A Three Gate Optimal Flow Control Approach for Automatic Control of Small Hydro Power Plants Using Neural Networks

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ABSTRACT

This paper presents a flow control approach for the speed control of hydro turbines. Power can be controlled by controlling the rotary motion of the spear valve. In this paper, a flow control based model is proposed for the automatic control of small hydro power plants. In the proposed model, a servomotor is used to control the flow of water by controlling the rotational motion of the spear valve. The spear valve causes a 'continuous' control of the flow of water. 'Discrete' flow control is achieved by the use of butterfly gates which are activated by DC motors. The suitability of servomotors for the control of small hydro power plants is discussed and PI controllers are used to further enhance their governing capability. State space representation is used to mathematically model the proposed model. Extensive simulations are performed to analyze the behaviour of the proposed model. Parameter optimization is performed using Artificial Neural Networks.

Keywords - Speed Control, Ballasts, Automatic Control, Servomotor, Proportional Integral Controller, Stochastic Load Disturbance, Artificial Neural Networks.

1. INTRODUCTION

In an electric power system, consumers require power at rated frequency and voltage. To maintain these parameters within the prescribed limits, controls are required on the system. Voltage is maintained by control of excitation of the generator and frequency is maintained by eliminating mismatch between generation and load demand. The second problem of maintenance of constant frequency is analyzed in this paper. A new scheme is proposed for the speed control of hydro turbines. Power can be controlled by controlling the rotary motion of the spear valve. This scheme regulates the flow of water being fed to the turbine in accordance with the load perturbations and thereby maintains the frequency of the system at the desired level [1-3].

2. CONVENTIONAL GOVERNOR TYPES AND CHARACTERISTICS

Conventional Governor Systems can be classified as mechanical-hydraulic governors, electro hydraulic governors or mechanical types. Mechanical hydraulic governors are sophisticated devices, which are generally used in large hydro power systems. They require heavy maintenance and are expensive to install, making their usage in small hydro power plants uneconomical. Electro hydraulic governors are complex devices needing precision design and are expensive. Mechanical governors incorporate a massive fly ball arrangement and usually do not provide flow control. They require an elaborate set of complex guide vanes, inlet valves and jet deflectors. Conventional governing systems therefore, because of their cost and complexity, are not ideally suited for isolated, small hydro power plants that are not grid connected. The current trend is therefore to use load side regulation. [4, 5]

3. ELECTRONIC LOAD CONTROLLER FOR WATER TURBINES

Electronic load controllers govern the turbine speed by adjusting the electrical load on the alternator. As lights and electrical appliances are turned on and off the electronic controller varies the amount of power that is fed into a 'ballast' load. The load controller therefore maintains a constant electrical load on a generator in spite of changing user loads. This permits the use of a turbine with no flow regulating devices and their governor control system. Load controllers however waste precious energy, which could have otherwise been used gainfully. Also they do not carry out flow control, implying that mineral rich water is made to spill away, which could have been diverted at high head for irrigation purposes.

4. PROPOSED SCHEME

A combination of one or more gates may be used to regulate the flow of water to the turbine so as to generate power in consonance with the load demand. Using more than one gate for implementing flow control is an attractive proposition as it allows the use of smaller servomotors/ dc motors as against one big servomotor which may not be economically feasible.

In the proposed scheme two types of gates are proposed: 'On-Off' gate, which causes a discrete power flow and a 'Continuous' gate that causes a gradual power flow. 'On-Off' gates are controlled by dc motors while 'Continuous' gates are controlled by servomotors.

These gates are spear valve based (for 'continuous' flow control) or butterfly gate based (for 'discrete' flow control). The number of gates to be employed and the actual power control ratio of the gates may be decided depending on the nominal loading, as well as the variation in demand of a particular site.

4.1 Servomotor as a Governor

In our scheme, we have proposed the use of a servomotor as a governor. A servo motor may be thought of as a precision electric motor whose function is to cause motion in the form of rotation or linear motion in proportion to a supplied electrical command signal. We have used Type Zero servomechanism for our proposed system. A feedback control system of Type Zero is generally referred to as a regulator system. Such systems are designed primarily to maintain the controlled variable constant at a certain desired value despite disturbance. A DC servomotor is an example of a type zero servo mechanism. We have considered the use of a DC servo motor for our model. Servo motors are preferred for the control of small hydro power systems as they have a simple design, require less maintenance and are less expensive than conventional governors.

4.2 PID Controller

PID controllers are commonly used to regulate the time-domain behavior of many different types of dynamic plants. These controllers are extremely popular because they can usually provide good closed-loop response characteristics, can be tuned using relatively simple design rules, and are easy to construct using either analog or digital components. A PID controller treats the error in three different ways: proportional, integral and derivative [6, 7]. The transfer function of a PID controller is given below

$$K(s) = \frac{v(s)}{e(s)} = (K_p + \frac{K_I}{s} + K_D s) \tag{1}$$

Where,
$e(s)$ is the controller input,
$v(s)$ is the controller output

Dramatic swings in the control effort can be troublesome in applications that require slow and steady changes in the controller's output due to the bursty nature of correction signals provided. For such applications it is advantageous to forego derivative action altogether. Derivative action is also a problem for applications that involve noisy measurements. Hence we have ignored the derivative portion in our model. In our model, a PI controller is superimposed on the servomotor.

4.3 Load Disturbance Modeling

The model discussed subsequently has been subjected to two types of disturbances. The first type is a simple step increase in load. The value chosen for this type of disturbance is 3 percent as it is appreciated that the magnitude of disturbance as compared to the loading will be higher in a small hydro power plant, given its smaller capacity. The second type of disturbance is the stochastic disturbance which is introduced to model random switching on / off of appliances by the users, independent of each other. Hence, to model this random, independent phenomenon, Gaussian distribution has been chosen.

4.4 Three Gate Model of Small Hydro Power Plant

This model is assumed to have three gates through which flow control is effected in response to a change in the user demand (load). Two gates are On / Off gates, which generates 30 percent power each. The Third gate is a continuously controlled gate, which generates the balance 40 percent power. The model was created using Simulink utility of Matlab.

Three gates i.e two numbers of Discrete Gates and one Continuously controlled Gate, provide 30, 30 and 40 percent of the total power respectively. Initially, at 58 percent loading, Discrete Gate 1 is On and Discrete Gate 2 is Off. As the loading begins to increase from 58 percent due to the step increase of 03 percent, the Continuously controlled gate admits additional water to take the loading upto 60 percent. Beyond 60 percent loading, the Continuously controlled gate switches off completely and the Discrete gate 2 switches on and generates 30 percent power. Finally, as the overall loading is now 61 percent (58 + 3), the Continuously controlled gate opens so as to admit water required to generate the additional one percent power. This scheme therefore splits the overall flow into three sub flows that are individually controlled. A change in overall flow can therefore be caused by changing a smaller sub flow. Power control ratio of the gates may be decided depending on the nominal loading as well as the variation in demand of a particular site. This operation is also explained by the following table.

Table 1. Showing the Working Principle of Three Gates Model

Loading (Percentage)	**Gate 1 (Discrete)** (Position with Flow Percentage)	**Gate 2 (Discrete)** (Position with Flow Percentage)	**Gate 3 (Continuous)** (Position with Flow Percentage)
58	On (30)	Off (0)	On (28)
60	On (30)	On (30)	Off (0)
61	On (30)	On (30)	On (1)

These gates are positioned below the penstock and regulate the flow of water into the turbine. The proposed scheme incorporates flow control, thereby preventing the wastage of power and conserving power and mineral rich water at a high head, which could be used for irrigation purposes. Hence it is better than the Electronic Load controller, which wastes precious energy that could have otherwise been used gainfully.

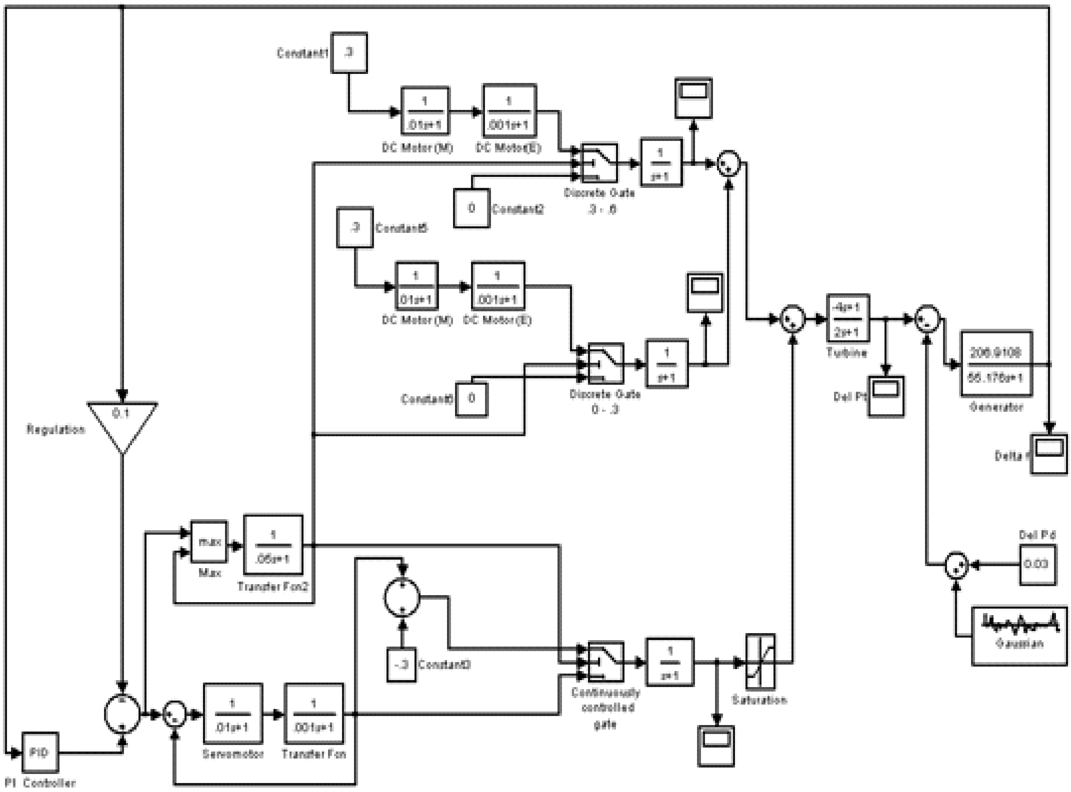

Fig. 1. Proposed three gate model of a small hydro power plant.

5. MATHEMATICAL MODELING OF THE PROPOSED SCHEME

For our analysis, we have considered a simplified model of a small hydro power plant where a servomotor regulates a single gate, which provides up to 100 percent flow control (refer to figure 2). The same model may be used for analyzing the behaviour of the three gate model with respect to change in frequency and turbine power for loadings less than 30 percent as only the servomotor controlled gate is operative at such loadings. This model may also be used to carry out an approximate analysis of the three gate model for loadings greater than 40 percent under the condition that flow of water due to the operation of the three gates is identical to a one gate model from the turbine point of view. The approximate transfer function for the servo motor based governor is considered for the analysis and is given by equattion (2)

$$G(s) = \frac{1}{(1+sT_1)} \quad \frac{1}{(1+sT_2)} \tag{2}$$

Where,

T_1 = mechanical time constant , T_2 = electrical time constant

In addition, unity gain is applied as a feedback. A PI controller with the following transfer function is superimposed on the servomotor based governor:

$$G(s) = K_{pl} + \frac{K_i}{s} \tag{3}$$

Where,

K_{pl} = Proportional constant , K_i = Integral constant

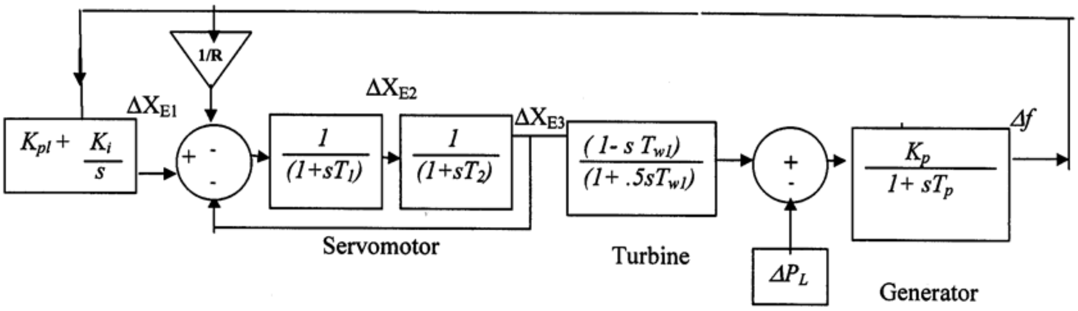

Fig. 2. Model of a small hydro power plant using servomotor as a governor.

The system can be reduced to a simpler state by employing partial fraction method as follows:

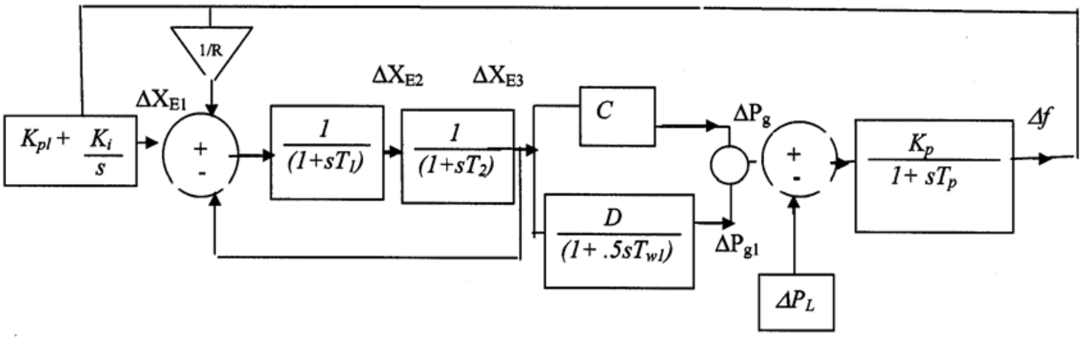

Fig. 3. Simplified representation using partial fractions.

Where,

$C = -2, D = 3,$

and where Δf is generator frequency relative to its nominal value (Hz), ΔP_L is the electrical perturbation (MW), T_{w1} is the water starting time of the turbine (s), K_{pl} is the proportional gain, K_i is the integral gain, $\{\Delta X_{E1}, \Delta X_{E2}, \Delta X_{E3}\}$ are the variables for positional change, $\{\Delta P_g, \Delta P_{g1}\}$ are the variables for power change in turbine, R is the speed regulation due to governor action (Hz/ pu MW), K_p is the generator gain (Hz /pu MW), and T_p is the generator time constant (s).

The state variable differential equations for the governor can be written as follows:-

$$\frac{d}{dt}\Delta X_{E1} = K_i \Delta f + K_{pl}\frac{d}{dt}\Delta f \tag{1a}$$

$$\frac{d}{dt}\Delta X_{E2} = \frac{-1}{T_1}\Delta X_{E2} - \frac{1}{T_1}\left[\Delta X_{E3} + \frac{1}{R}\Delta f - \Delta X_{E1}\right] \tag{2a}$$

$$\frac{d}{dt}\Delta X_{E3} = \frac{-1}{T_2}\Delta X_{E3} + \frac{1}{T_2}\Delta X_{E2} \tag{3a}$$

The change in power generated can be written as follows:

$$\Delta P_g = C\,[\Delta X_{E3}] + \Delta P_{g1} \tag{4a}$$

The state variable differential equation for the hydro turbine can be written as follows:

$$\frac{d}{dt}\Delta P_{g1} = \frac{-1}{0.5\,T_{w1}}\Delta P_{g1} + \frac{D}{0.5\,T_{w1}}[\Delta X_{E3}] \tag{5a}$$

$$\frac{d}{dt}\Delta f = \frac{-1}{T_p}\Delta f + \frac{K_p}{T_p}[\Delta P_{g1} + C\,.\,\Delta X_{E3} - \Delta P_L] \tag{6a}$$

Hence (1a) becomes

$$\frac{d}{dt}\Delta X_{E1} = K_i\Delta f + K_{pl}\left[\frac{-1}{T_p}\Delta f + \frac{K_p}{T_p}[\Delta P_{g1} + C\,.\,\Delta X_{E3} - \Delta P_L]\right] \tag{7a}$$

The system dynamics is described by a set of state differential equations:

$$\dot{\underline{X}} = [A]\,\underline{X} + [B]\,\underline{\mu} + [\Gamma]\,\underline{p} \tag{8a}$$

Where X, μ and p are the state, control and disturbance vectors respectively and $[A]$, $[B]$ and $[\Gamma]$ are constant matrices of appropriate dimensions associated with the above vectors. Equation (8a) may be written as follows:

$$\left|\begin{array}{c} \dot{\Delta f} \\ \dot{\Delta P}_{g1} \\ \dot{\Delta X}_{E3} \\ \dot{\Delta X}_{E2} \\ \dot{\Delta X}_{E1} \end{array}\right| = \left|\begin{array}{ccccc} \frac{-1}{T_p} & \frac{K_p}{T_p} & \frac{C\,K_p}{T_p} & 0 & 0 \\ 0 & \frac{-1}{.5T_{W1}} & \frac{D}{.5T_{W1}} & 0 & 0 \\ 0 & 0 & \frac{-1}{T_2} & \frac{1}{T_2} & 0 \\ \frac{-1}{RT_1} & 0 & \frac{-1}{T_1} & \frac{-1}{T_1} & \frac{1}{T_1} \\ K_i-\frac{K_{pl}}{T_p} & \frac{K_pK_{pl}}{T_p} & \frac{K_pK_{pl}C}{T_p} & 0 & 0 \end{array}\right| \left|\begin{array}{c} \Delta f \\ \Delta P_{g1} \\ \Delta X_{E3} \\ \Delta X_{E2} \\ \Delta X_{E1} \end{array}\right| + \left|\begin{array}{c} \frac{-K_p}{T_p} \\ 0 \\ 0 \\ 0 \\ \frac{-K_pK_{pl}}{T_p} \end{array}\right| \Delta P_L$$

5.1 Solution of the State Space Equations

The state space equations were solved using the standard State Space Model representation available in Matlab. The syntax for obtaining the standard State Space model is:

ModelName = **ss**([*a*], [*b*], [*c*], [*d*])

Where,

ModelName is the user specified name of the State Space model to be generated

a is the 2D real valued system matrix

b is the 2D real valued input matrix
c is the 2D real valued output matrix
d is the 2D real valued feedthrough matrix.

For construction of the system matrix a and the input matrix b, we considered the data of the model as given at the end of the paper with water starting time = 4 seconds. Based on this data, state space matrices were generated as follows:

$$a = \begin{pmatrix} -.0181225 & 3.74973 & -7.499456 & 0 & 0 \\ 0 & -.5 & 1.5 & 0 & 0 \\ 0 & 0 & -1000 & 1000 & 0 \\ -10 & 0 & -100 & -100 & 100 \\ -.00311486 & 0.20998477 & -.419969 & 0 & 0 \end{pmatrix}$$

$$b = \begin{pmatrix} -.01124916 \\ 0 \\ 0 \\ 0 \\ -.006299541 \end{pmatrix}$$

$$c = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$d = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

The model was subjected to a step disturbance by the following command:

```
step( ModelName)
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The solution of the change in frequency, Δf parameter of the State Space model is as follows:

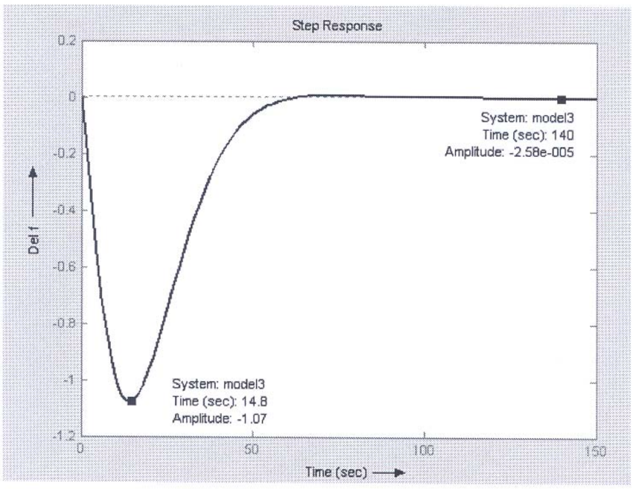

Fig. 4. Δf (Hz) versus time (sec) for the proposed model.

This figure is in conformity with the results obtained by simulation, thereby proving the correctness of the mathematical model.

6. SIMULATION OF PROPOSED MODEL FOR REALISTIC LOAD DISTURBANCES

The model was subjected to a step disturbance of 3 percent coupled with a Gaussian Stochastic disturbance with mean zero and variance 1e^{-6}. Simulations were carried out for varying water starting times using Matlab software. The results presented here correspond to water starting time of four seconds.

We note here that the transitions in the scopes of the three gates are as discussed in the three gate model.

6.1 Simulations of Proposed Three Gate Model

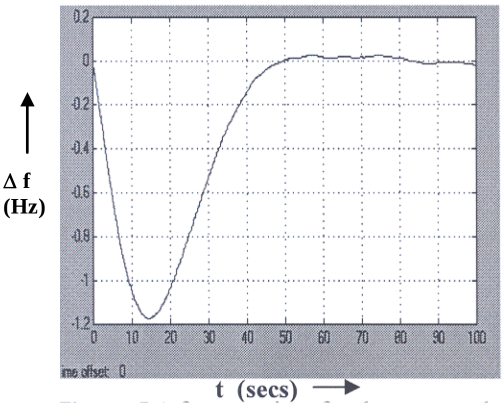

Fig. 5. Δ f versus time for the proposed model.

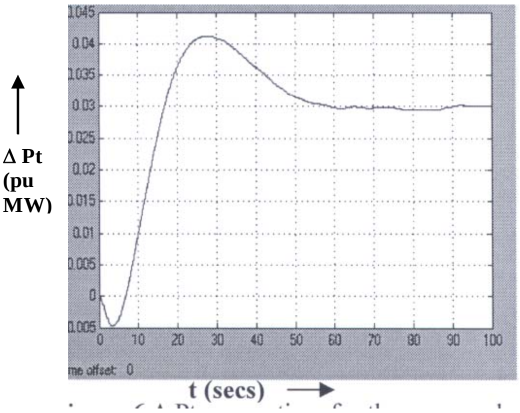

Fig. 6. Δ Pt versus time for the proposed model.

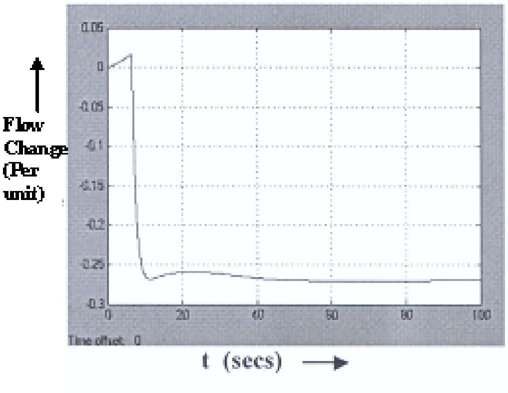

Fig. 7. Output flow change versus time of continuous gate.

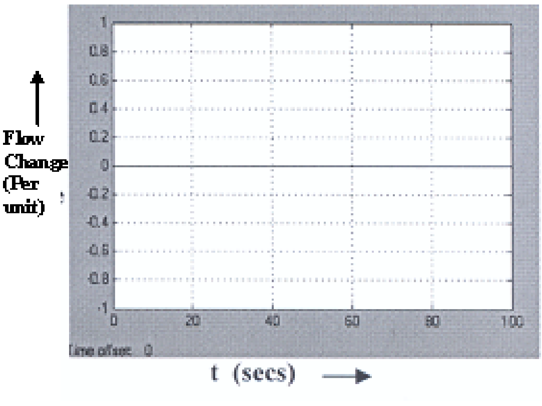

Fig. 8. Output flow change versus time of discrete gate 1.

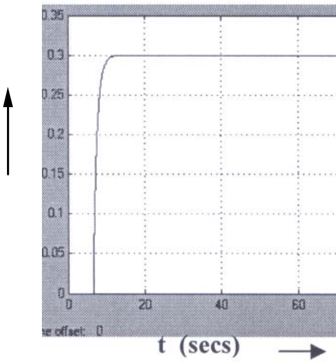

Fig. 9. Output flow change versus time of discrete gate 2.

6.2 Summary of Results

The results of the simulations may be summarised as:

1. Steady state is attained for both D f and D Pt.
2. Increase in Tw leads to increase in perturbations.
3. Switching of gates effectively results in meeting the required demand of the user without loss of steady state.
4. A combination of PI controllers with Servomotors is ideally suited for governing purposes.
5. The values of the Proportional Constant and the Integral Constant in the PI Controller play a significant role in determining the stabilizing time. There is thus a need to optimize these parameters for a given model.
6. Hydro turbines have a peculiar response due to water inertia; a change in gate position produces an initial turbine power change, which is opposite to that sought. This effect becomes more pronounced with increasing Tw times.
7. Gaussian Disturbances in the load tend to manifest themselves in Df and DPt values.

7. PARAMETER OPTIMISATION USING ANN

An ANN model has been developed for tuning the Proportional Integral derivative controller for the automatic control of small hydro power plants using servomotor as a governor. Feed forward Multilayer Perceptron ANNs can approximate any continuous function over a compact set to arbitrary accuracy making it suitable for control of SHP plants. The ANN has been employed in ‘off line’ mode. It was observed that Parameter optimization of Kp and Ki values is independent of the magnitude of the step disturbance and depends upon the desired regulation parameter, the nominal loading and the available water starting time at the proposed site. A data set is first prepared with the optimum values of the PI controller constants for various nominal loadings, water starting times and values of regulation parameter. The network is trained until a good agreement between the predicted gain settings and actual gains is reached. Once the network is adequately trained, the network is again tested to ensure it can adequately predict the correct PI controller constants for the values of nominal loading, water starting times and desired regulation parameter.

Performance of the ANN controller for the three gate model for water starting time of 4 seconds is given below. The nominal loading range is set to 38% to 78% as an example. The range can be expanded depending on the variation of demand at a particular site.

Table 2. Input Training Data for ANN Process (Tw = 4 seconds)

Loading 1/R	0.38	0.48	0.58	0.68	0.78
0.1	Kp =.056 Ki=.0019	Kp=.056 Ki=.002	Kp=0.056 Ki=.0021	Kp=0.056 Ki=.0022	Kp=0.056 Ki=.0023
0.15	Kp =.106 Ki=.0019	Kp=.106 Ki=.002	Kp=0.106 Ki=.0021	Kp=0.106 Ki=.0022	Kp=0.106 Ki=.0023
0.2	Kp=.156 Ki=.0019	Kp=0.156 Ki=.002	Kp=0.156 Ki=.0021	Kp=0.156 Ki=.0022	Kp=0.156 Ki=.0023
0.25	Kp =.206 Ki=.0019	Kp=.206 Ki=.002	Kp=0.206 Ki=.0021	Kp=0.206 Ki=.0022	Kp=0.206 Ki=.0023
0.3	Kp=0.256 Ki=.0019	Kp=0.256 Ki=.002	Kp=0.256 Ki=.0021	Kp=.256 Ki=.0022	Kp=.256 Ki=.0023

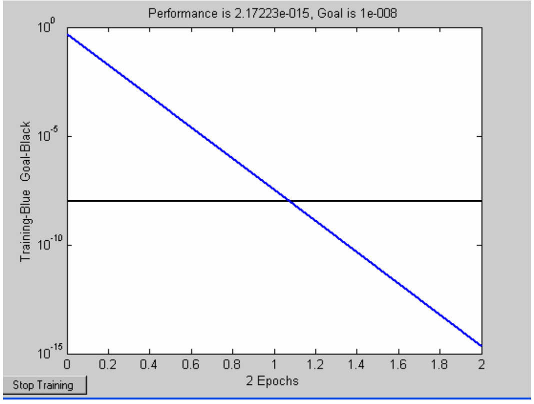

Fig. 10. Graph showing ANN training.

Table 3. Performance of the ANN after Training (Tw = 4 seconds)

Loading 1/R	0.38	0.48	0.58	0.68	0.78
	Kp =.056 Ki=.0019	Kp=.056 Ki=.002	Kp=0.056 Ki=.0021	Kp=0.056 Ki=.0022	Kp=0.056 Ki=.0023
0.2	Kp=.156 Ki=.0019	Kp=0.156 Ki=.002	Kp=0.156 Ki=.0021	Kp=0.156 Ki=.0022	Kp=0.156 Ki=.0023
0.3	Kp=0.256 Ki=.0019	Kp=0.256 Ki=.002	Kp=0.256 Ki=.0021	Kp=.256 Ki=.0022	Kp=.256 Ki=.0023
0.4	Kp=.356 Ki=.0019	Kp=0.356 Ki=.002	Kp=.356 Ki=.0021	Kp=.356 Ki=.0022	Kp=.356 Ki=.0023
0.5	Kp=.456 Ki=.0019	Kp=.456 Ki=.002	Kp=.456 Ki=.0021	Kp=.456 Ki=.0022	Kp=.456 Ki=.0023

8. CONCLUSION

This work has proposed a novel technique of power generation using flow control. Towards the development of this technique, the suitability of servo motor as a governor for small hydro power plants was established. Exhaustive simulations were performed on both the conventional control schemes as well as proposed control scheme using the Simulink utility of Matlab software to ascertain the efficacy of the proposed model. These simulations have demonstrated the suitability of the proposed model for the control of small hydro power plants. Predictions made by the ANN controller are in good agreement with the actual values of Kp and Ki.

Data for Construction of Model

The following data has been considered for constructing the model.

1. Total rated capacity : 20 MW
2. Normal operating Load : 10 MW
3. Inertia Constant H : 7.75 seconds (2<H<8)
4. Regulation R : 10 Hz / pu MW (2<R<10)

Assumption: Load - frequency dependency is linear.

Nominal Load = 58 % = 0.58;

Δ Pd = 3 % = 0.03

The damping parameter $D = \partial Pd / \partial f = \frac{0.58 \times 10}{60 \times 20} = 0.00483$ pu MW / Hz

Generator parameters.

$$Kp = \frac{1}{D} = 206.91 \text{ Hz / pu MW}$$

$$Tp = \frac{2 \times H}{f^0 \times D} = 55.18 \text{ seconds}$$

The open loop transfer function of a servomotor is given by

$$G(s)H(s) = \frac{-K_n K_a K_g / K_e}{(1+T_f S)(1+T_m s)}$$

where,

K_a = net control field amperes per volt actuating error signal,

K_g = no-load amplidyne terminal voltage per net control field current,

$T_f = \frac{L_f}{R_f}$ = time constant of quadrature field of amplidyne, seconds,

T_m = $\frac{JR_a}{K_T K_e}$ = time constant of motor and load, seconds,

K_c = motor volts per radian per second of motor,

K_n = voltage from tachometer per radian per second of motor.

For our model, we have considered the following values:

K_n = 1

$K_a K_g / K_e$ =1

T_f = 0.001 seconds

T_m = 0.01 seconds

PI Controller parameters: $K_{pl} = 0.056$, $K_i = -0.0021$

9. REFERENCES

[1] Andersson, P.M., and Fouad,A.A. (2003) *Power System Control & Stability*, IInd Edition, John Wiley & Sons, Inc., 111, River Street, Hoboken, NJ., IEEE Series on Power Engineering.

[2] Bhatti, T.S., Bansal, R.C. and Kothari, D.P., (2004) *Small hydro power plants*, Dhanpat Rai & Co., New Delhi

[3] Carstens, J.R, (1990) *Automatic Control Systems & Components*, Prentice –Hall, Inc., New Jersey.U.S.A.

[4] Elgerd, O.I. (1982) *Electric energy systems theory: An Introduction* Tata McGraw –Hill, New Delhi.

[5] Goyal, H., Bhatti, T.S., and Kothari, D.P.(2004) Control of small hydro power plants : a review, accepted for publication in *International Journal of Energy Technology and Policy.*

[6] Harvey, A., Brown, A., Hettiarachi, P. and Inversin, A. (1993), *Micro Hydel Design Manual, A Guide to Small Scale Water Power Schemes*, Intermediate Technology Publications.

[7] Kundur, P. (1994) *Power system stability and Control* Tata-McGraw Hill Co. 1221, Avenue of the Americas, New York, NY