.g., the gate opening) to the input signal (e.g., the electrical power demand). The transfer function can be derived using either empirical or analytical methods. The primary responsibility of a governor is to control the vehicle's speed and/or load. Primary purpose of the speed and load controller is to transmit back speed errors to modify the gate position. The speed governor is fitted with a droop feature to enable excellent and stable parallel functioning of numerous units. The load-sharing capabilities offered by Droop are intended to be fair and equitable across the various producing units. As a result, a sizeable transient droop in conjunction with an extended resetting time is necessary for reliable control performance [28]. This may be accomplished by the use of rate feedback or through the provision of compensation for a momentary loss in gain.

3.2. Mechanical-hydraulic governor model

Mechanical-hydraulic governor model typically includes three main components: the governor mechanism, the hydraulic servo system, and the turbine. The governor mechanism is responsible for converting the mechanical input signal (e.g., the rotational speed of the turbine) into a hydraulic signal that controls the position of the hydraulic servo valve. The hydraulic servo system then converts the hydraulic signal into a mechanical force that controls the position of the turbine's wicket gates, which regulate the water flow to the turbine. The mechanical-hydraulic governor is made up of many parts, such as a relay valve, a gate servomotor, a dashpot for transient droop correction, calculation functions, and speed sensors. Transfer function of relay, gate, and valve servomotor is shown in equations 2-5;

$$\frac{g}{a} = \frac{K_1}{S} \tag{2}$$

The pilot valve with pilot servo transfer function is

$$\frac{a}{b} = \frac{K_2}{1+S\,T_P} \tag{3}$$

T_P is set by the ratio of the levers that provide feedback, and K_2 is a function of the pilot valve's port area.

$$\frac{g}{b} = \frac{K_1K_2}{s(1+s\,T_P)} = \frac{K_S}{s(1+s\,T_P)}$$

(4)

Where K_s is servo gain;

Transfer function of dashpot is provided by

$$\frac{d}{g} = R_T\,\frac{sT_R}{s(1+s\,T_R)}$$

(5)

Lever ratio controls the amount of temporary droop, while the needle valve setting controls the amount of time needed to reset and wash out the system. System stability analysis is appropriate with a block diagram representation of the controlling system.

3.3.Excitation system modeling

There are many different kinds of excitation systems, but they all consist of basic components like DC or AC exciters, rectifiers, amplifiers, stabilizing feedback circuits, signal detectors, & signal processors [28].

4. Materialistic Approach for PI tunning & Problem formulation

A popular technique for fine-tuning control loops is the Ziegler-Nichols (ZN) approach. It was initially discussed in a 1942 study written by J.G. Ziegler and N.B. Nichols. The materialistic approach for PI tuning involves a systematic method for tuning parameters of proportional-integral (PI) controller based on the physical properties and characteristics of the system being controlled. This approach is based on the understanding that the performance of the PI controller is highly dependent on the dynamics of the controlled system and the interaction between the system and the controller.

The problem formulation for PI tuning involves defining the objective function and constraints for the optimization problem. The objective function is typically defined as a measure of the performance of the PI controller. The constraints can include limits on the values of the PI controller parameters, such as the maximum and minimum values of the proportional and integral gains. In order to determine the proportional (KP) and integral gain (Ki) of the PI controller used in hydropower plants, this study utilized a number of optimization approaches, as shown below. The fitness function is MAE and performance is evaluated using MAE, MSE, MAPE & RMSE errors using equations 6-9 respectively.

$$\text{MSE}=\frac{1}{n}*\Sigma(\text{desired o/p value}-\text{actual o/p value})^2 \tag{6}$$

where, n = number of items

$$\text{MAE}=\frac{1}{n}\sum_{t=1}^{n}|e_t| \tag{7}$$

$$\text{MAPE}=\frac{100\%}{n}\sum_{t=1}^{n}\left|\frac{e_t}{y_t}\right| \tag{8}$$

$$\text{RMSE}=\sqrt{\frac{1}{n}\sum_{t=1}^{n}e_t{}^2} \tag{9}$$

5. Simulation model of Hydro Power Plant

A hydropower plant simulation model is an electronic representation of such a facility, designed to replicate its operation under varying environmental and mechanical circumstances. The model typically includes mathematical equations describing the power plant's physical processes and components.

The simulation model can be used to predict the power output and efficiency of the hydropower plant under various scenarios, such as changes in water flow rates, operating schedules, and maintenance requirements. It can also be used to optimize the operation of the power plant and identify opportunities to improve its performance, such as by adjusting the operating parameters of the turbines or optimizing the water flow through the penstocks.

A simulation system for exploring hydraulic transients in hydroelectric power plants was developed using MATLAB/Simulink. Three subsystems were used to simplify system layouts i.e., Hydraulic turbine, Excitation System and Synchronous Generator respectively and create reconstructed systems. The integration of three subsystems is shown in Figure 3.

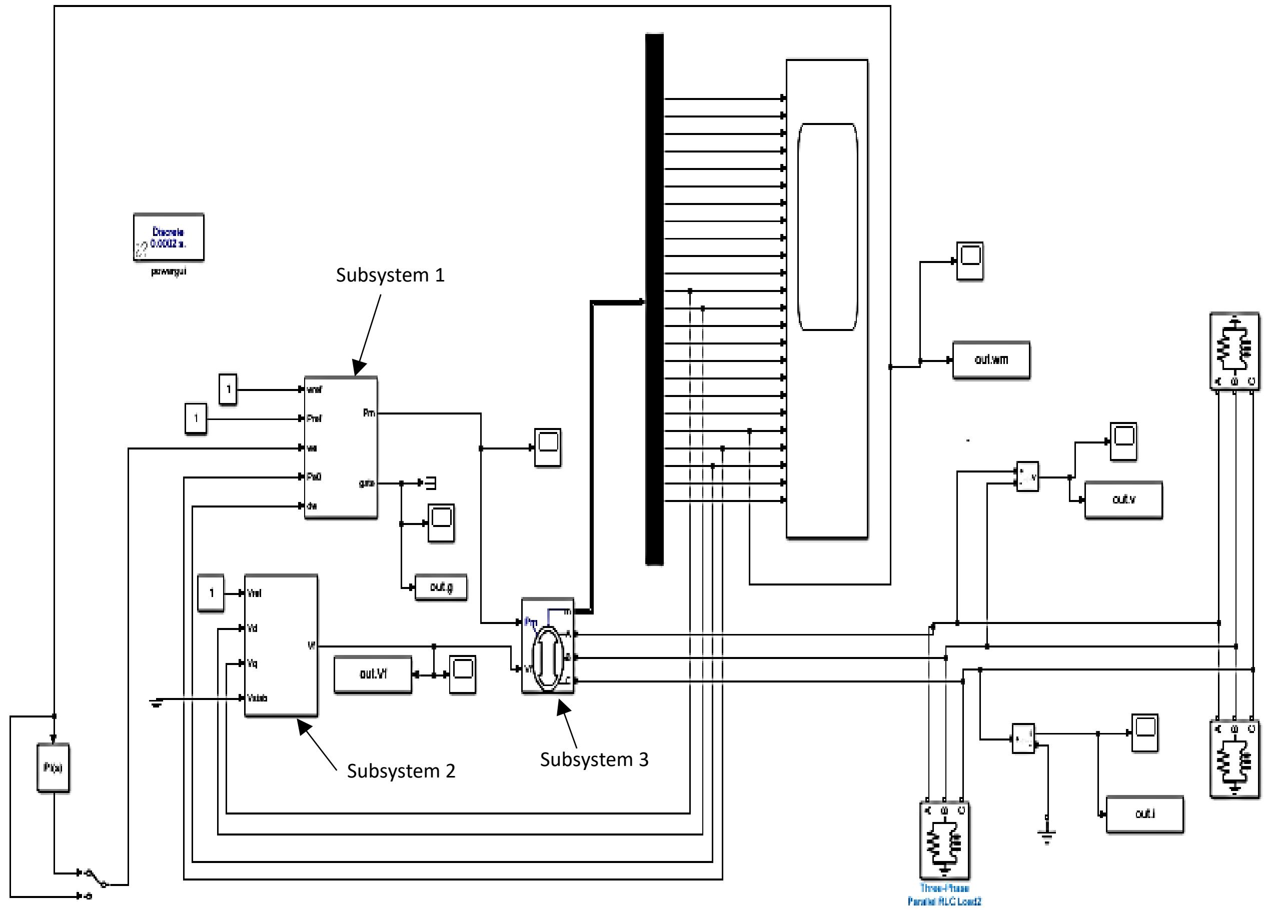

Fig. 3. Hydropower plant with PI controller

In Figure 3, a PI controller is added. It allows for running the plant under a variety of operational situations. As a result, all plant data is used to simulate hydraulic transients for a variety of scenarios. To run under a variety of operational situations, all of these simulations. The specifications of these units are given in the next section.

5.1. Turbine and Governor Parameters

The regulating system, often known as the governor, is the hydraulic turbine's primary controller. Governor adjusts water flow through a turbine to control its speed and power output. Governor has control over frequency of system as well as speed-producing units [28].

Hydro Power Plant Parameters	
1. Turbine and Governor Parameters	T_w is water starting time= 3 Reference frequency; ω_{ref} = 1p.u. Servo-motor parameters T_a = 0.07, K_a =10/3 Permanent droop and regulator are; R_p =0.05, K_p = 3, K_i = 0.10, K_d = 3.26, T_d =0.02 Gas turbine fuel valve opening limits are g_{min} =0.01, g_{max} =0.97518, v_{gmin} =-0.1, v_{gmax} =0.
2. Exciter Parameters	Reference voltage; V_{ref} = 1 Terminal voltage; V_{ter} = 1 Transient gain reduction; Tb and Tc = 0.00001, 0.00001 Gas turbine fuel valve opening limits are; V_{rmax} = -15, V_{rmin} = 7.3 LPF time constant Tr(s), T_r =0.87 Regulator gain and time constant; K_a =200, T_a =0.02 Exciter parameters; K_e =1, T_e = 0.08 Damping filter gain and time constant; K_f =0.03, T_f =1 Initial value of voltage; V_f =1.2911
3. Synchronous Generator Parameters	Nominal power, line-to-line voltage, frequency is; P_n =1.3 MW, V_n =415V, f =50

	Reactance's are; Xd =0.911, Xd' =0.408, Xd'' =0.329, Xq =0.580, Xq'' =0.350, X1 =0.3. Tie constants; Td' =0.7, Td'' =0.035, $Tq0''$ =0.033, Stator resistance; Rs =0.03 Inertia coefficient; H =1, pole pairs; P =4, Vf =1
4. PID Controller Parameter	Kp = 0.01, Ki = -0.88, Kd = 0.

6. Results and Conclusion

As seen in Figures 5 and 6, the load in this plant is connected to a synchronous generator through a transmission line. The generator has a 1.2 MW load. Since the oscillations during the transient period are so enormous, they interfere with the generator's gate functioning and mechanical input. A PID controller is utilized for error reduction after tuning its parameters i.e., K_p and K_i using six different techniques. A comparison of results is given in Table 1.

Table 1. Different Errors comparison results

Techniques	MAE	MSE	MAPE	RMSE
PI [K_p, K_i]	0.18082839	0.05377593	0.18082839	0.23189637
PSO	0.00805725	0.00009674	0.01191551	0.00980553
FF	0.00802079	0.00009549	0.00801867	0.00976469
CC	0.02752624	0.00080418	0.02752262	0.02969827
GWO	0.02752263	0.00080415	0.02752263	0.02835751
BWO	0.00799788	0.00009485	0.00799787	0.00973888

According to waveforms, there were several irregularities in mechanical power (input to the generator) & gate functioning when the plant was first linked to its load. Using a PI controller with PSO, FF, CUCKOO, GWO, and BWO drastically reduced the MSE, MAPE, MAE, and RMSE errors. As shown in table 1, BWO gives better results as compared to other techniques (PI, FF, GWO, CUCKOO, & PSO). Additionally regulated were the maximum overshoot and maximum undershoot. We may conclude that the oscillations and errors were lower during the transient phase by using BWO. In addition to that in the future, that system is connected with the main system or microgrid for better performance.

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