MODELLING AND SIMULATION OF MICRO HYDRO POWER PLANT USING MATLAB SIMULINK

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ABSTRACT

Micro-hydro-electric power is both an efficient and reliable form of clean source of renewable energy. It can be an excellent method of harnessing renewable energy from small rivers and streams. The micro-hydro project designed to be a run -of-river type, because it requires very little or no reservoir in order to power the turbine. The water will run straight through the turbine and back into the river or stream to use it for the other purposes. This has a minimal environmental impact on the local ecosystem.

Hydro power plant mainly consists of three sections, 'governor (controller), hydro servo system and hydro turbine'. Integrally this section is known as hydro turbine governor which is coupled to a synchronous generator to drive the shaft so that the mechanical energy of turbine is converted to the electrical energy. This system is supplying power to a common electrical three phase parallel RLC load. Models are simulated on MATLAB/Simulink.

The speed governing control system ensures the constant speed operation during variation of load. The transient behavior of generator voltage, current and the rotor speed are also captured. Restoration of steady state condition within few seconds while changing the load ensures the stability of the entire system.

Key Words: Hydro Turbine Governor, Mathematical Models, Matlab/Simulink, Micro Hydro-Electric Power Plants, Proportional, Integral And Differential Controller.

I. INTRODUCTION

Energy is one of the most fundamental elements of our universe. It is inevitability for survival and indispensable for development activities to promote education, health, transportation and infrastructure for attaining a reasonable standard of living and is also a critical factor for economic development and employment.

In the last decade, problems related to energy crisis such as oil crisis, climatic change, electrical demand and restrictions of whole sale markets have a risen world-wide. These difficulties are continuously increasing, which suggest the need of technological alternatives to assure their solution.

One of these technological alternatives is generating electricity as near as possible of the consumption site, using the renewable energy sources that do not cause environmental pollutions such as wind, solar, tidal and hydro-electric power plants. Hydro-electric power is a form of renewable energy resource, which comes from the flowing water. To generate electricity, water must be in motion. When the water is falling by the force of gravity, its potential energy converts into kinetic energy. This kinetic energy of the flowing water turns blades or vanes in a hydraulic turbines, the form of energy is changed to mechanical energy. The turbine turns the generator rotor which then converts this mechanical energy into electrical energy. The power generated from falling water has been harnessed in various applications such as milling grains, sawing wood and pumping water for irrigation. The slow-moving water wheels were used to harness the mechanical power from flowing water. The design and efficiency improvements made to these early water wheels led to the rise of the hydro-electric turbines. The first hydro-electric power systems were developed in the 1880's. According to the international energy agency (IEA), large-scale hydroelectric plants currently supply 16% of the world's electricity. However, such kind of projects requires tremendous amounts of land impoundment, dams and flood control, and often they produce environmental impacts.

Micro-hydro-electric power plants are one of an alternative source of energy generation. They are the smallest type of hydro-electric energy systems. They generate between (5) and (100) Kilowatt of power when they are installed across rivers and streams. The advantages of micro-hydro-electric power plant has over the fossil and nuclear power plant are

- It has ability to generate power near when its needed, reducing the power inevitably lost during transmission.
- It can deal more economically with varying peak load demand, while the fossil-fuel or nuclear power plants can provide the base load only, due to their operational requirements and their long start-up times.
- It is able to start-up quickly and made rapid adjustments in output power.
- It does not cause pollution of air or water.
- It has low failure rate, low operating cost and is reliable.
- It acts much like a battery, storing power in the form of water.

In particular, the advantages that micro-hydro-electric power plant has over the same size wind, wave and solar power plants are:

- High efficiency (70-90%), by far the best of all energy technologies.
- High capacity factors (> 50%) compared with 10% for solar and 30% for wind power plant.
-Slow rate of change; the output power varies only gradually from day to day not from minute to minute.
- The output power is maximum in winter.

Comparative study between small-hydro-electric power plants (up to 10 MW capacity) and micro-hydro-electric power plants (up to 100 KW capacity) reveals that the former one is more capital intensive and involves major political decisions causing difficulties in different implementation phases. On the other hand micro-hydroelectric power plants are low cost, small sized and can be installed to serve a small community making its implementation more appropriate in the socio-political context. Many of these systems are "run-of-river" which does not require an impoundment. Instead, a fraction of the water stream is diverted through a pipe or channel to a small turbine that sits across the stream, as shown in figure.

So, there is a scope for harnessing the micro-hydro-electric power plant potentiality by identifying proper site and designing appropriate power generation systems.

II. HYDRO TURBINE GOVERNOR

Micro hydro power plant is the conventional source of energy. It has basically its two main sections, firstly the mechanical part of the plant which includes hydraulic turbine, penstock, controller, hydraulic servo motor, control valve etc. Second part of the plant is electrical section which mainly consists of generator and load.

The combined form of hydraulic turbine, controller and hydro-electric servo system is known hydro turbine governor. In order to explain the mathematical modelling of hydro turbine governor, this chapter is introduced.

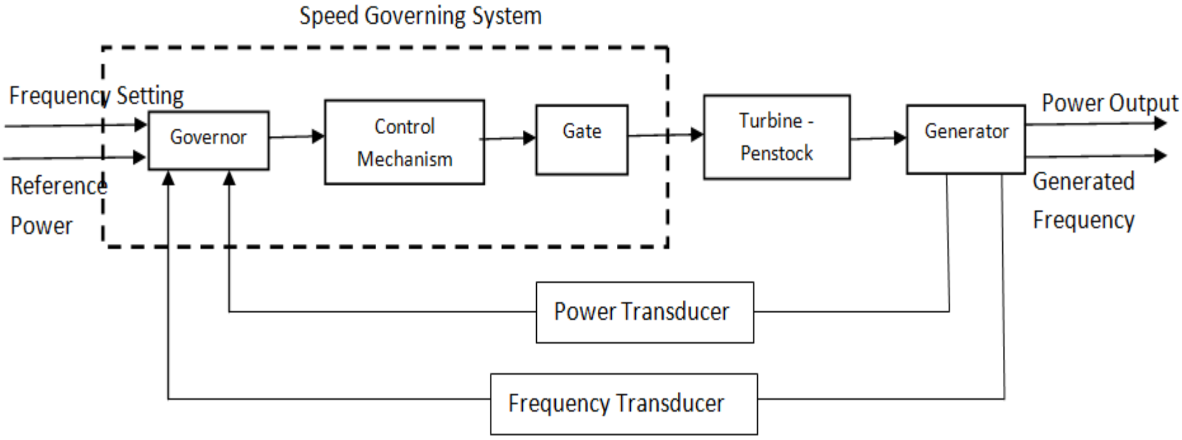

Figure 1.0 Functional Block Diagram of a Hydraulic Power Plant

Figure 1.0 shows a complete block diagram of hydro power plant. The stored water at certain head contains potential energy. This energy is converted to kinetic energy. When it is allowed to pass through the penstock, this kinetic energy is converted to mechanical energy (rotational energy) which allows water to fall on the runner blades of the turbine. As the shaft of the generator is coupled to the turbine, the generator produces electrical energy by converting the mechanical energy into electrical energy. The speed governing system of turbine adjusts the generator speed based on the feedback signals of the deviations of both system frequency and power with respect to their reference settings. This ensures power generation at synchronous frequency.

2.1 Mathematical Model of Hydro Turbine Governor System

Due to variation of load throughout the day, the generated frequency of the system fluctuates. The hydro turbine governor is used to maintain a constant turbine speed hence the frequency and active power in response to load variation. The turbine governor regulates water input into a turbine, which in turn rotates the generator to produce electricity [3]. This section details the modelling of the mechanical-hydraulic turbine governing system. A mathematical representation of a hydraulic governing system including both the turbine-penstock and the governing system is introduced here. Hydro turbine governing systems are strongly influenced by the effects of water inertia [4, 5]. To adjust the gate opening of the wicket gate, the servomotor controls a pilot valve. The servomotor is activated by the signals generated from the turbine governor. Equation 1[3] is derived based on the assumption of short penstock, insignificant water hammer and incompressible flow of fluid through penstock. It defines the characteristics of per unit turbine flow in terms of water time constant and head.

$$\frac{dq}{dt} = (hs - h - hl)\,\frac{gA}{L}) \quad \text{..........}(1)$$

Where,

q = per-unit turbine flow

h_s= static head of the water column

h = head at the turbine admission

h_l= per-unit conduit head losses

L = length of the conduit section

A = cross section area of the penstock

g = gravitational acceleration

The function of flow and toque of Francis turbine are given by Equation 2 and 3

$Q = Q(H, x, y)$…………………………………………………………(2)

$M_t = M_t(H, x, y)$ ………………………………………………………(3)

Where Q is flow rate, M_t is turbine torque, H is hydro-turbine water head, y is gate opening and x is hydro-turbine speed. When the parameters of turbine vary in the small range at a stable operating point, the above two functions for water flow and toque can be linearized (Equation 4 and 5) [1] as:

$q = e_{qy}y + e_{qx}x + e_{qh}h$ ……………………………………(4)

$M_t = e_y y + e_x x + e_h h$ ………………………………………..(5)

$e_y = \frac{\partial mt}{\partial y}$, Partial derivative of the torque to gate opening

$e_x = \frac{\partial mt}{\partial x}$, Partial derivative of the torque to speed of turbine

$e_h = \frac{\partial mt}{\partial h}$, Partial derivative of the torque to the water head of turbine

$e_{qy} = \frac{\partial q}{\partial y}$, Partial derivative of flow to gate opening

$e_{qx} = \frac{\partial q}{\partial x}$, Partial derivative of flow to speed of the turbine

$e_{qh} = \frac{\partial q}{\partial h}$, Partial derivative of flow to the head of turbine.

2.1.1 Modelling of Controller

Here the PID controller is used as the controller. The error in speed is fed as input to the controller and PID controller attempts to reduce the difference between the actual speed and the reference speed by adjusting the constants of the controller. The name derives from three functions involved in calculating the corrections and is accordingly sometimes called three term control: *P* stands for proportional, *I* stand for integrator and *D* stands for derivative [6] controls. These values can be interpreted in terms of time: *P* depends on the *present* error, *I* on the accumulation of past errors, and *D* is a prediction of future errors, based on current rate of change.

The output signal of the PID controller can be written in terms of the error signal as Equation 6

$\theta(t) = k_p e(t) + k_i \int e(t)\,dt + k_d \frac{de(t)}{dt}$…………………………………(6)

Taking Laplace transform on both sides of the Equation 3.6, we have

$\theta(s) = k_p E(s) + k_i \frac{E(s)}{s} + k_d sE(s)$…………………………………..…(7)

The transfer function of the PID controller is

$C(s) = \frac{Q(s)}{E(s)} = k_p + \frac{k_i}{s} + k_d s$……………………………………………..(8)

Where, $\theta(s)$the output of the PID controller represents position signal

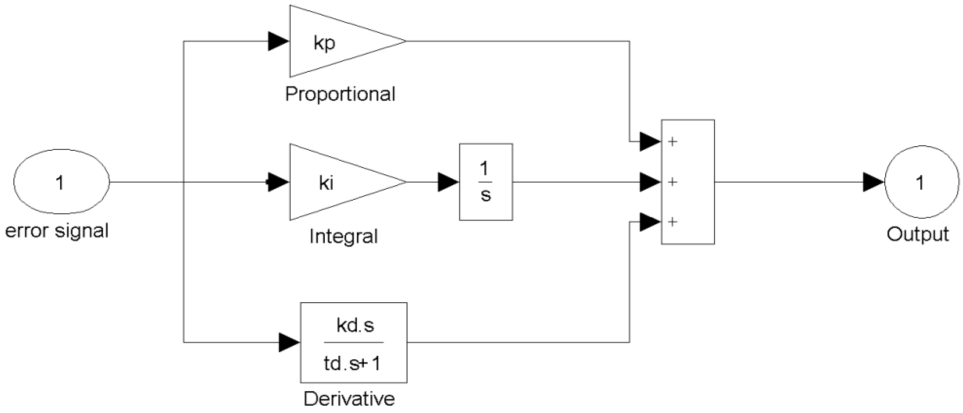

Figure 2 Simulink Model of a Controller

2.1.2 Modelling of Electro Hydro Servo System

In the model of hydro turbine governor servo motor is used to control the gate valve according to the signal of the controller. The controller nullifies the error in speed signal by sending a signal to the servo motor to control the valve.

The torque of the motor is the function of speed and error signal.

$T_m = f(\dot{\theta}, e)$……………………………………………………………………………(9)

The torque (Equation 9) of the servo motor can be expanded using Taylor`s series as shown in Equation10 [7].

$T_m = (t_a(0) + \frac{dt_a}{de}\left(e(t) - e(0)\right) + \cdots + \frac{dt_a}{d\dot{\theta}}\left(\dot{\theta}(t) - \dot{\theta}(0)\right) + \cdots$ …………………………..(10)

By neglecting higher order terms and considering zero initial condition, Equation 3.10 can be rewritten as

$T_m = k_e(t) - f\dot{\theta}(t)$ ………………………………………………………………………..(11)

Where $K = \frac{dT_m}{de}$ and $f = -\frac{dT_m}{d\dot{\theta}}$

We know the mechanical relations for the motor is,

$T_m = J\ddot{\theta} + B\dot{\theta}$……………………………………………………………………………..(12)

Where, *J* and *B* are friction coefficient and moment of inertia respectively.

From Equations 11 and 12 above [28] we can write,

$K_e(t) - f\dot{\theta}(t) = J\ddot{\theta} + B\dot{\theta}$………………………………………..(13)

Taking Laplace transform on both sides, we have

$\frac{\theta(s)}{E(s)} = \frac{K}{Js^2+(B+f)s} = \frac{K}{s(Js+B+f)} = \frac{K}{s(t_a s+1)}$………………………...(14)

Where $K_a = \frac{K}{B+f}$ and $t_a = \frac{J}{B+f}$are gain and time constant respectively.

Here, servo motor controls the gate opening position according to change in speed at shaft of the generator to maintain the constant speed/frequency. Here, the change in speed of the generator acts as the control signal. Equation 14[4] is the required transfer function to develop the complete block diagram [7] of the hydro-electric servo system (Figure 3).

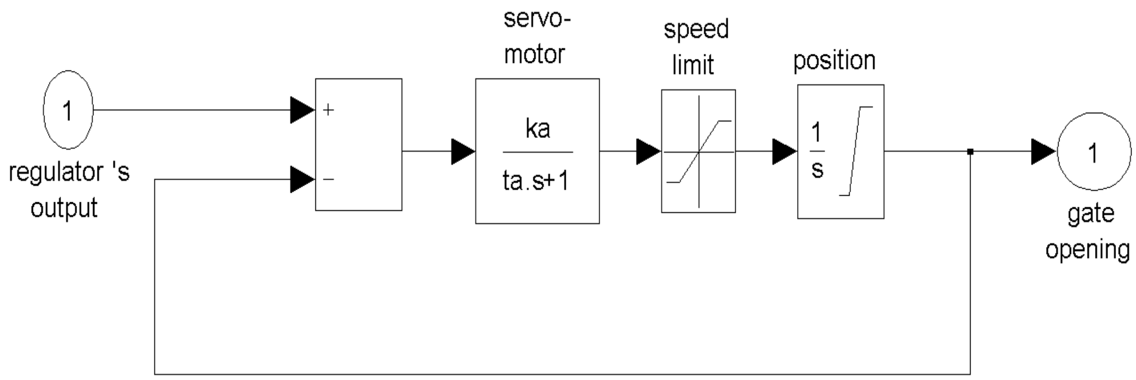

Figure 3 Model of Hydro-Electric Servo System

2.1.3 Modelling of Hydraulic Turbine

This section deals with the equations describing variation in flow and developed mechanical power with respect to the turbine speed, gate opening and runner blade movement of hydro turbine. Francis is used in range of application in the hydraulic industry because it performs its operation at highest efficiency comparatively other. So that Francis turbine is used in this modelling hence the pressure of the fluid will decrease during the passage of water flow through the turbine [2]. The output power of turbine is reduced due to fall of pressure across the turbine. As the developed power in the turbine varies with the flow rate, so the system operates or gains the steady state when the flow through the penstock gets constant.

The equations related to the transient performance of the hydraulic turbines are based on the following assumption [10].

- The hydraulic turbine`s blade is considered as smooth i.e. its frictional resistance is neglected.
- The water hammer on penstock is neglected.
- The fluid is considered as incompressible.
- The velocity of water in penstock varies directly with gate opening.
- The developed output power of turbine is proportional to the product of head and velocity of flow.

Equation 15 and 16 [10] represents the flow rate and the developed mechanical power at the shaft respectively in terms gate opening of the system and the net head.

$Q = G\sqrt{H}$……………………………………………………….(15)

Where Q is Flow rate in m^3/sec, G is gate opening in rad,H is net head in meter.

The developed power, *Pm* in turbine can be written as

$P_m = A_t H(Q - Q_{nl})$……………………………………………….(16)

Where, A_t is the turbine gain $A_t = \frac{1}{\overline{g_{FL}} - \overline{g_{NL}}}$, Q_{nl} is the no load flow rate

$\overline{g_{FL}}$ and $\overline{g_{NL}}$ are the full load and no load gate opening in pu .

Equation 15 is modified to describe the motion of the water in penstock by Equation 15.

$U = K_u G\sqrt{H}$………………………………………………………….(17)

Where, U is the velocity of the water in penstock and K_u is a proportional constant.

Once the velocity of the water in penstock is determined, the relation of flow rate, head could be established 18 and 20.

$Q = AU$ ……………………………………………………………………(18)

The acceleration of the fluid in the penstock is described by Equation 19 [10]

$\frac{dU}{dt} = -\frac{a_g}{L}(H - H_0)$……………………………………………………….(19)

Where,

a_g is the acceleration due gravity, L is the length of penstock.

Normalizing Equation 17about the rated values

$\bar{H} = (\bar{U}/\bar{G})^2$ ……………………………………………………….(20)

$\frac{\bar{U}}{\bar{H} - \bar{H}_0} = \frac{-1}{T_w s}$…………………………………………………………(21)

Where, $\frac{LQ_r}{a_g A H_r}$ is the water starting time at rated load. Q_r and H_r are rated water flow rate and head respectively.

The mechanical power output is given by

$P_m = P - P_l$ …………………………………………………………(22)

Where P_l is the fixed power loss in turbine due to friction.

$P_l = U_{NL} H$ ………………………………………………………….(23)

Where U_{NL} stands for no load speed.

The hydraulic characteristics and mechanical power output of the turbine is modelled here. The nonlinear characteristics of hydraulic turbine are neglected in this model. The complete block diagram of hydro turbine model is shown in Figure 4. The actuator's (hydro-electric servo motor) output is the gate opening and it controls the valve to maintain a uniform speed by regulating the rate of water flow. The transfer function represented by Equation 21 relates the flow rate *Q* and net head *H*. Here (*H-H0*) is entered as an input and the flow rate is the output signal of the transfer function. H_0 has been assumed a static head with reference value of 1pu.

Using a summation block, the signal (H-H_0) is obtained. According to Equation 21, $\frac{1}{T_w}$ ismultiplied with the signal (H-H_0) and integrated to obtain the flow rate *Q*. To find the actualwater flow rate the no load flow is subtracted from *Q* using a sum block. Using the signal *Q*and 1/*G* and a product block, a new signal *Q/G* is produced, the square root of which gives theactual value of head, H according to Equation 15. Turbine frictional factor is neglected in thismodelling. To get the value of *Pm*, Equation 16 is used. Equation 16 establish the relation between the develop power at turbine, actual water flow rate and the Head.

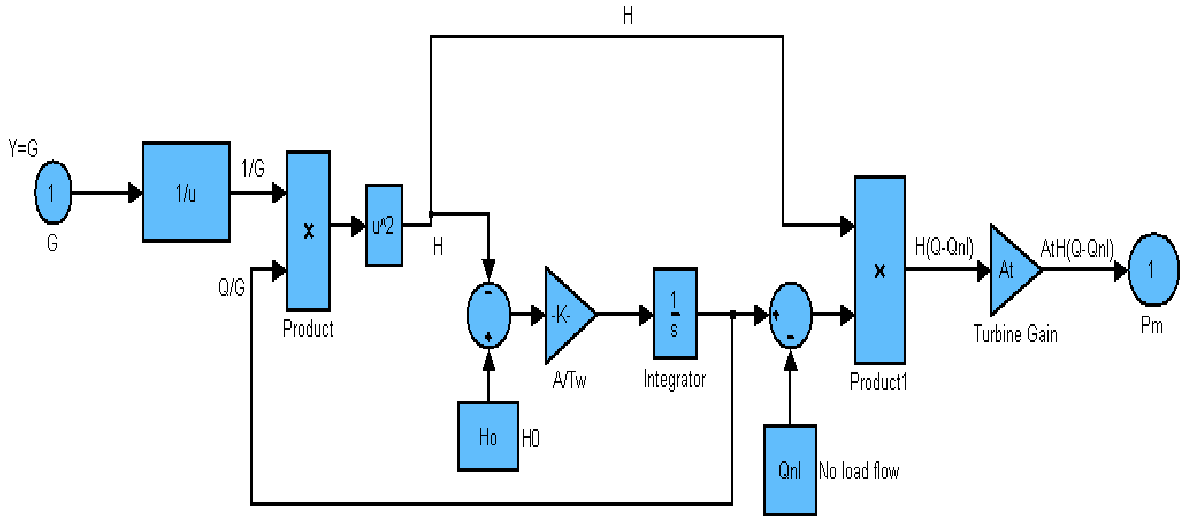

Figure 2.6 MATLAB/Simulink Model of Hydro Turbine

2.1.4 MATLAB/Simulink Model of Hydro Turbine Governor

Hydro turbine governor is a major part of hydro power plant. It is basically used for two purposes - firstly, it develops mechanical power at the shaft of the generator which is fed to the generator for production of electricity. And secondly, it controls the variation of speed of the generator such that the generated frequency remains constant. The PID controller, hydroelectric servo system and hydraulic turbine are the main components of the hydro turbine governor. The mathematical modelling and block formation has been done in the previous section of this chapter. These block model of components are connected in such a manner that the generated frequency remains constant. The block diagram of hydro turbine governor is shown in Figure 4. The first element of the governor is PID controller. The error in speed and deviation of power is entered as input to the controller, which generate the position signal at the input of the hydro-electric servo motor. Further the servo motor response by controlling the valve according to input signal to the servo mechanism. The valve is used to control the flow rate such that the generated frequency of the system remains constant.

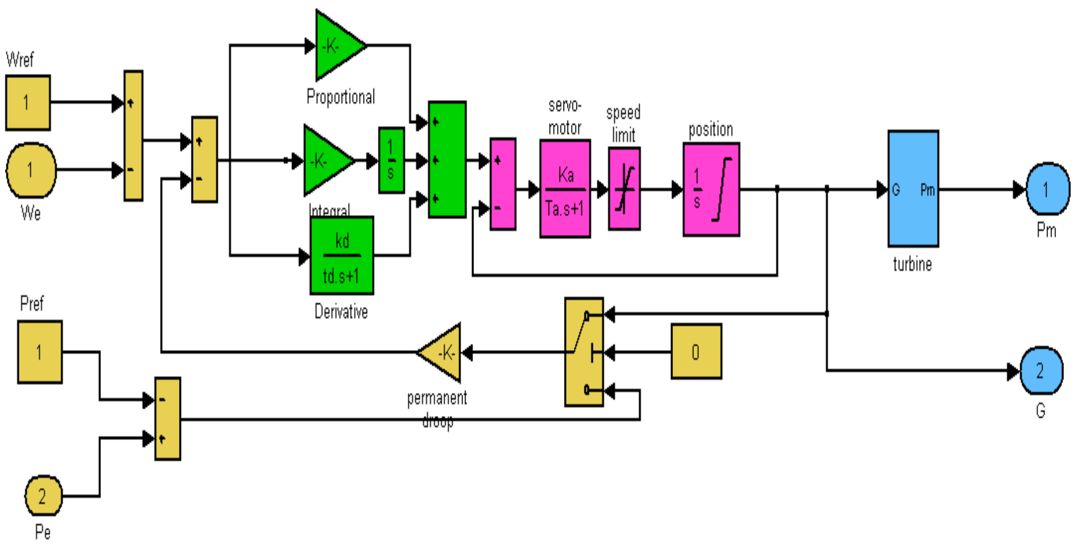

Figure 4 Block Model of Hydro Turbine Governor

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III. SYNCHRONOUS GENERATOR MODELS

The mathematical model of a synchronous machine uses Park's equations for the electrical dynamics [8]. Equations 24 to 27 are here used to model the electrical dynamics of the synchronous generator [9].

$$T''_{d0}\frac{dE''_q}{dt} = E'q - E''q + (X_d{}' - X''_d)I_d \quad (24)$$

$$T''_{q0}\frac{dE''_d}{dt} = E'd - E''d + (X_q{}' - X''_q)I_q \quad (25)$$

$$T'_{d0}\frac{dE'_q}{dt} = E'f - E'q + (X_d - X'_d)I_d \quad (26)$$

$$T'_{q0}\frac{dE'_d}{dt} = -E'd - Eq'' + (X_q - X'_q)I_q \quad (27)$$

On the basis of these generalized equations, the synchronous machine model is simulated in MATLAB/Simulink software. This model is available as a single block (Figure 4) with various terminals in MATLAB/Simulink library. The model takes into account the dynamics of the stator, field, and damper windings.

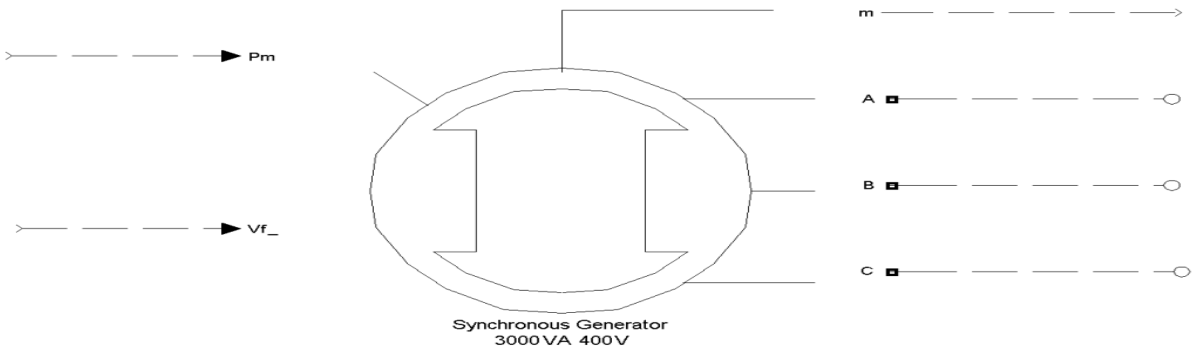

Figure 4 Block Diagram of Synchronous Machine

IV.MATLAB/SIMULINK MODEL OF MICRO HYDRO POWER PLANT

The individual sub-models like hydro turbine governor, synchronous generator, excitation system and 3-phase RLC load are now connected together to form the complete block diagram of micro hydro power plant (Figure 5).

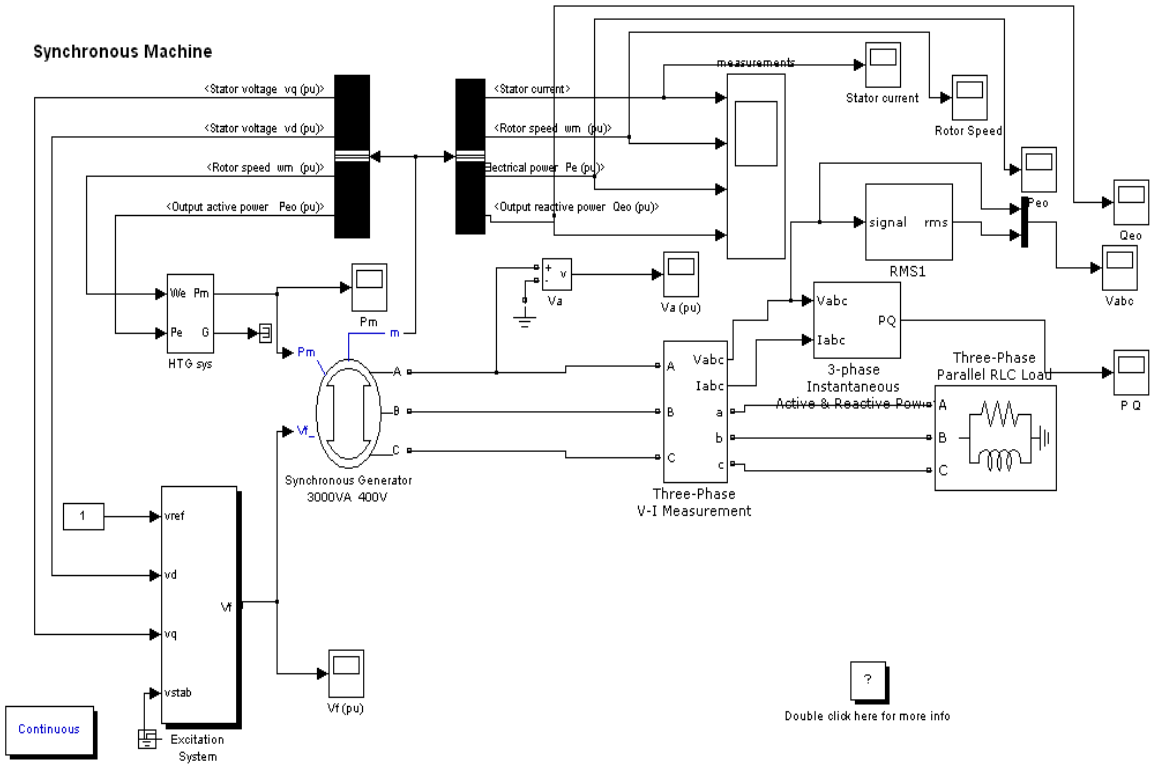

Figure 5 MATLAB/Simulink Model of a Hydro Power Plant

V. SIMULATION RESULTS OF MICRO HYDRO POWER PLANT MODEL

The under damped rotor speed characteristic of hydro (synchronous) generator is shown in Fig 6.

From the characteristics, it is observed that the transient time is 40s. After 17s its speed reaches steady state at synchronous speed. With sudden application of mechanical torque input to the shaft of alternator, the load angle settles to a steady state value after few oscillations owing to system damping following the swing equation and power angle characteristics. Moreover, the governor setting *kp*= 0.613 *ki*= 0.104 and *kd*= .0002 chosen by trial and error method helps to keep the speed near synchronous speed (1.02pu).

Figure 7 shows the stator current characteristics of the generator. When the load is changed, due to the presence of the transient and sub-transient reactance, envelop of three phase current shows under damped response at initial stage. After that it gains the steady state characteristics. It is observed from the plot that the transient period is 15s for three phase stator current.

Figure 8 shows the same characteristics for 0.2s from a close view.

Active power characteristics (Figure 9) of synchronous generator, which shows a steady state value of 0.6 pu i.e. 1800 W is nothing but the actual load connected to the plant. It is observed that the steady state is obtained around 27 sec. To reach the stable operating point on power - angle characteristics, few oscillations around this point occurs. This leads to initial overshoots and undershoots of the power characteristics.

Figure 10 shows that the reactive power characteristics complete its transient period in 27 seconds and steady state value achieved is 0.261pu is obtained which matches the actual reactive load connected.

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The nature of the plots during transient condition is under damped which projects the stable operation of the system. The stator phase voltage (Phase A) plot is shown in Figure 11.The magnitude of phase voltage observed is 231 Volt which is the rated voltage (Phase) output of the generator. It reaches steady state very quickly and follows a sinusoidal pattern during steady state. Three phase voltages lag each other by 120 deg.

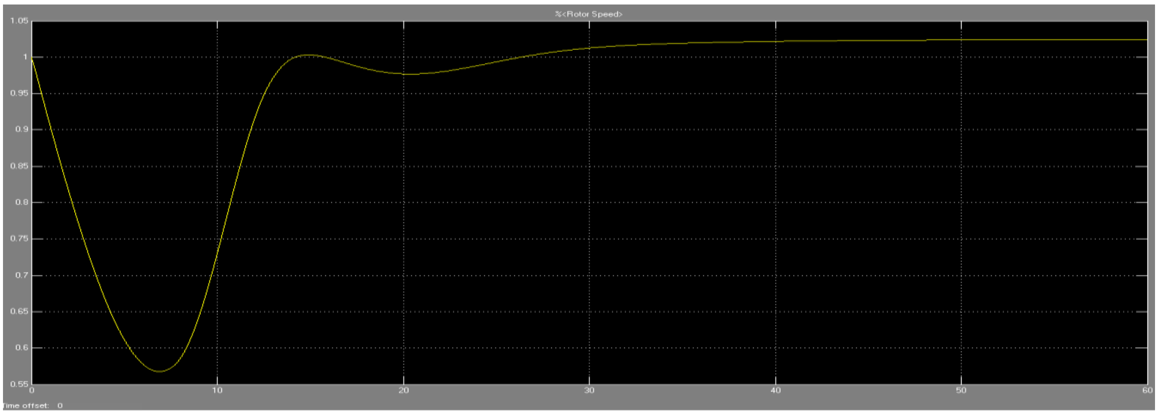

Figure 6 Synchronous Generator Speed Characteristics (in *y*-Axis Speed in pu and in Sec)

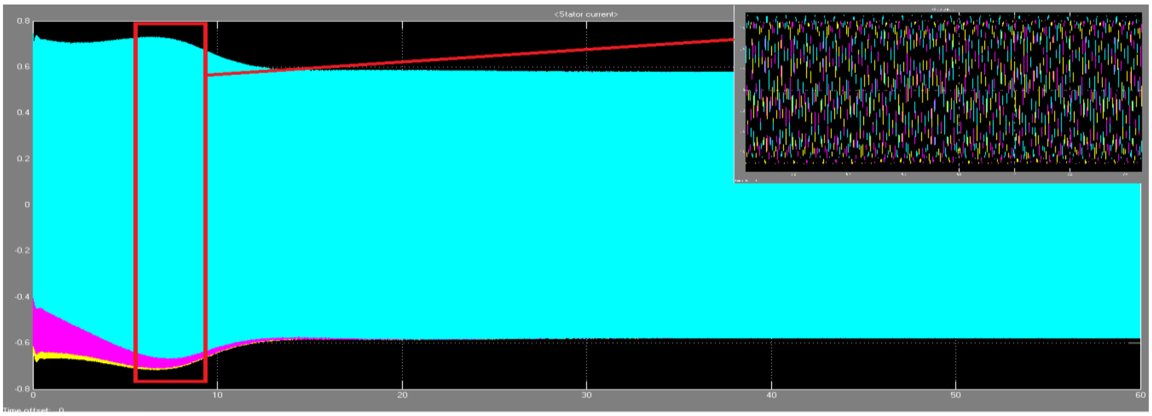

Figure 7 Stator Three Phase Current Characteristics of a Hydro Power Plant (in *y* and in *x*-Axis Time in Sec)

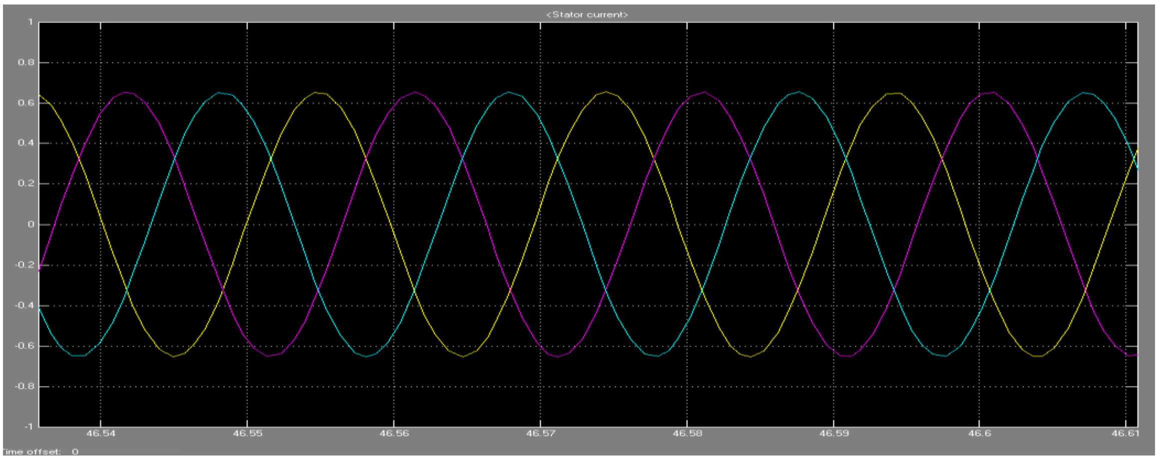

Figure 8 Stator Three Phase Current Characteristics for 0.2sec at Steady State (in *y*-Axis Current in pu and in *x*-Axis Time in Sec)

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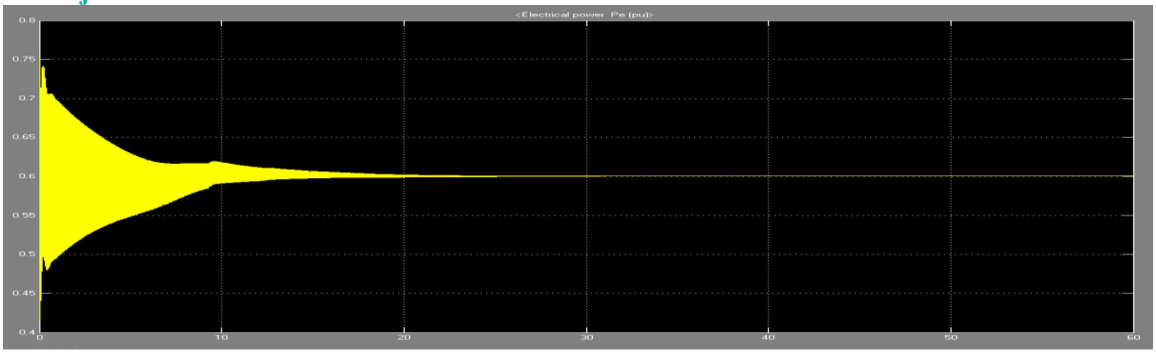

Figure 9 Active Power Characteristics of Hydro Power Plant (in *y*-Axis Active Power in pu and in *x* Axis Time in Sec)

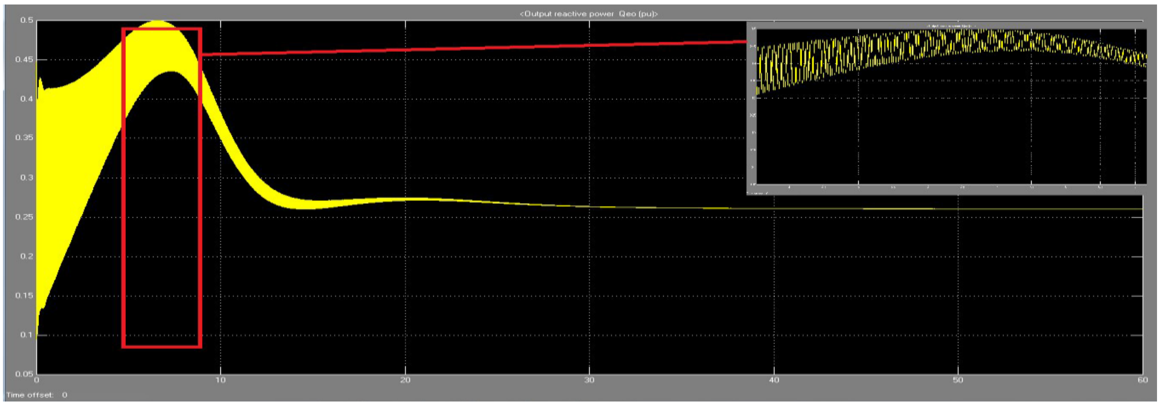

Fig 10 Reactive Power Characteristics of Hydro Power Plant (in *y*-Axis Reactive Power *x*-Axis Time in sec)

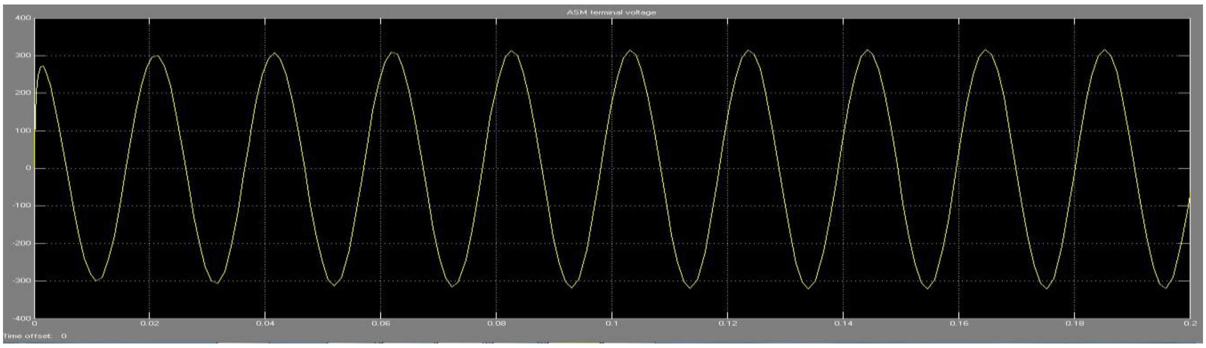

Fig 11 Phase Voltage Characteristics of Stator (in *y*-Axis Voltage in Volt and in *x*-Axis Time in Sec)

VI. CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

The modelling of micro hydro power plant is done in this thesis by using MALAB/Simulink. Introduction of micro hydro power plant reduces a lot of burden without any adverse effect on environment while meeting the localized power requirement. The simulation results shows that with proper choice of governing system for micro hydro power plant leads to proper load sharing, constant voltage output and constant speed with variation of load values. This leads to an economical operation of the system.

6.2 Future Scope

The modelling of this system can be made more accurate and attractive by introducing voltage regulator block, battery storage system, reactive power control block etc. Introduction of FACTS device blocks to control the power quality of the system may be incorporated in the modelling. The system capacity may be enhanced up to 100kW (maximum limit of micro power generation) and other option for connecting other renewable energy sources may be exercised. This may be tested for some realistic load patterns of some chosen areas.

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