

MODELLING AND SIMULATION OF HYDROPOWER PLANT USING PSO-TUNED CONTROLLER

Hari O. Bansal,* Tanuj Sen,* and Hanuman P. Agrawal**

Abstract

As the world turns towards cleaner sources of energy, the hydraulic power plants are being set-up to minimize the dependence on fossil fuel. This paper presents a dynamic model of a small hydropower plant. The proposed system senses the requirement of electrical power at the load end and generates the required mechanical power to meet out the said demand. The mechanical power output of the turbine is controlled by changing the gate position. It limits the amount of water turning the turbine, which, in turn, is controlled through a servomotor mechanism consisting of a proportional integral derivative (PID) controller. The PID controller is tuned using classical techniques and particle swarm optimization technique. The performance of the controller is found to be much better and stable in the latter case. The frequency deviation of the power supplied is also controlled and presented here for various load swings.

Key Words

Particle swarm optimization, frequency deviation, power surge, servomotor-controlled gate position, turbine, electrical power, mechanical power

1. Introduction

Electricity has become an integral part in every human's life. Nearly, all the appliances and systems used today, both in households and in the industrial framework, require electricity to function. Therefore, it has become almost impossible to think about life without electricity. The demand for electricity has grown manifolds over the years since its inception in the late 19th century and continues to grow at an ever-increasing rate.

The electricity is generated by power-generating stations which can be classified based on the types of resources they utilize for power generation. Some power stations use

the energy provided by fossil fuels, whereas others use non-renewable sources of energy. Renewable energy sources include water, wind, solar, geothermal or tidal which are used in the generation of electrical energy [1].

This paper focuses on the aspects of a hydropower station which uses water energy to generate electricity. There is a lot of untapped hydropower available which can be harnessed to minimize dependence on fossil fuels [2]. These plants normally involve building dams which block the flow of water forming reservoirs in the course of a river. The water falls from a great height and has enough potential energy to turn the turbines which acts as prime movers to the generators. This produces electricity that can be distributed to households as well as industries through a power grid. For better energy exploitation from a small-scale hydropower plants, their location is very important. Hydropower system planning is proposed in [3] for optimal utilization of resources.

It is of great importance to study the behaviour of a power plant when there are sudden or gradual changes in the load and also to reduce energy loss in the electromechanical energy conversion process. In this work, a model is proposed which tries to minimize the difference between the mechanical and the electrical power through a negative feedback. The demanded electrical power is tracked at the load end and inlet gates are opened/closed through a servomotor mechanism to produce the required mechanical power to meet out electrical power demand. The simulations for various changes in electrical load are provided to show the system response as to how quickly mechanical power can follow these changes. The effect of frequency deviation is studied in [1], [4]. The sensitivity of hydropower performance with climate change is studied in [5].

To obtain efficient gate control, a proportional integral derivative (PID) controller is added to the servomotor mechanism whose parameters are determined using a particle swarm optimization (PSO) technique. The performance indices, namely, integral square error (ISE), integral absolute error (IAE), integral time absolute error (ITAE) and integral square absolute error (ISAE) are used to determine the optimal values of controller parameters [6], [7] and [8]. The results are tested and compared with the results available using classical methods.

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In most practical cases, the power plant operates at nearly about half of its rated capacity or power rating. If a power plant operates at its rated capacity and the demand is less, then it results in loss of energy. Therefore, a need arises for efficient power systems which can produce the demanded power efficiently. To minimize losses and improve energy efficiency in the electromechanical energy conversion process, turbine rotations need to be controlled which is achieved by controlling the water inflow and, thus, by controlling the gate opening.

The relationship between gate opening/closing and turbine power needs to be determined which would also depend upon the gate control technique. The supply to the grid must be at a constant frequency and to attain, frequency deviation is taken as a prime control parameter [1], [4], [9], [10]. The frequency deviation value is fed back and compared with a reference value of zero and this error signal acts as control signal for the servomotor mechanism. The deviation in frequency arises due to sudden changes in the load and also due to mismatches between mechanical and electrical power. Thus, in addition to control the frequency deviation, one should also minimize the difference between mechanical and electrical power for efficient plant control and energy generation.

2. Proposed Methodology

In this paper, the difference between mechanical power generated and required electrical power is tracked at every instant and sent as a feedback. Further, to achieve zero frequency deviation, the transfer function of the generator is modified with a feedback loop involving a gain. Later, in this work, the relationship between the feedback gain and the frequency deviation is also shown.

The servomotor along with a PID controller uses this error signal for efficient control of the gate opening. This controller can be tuned using preferred classical methods such as the Ziegler–Nichols or Cohen–Coon method. However, these days, many intelligent tuning algorithms such as genetic algorithm, artificial neural network and PSO technique are applied to tune the controller parameters [6, 12, 13]. In this work, authors have used PSO which improves the results significantly.

PSO involves determination of the best fit result using some objective function as the reference. Here, the performance indices are the objective function which are used to calculate the fitness of a variable's position and hence determine the optimal solution. This algorithm works by simultaneously maintaining several candidate solutions in the search space. During each iteration, each candidate solution is evaluated by the objective function being optimized that determines the fitness of that solution. Each candidate solution can be thought of as a particle "flying" through the fitness landscape finding the maximum or minimum of the objective function. Initially, the PSO algorithm chooses candidate solutions randomly within the search space. The search space is composed of all the possible solutions along the x -axis. It should be noted that the PSO algorithm has no knowledge of the underlying objective function, and thus has no way of knowing if any

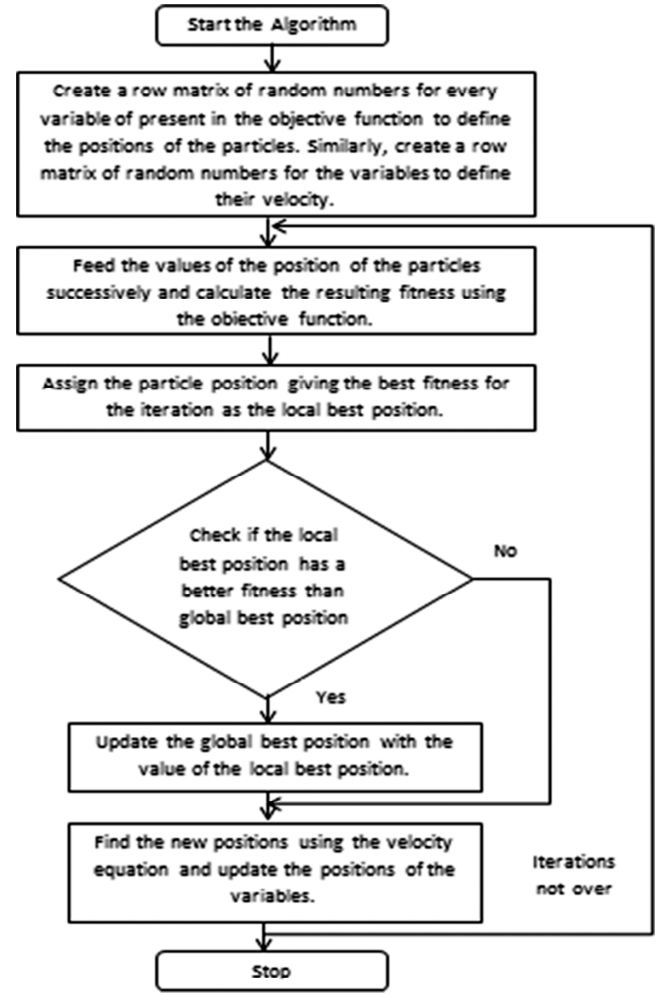


Figure 1. Flowchart for particle swarm optimization.

of the candidate solutions are near to or far away from a local or global maximum. The PSO algorithm simply uses the objective function to evaluate its candidate solutions, and operates upon the resultant fitness values [6]. The following performance indices are used as objective functions where $e(t)$ stands for error signal with respect to time:

$$IAE = \int_0^{\tau} |e(t)| dt \quad (1)$$

$$ISAE = \int_0^{\tau} |e(t)|^2 dt \quad (2)$$

$$ITAE = \int_0^{\tau} t |e(t)|^2 dt \quad (3)$$

$$ISE = \int_0^{\tau} e(t)^2 dt \quad (4)$$

Computational methods are used for self-tuning or auto-tuning of controllers. Self-tuning controllers essentially set the controller parameters (K_p , K_d , etc.). It also compares the outputs to see if there are any process variations; if so, the controller parameters are reset to give the desired response [7]. The flowchart of PSO technique is shown as flowchart in Fig. 1.

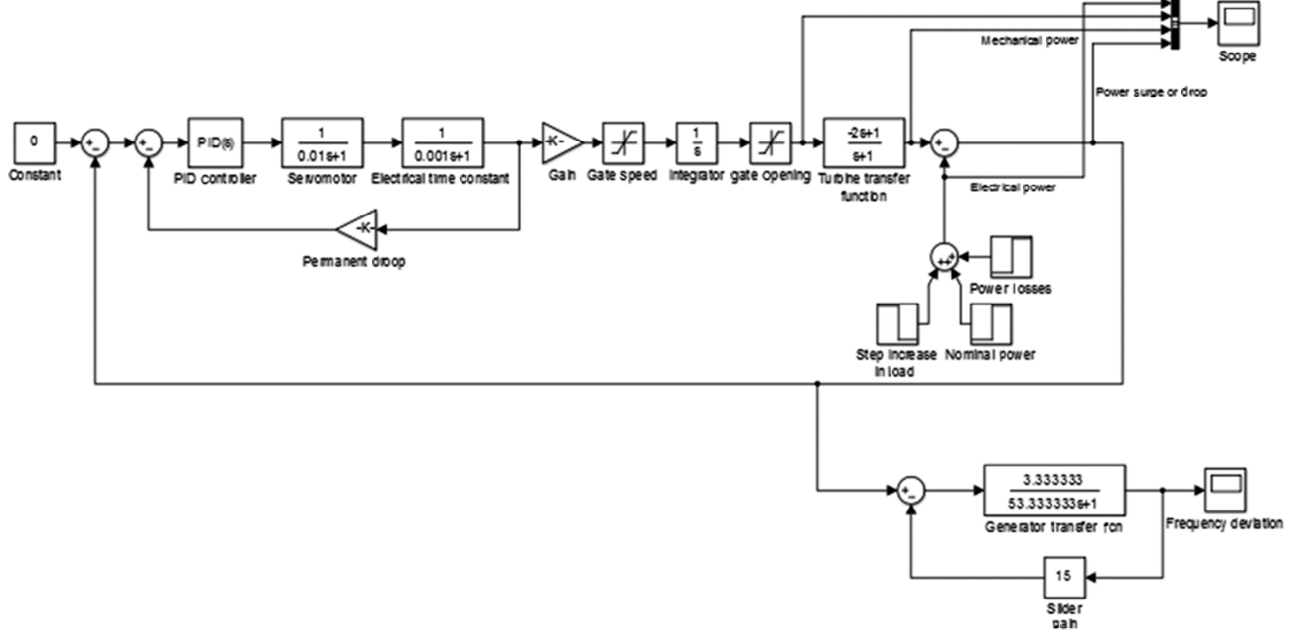


Figure 2. Dynamic model of a small hydropower system using servomotor control.

3. Proposed Model

Figure 2 depicts the proposed model used to frame the small hydropower system. This model depicts the behaviour of the hydro-electric power system when it experiences a sudden change in the electrical load connected across its output terminals. The frequency deviation of the current is proportional to the accelerating torque provided to the prime mover. This is used to control the functioning of the servomotor controlling the movement and opening of the gates.

The servomotor regulates the gate opening in accordance with the electrical power required. The servomotor generally possesses both mechanical and electrical characteristics and to depict these their time constants are taken as 0.01 and 0.001 s, respectively, as the electrical response is always faster than its mechanical response [1]. A feedback loop which accounts for the permanent droop (5%) is also included here [4].

The output of the servomotor set-up is amplified (gain should be typically between 5 and 10) to provide effective control of the water gates [1]. The output of the amplifier is the speed of the motor which controls the movement of the gate. Angular velocity of motor is controlled between 0.01 and -0.01 p.u. The output of this block is integrated to provide opening of the gate between 0 and 1 p.u.

The gate opening controls the amount of water entering the turbine system. To replicate the functioning of the turbine system, transfer function of the turbine is formulated as in [4] and shown in (5) and (6). Water time constant (T_w) is an important parameter which basically represent the acceleration time and is given in (6)

$$T(s) = \frac{1 - sT_w}{1 + s\frac{T_w}{2}} \quad (5)$$

and

$$T_w = \frac{Lq_{base}}{Ah_{base}} \quad (6)$$

where L is the Penstock length in meters, A is the Penstock area in square meters, q_{base} is the turbine flow rate and h_{base} is the available static head.

The mechanical power developed can be found out through the product of the gate opening value and the turbine transfer function [4] and the same can be calculated by the following equation:

$$P_m = G \frac{1 - sT_w}{1 + s\frac{T_w}{2}} \quad (7)$$

where G is the per unit gate opening.

The behaviour of generator due to variations in accelerating power is studied for finding out the frequency deviation. The generator transfer function is so framed that it gives the deviation in its operating frequency and shown in the following equation [11]:

$$G_{sys}(S) = \frac{\Delta f}{\Delta P_e} = \frac{1}{K_{sys}(1 + sT_{sys})} \quad (8)$$

where Δf is the deviation in the frequency; ΔP_e is the power difference (mechanical–electrical), K_{sys} is the system frequency characteristic constant; T_{sys} is the inherent time delay.

On considering the value of $1/K_{sys}$ to be a new constant, this equation can also be written as follows:

$$G_{sys}(S) = \frac{K_p}{1 + sT_p} \quad (9)$$

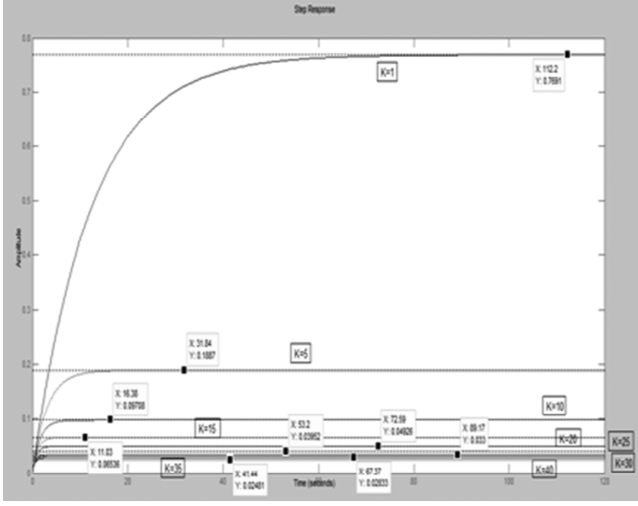


Figure 3. Step response of generator with feedback loop for various values of loop gain K .

In addition to this, a feedback loop (gain K) is added to stabilize the frequency of operation and to minimize its deviations. The combined transfer function of the generator is given as follows:

$$G_{fb}(S) = \frac{K'K_p}{1 + sT_p + K'K_p} \quad (10)$$

This combined transfer function leads to a decrease in output with an increase in feedback gain. This can be efficiently utilized to minimize the frequency deviation and to provide a better response. However, the value of feedback gain has to be decided optimally.

The step response showing the maximum value of frequency deviation is found for several values of gain K and shown in Fig. 3. It infers that an inverse relationship exists between the value of K and frequency deviation. For most generators, the operating frequency is limited to the deviation in a range of about $\pm 5\%$ and hence the corresponding value of K is chosen to be 15.

The value of the mean electrical power is taken as 0.48 p.u. [1]. In most cases, it is found that the mean power derived from a power system is almost about 50% of its total capacity. Also, a value of 0.03 p.u. is added to mean electrical power to account for various losses in the generation system. The load swings have been taken in accordance with this mean value.

4. Simulation Results

The model's behaviour was studied for various types of disturbances at the load end. The ability of the power system to track changes in the electrical power demand and to respond accordingly by producing the required amount of mechanical power can be seen in the following graphs. Also, the frequency deviation using the generator having a feedback loop has also been depicted in the graphs.

Figure 4 shows the regulation in the mechanical power generated with step changes in the electrical power by

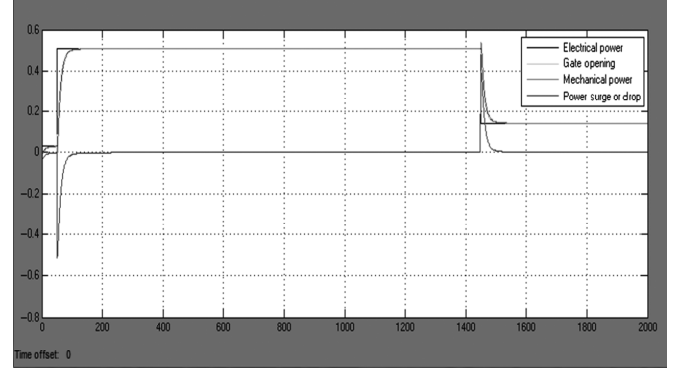


Figure 4. Response of the system due to step changes in the load.

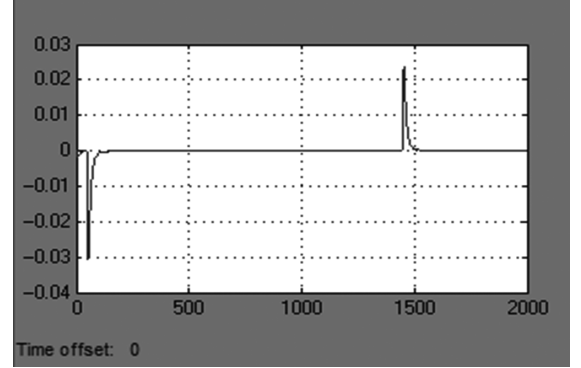


Figure 5. Frequency deviation due to step changes in the load.

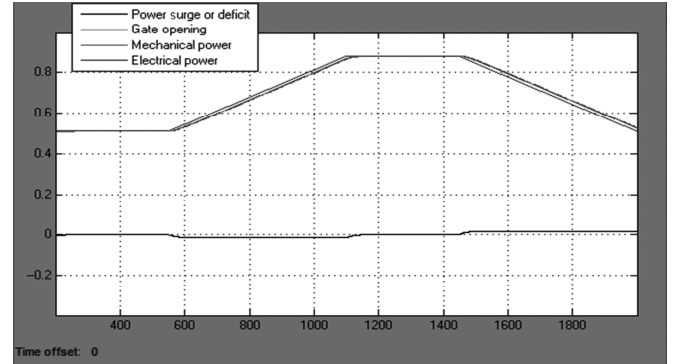


Figure 6. Response of the system due to ramp changes in the load.

controlling the opening of the turbine gates. From the figure, it is evident that the mechanical power exactly tracks the gate opening in p.u. terms, except for a slight lowering in the value when the gate starts opening initially. This is due to decreased pressure of water flow in turbine when gate starts opening. A similar but opposite is marked when gate starts closing. The system takes time in responding to the changes in the load. This is because the gate cannot open up to a defined level instantaneously but needs time to do so, and as a result the mechanical power

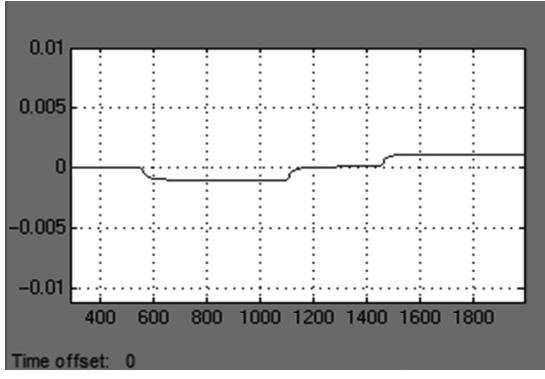


Figure 7. Frequency deviation for a ramp change in the load.

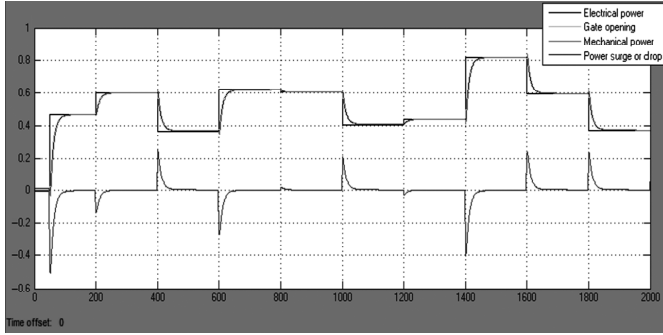


Figure 8. System response for Gaussian disturbances at the load.

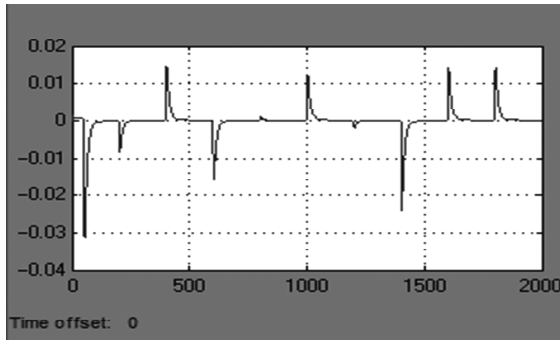


Figure 9. Frequency deviation due to Gaussian disturbance at the load.

lags behind. This causes a huge amount of power deficit in case of an increase in the load and a large power surge (as large as ± 0.5 p.u.) in case of a decrease, which will have detrimental effects.

The frequency deviation for the above mode of operation is shown in Fig. 5. From this figure, it can be observed that the maximum frequency deviation is around 0.03 p.u. of the optimal operation.

The next simulation was carried with the disturbances in load being modelled by a ramp signal. The disturbances were framed so as to increase the electrical power demand to a value of 0.85 p.u. from 0.48 p.u. over a period of 550 s and then decrease to the former value over the same time period. Figure 6 shows that the system responds better to ramp changes which are evident by almost negligible values of power surge or deficit. Figure 7 shows that frequency deviation is found to be around 0.09% which is almost 30 times lesser as compared to the case of step changes in the load.

Another simulation that is performed with a Gaussian disturbance in the load. The general daily demand for electrical power can be closely approximated by a Gaussian distribution. The changes are in the scale of seconds; however, such changes normally occur in the scale of hours. The response of system and resulting frequency deviation are provided in Figs. 8 and 9, respectively.

The response for Gaussian disturbance in the load is similar to the response for step changes as the changes in the load are step in nature. For large changes, the power surge or deficits are found to be of very large magnitude and the maximum value of this is 0.49 per unit. A similar response has been noticed in frequency deviation graph but frequency swing is still within acceptable limits.

The compensator formula used for PID controllers is given below:

$$PID = K_p + \frac{K_i}{s} + K_d \frac{N}{1 + N\frac{1}{s}} \quad (11)$$

where K_p , K_i and K_d are the PID controller parameters and N is the filter coefficient for the compensator formula.

For this proposed system, Table 1 provides the values of controller parameters determined for various performance indices using the PSO algorithm in MATLAB.

Table 1
PID Controller Parameter Values for Performance Indices using Particle Swarm Optimization

PID	ISE	ISAE	IAE
K_p	0.0053228610205	0.0085901336115	0.0066420881012
K_i	0.0000005070204	0.0000005787354	0.0000000555333
K_d	-0.0286146972905	0.0593693374328	0.0095600101920
N	0.0190941154141	0.0142723189800	0.0841167934577

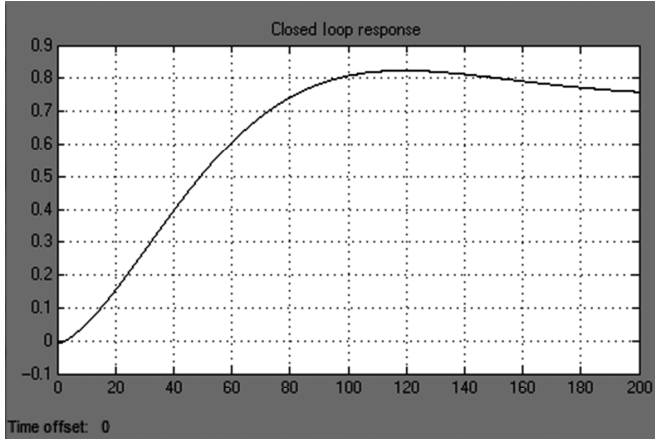


Figure 10. Step response of a classically tuned PID controller.

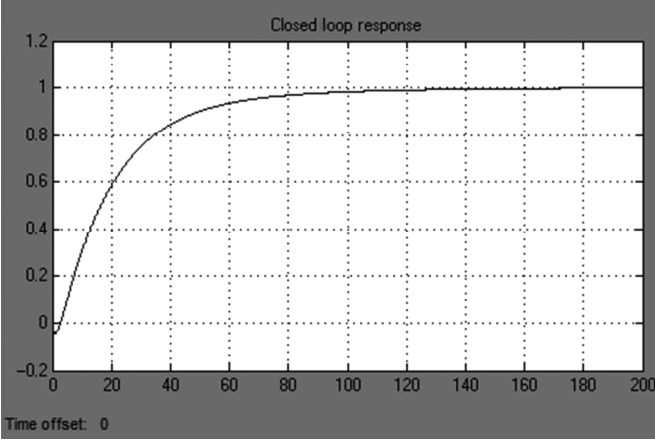


Figure 11. Step response of a PSO tuned controller with ISE.

Figures 10–13 show the step responses of the system for the PID controller tuned by various methods. The overshoot and settling time in case of classically tuned controller was found to be 10.712% and 127.6s, respectively. For PSO-tuned cases, none of the tuned controllers had any overshoot and the settling times were found to be 83.6, 50.1 and 72.3s using ISE, ISAE and IAE as the objective functions, respectively. Thereby, we see that the controller tuned using PSO-based ISAE provides the best response and hence chosen for the model.

Figure 14 shows gain margin, phase margin and other performance indices. These values prove that the proposed system is in the stable domain of operation.

5. Work Comparison

The proposed model has been derived after referring and analysing many papers on related topics. One such work is presented in [1] and the proposed work is compared with this.

In [1], the authors have prepared the model for responding to sudden changes in the load at the output. To show the performance of their model, they considered a step disturbance of 3% along with a Gaussian disturbance

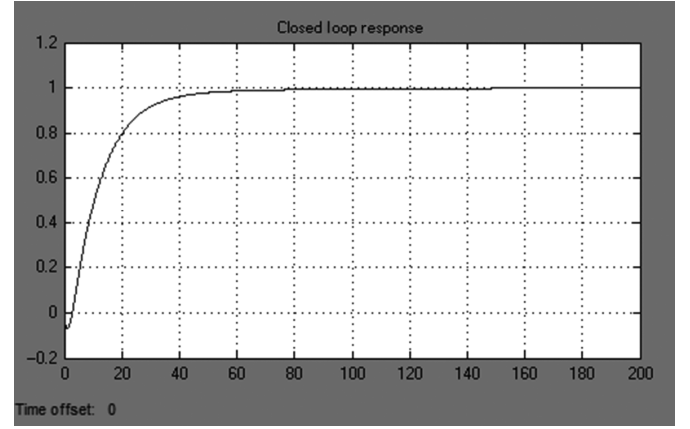


Figure 12. Step response of a PSO tuned controller with ISAE.

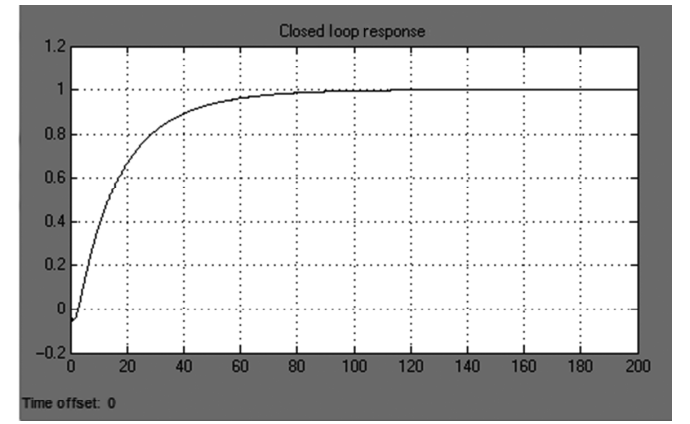


Figure 13. Step response of a PSO tuned controller with IAE.

having mean value zero and variance 1×10^{-6} to depict the sudden change in the load. They have used a controller whose parameter values are optimized using the artificial neural network (ANN) technique. The results obtained for the proposed model for similar conditions using the PSO technique are shown in Figs. 15 and 16.

Figure 15 shows generated mechanical power and its response to changes in the load. Figure 16 indicates the amount of frequency deviation encountered by the system due to 3% change in the load. This change is also accompanied by a continuous Gaussian disturbance for both the cases for which the outputs have been generated. Figure 15 shows no overshoot in the response and settles down to the required value of 0.03 p.u. in almost the same time as in the model to which the proposed work is being compared to. Also due to the introduction of the feedback loop to the generator block, the deviation in frequency for above-mentioned disturbance is very small. The maximum deviation in frequency for this load turns out to be only -19.2×10^{-4} p.u. or -0.096 Hz which is much less than -1.17 Hz obtained by the model to which the comparison is being made. Therefore, the results obtained for the proposed model are significantly better as compared to the one being taken into consideration.

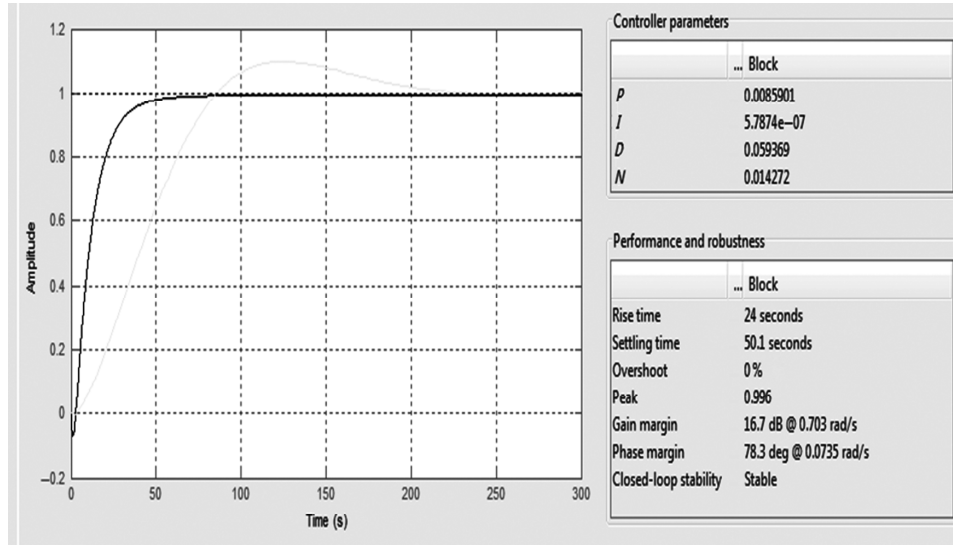


Figure 14. Gain margin and phase margin specifications.

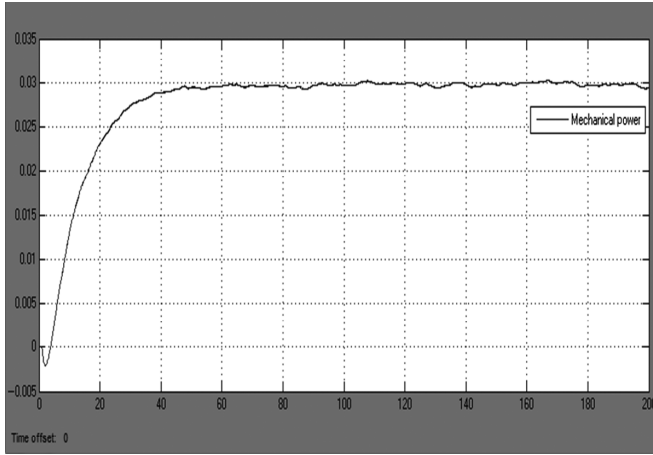


Figure 15. The Mechanical Power Generation in Response to the Change in the Load of 3% along with Gaussian Disturbance.

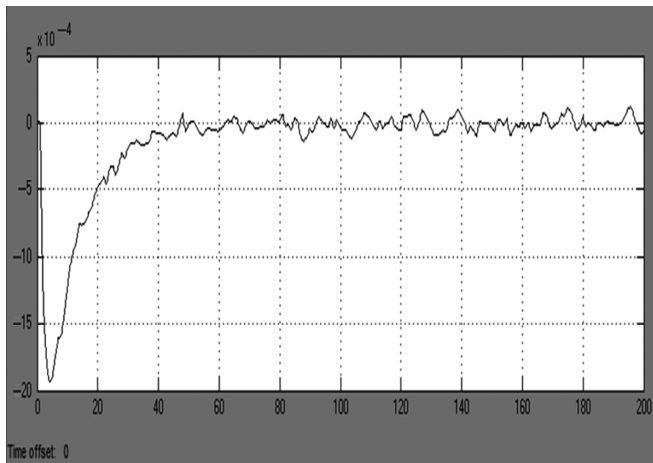


Figure 16. The Frequency Deviation Due to the Same Change in the Load of 3% along with Gaussian Disturbance.

6. Conclusion

This work presents an alternate approach to model a hydropower system which focuses on energy efficiency rather than frequency deviation as the basis. The difference between the mechanical power and the electrical power is minimized through feedback. The PID controller is used for efficient gate control which, in turn, controls the turbine rotations to minimize the power difference. An intelligent PSO technique is applied to tune controller parameters for system optimal performance. Furthermore, the frequency deviation is controlled using a gain in feedback. The performance of the hydroplant is discussed for different types of loads and it is observed that PSO-tuned controller outperforms the classical controller. The system is found to be stable after incorporating PID controllers in the model.

Appendix

The following data have been considered for constructing the small hydropower plant model.

(1) Total rated capacity: 25 kW; (2) normal operating load: 15 kW; (3) losses in the generator = 3%; (4) inertia constant H : 7.7 s ($2 < H < 8$); (5) nominal load = 48% = 0.48; (6) the damping parameter $D = \partial P_d / \partial f = (0.48 \times 15) / (60 \times 25) = 0.0048$ p.u. MW/Hz, where P_d is the extra power demanded due to changes in the load connected at the output; (7) $K_p = 1/D = 208.333$ Hz/p.u. MW and (8) $T_p = (2 \times H) / (f_0 \times D) = 53.3333$ s [1], where f_0 is the operating frequency of the system which has been taken here to be 60 Hz.

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