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# Control system approach to optimize the performance of off-grid micro hydro power plants

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**Abstract**
Small Hydro Power Plants are grabbing attention of many underdeveloped countries providing local power and a source of new capacity in established markets. Micro Hydro Power Plant is one among them that harnesses maximum power available in water and provides the best solution of power generation for areas like the hilly regions. Micro Hydro Power Plant has a huge potential of large amount of electricity generation out of a small water flow with minimal environmental impact. In this paper an approach is made towards the design of a control system for the Micro Hydro Power Plant which ensures optimum amount of power generation, all the time the plant runs. The intake water flow rate of Micro Hydro is controlled to generate the desired electrical power. The complete control system model is developed in MATLAB using Simulink. The transient behavior of generated active power, voltage and speed of synchronous machine are analyzed through the designed control system model.

**Keywords:** micro hydro power plant (MHP), optimum power, gate valve position, electrical power output, water flow rate

## 1. Introduction

Hydro electricity is basically the combination of water flow and vertical drop (head). The head creates pressure and the continuously flowing water gives liquid energy. Thus pressurized flowing water converts a very large percentage of the available energy into electricity with the aid of hydraulic turbine and generator. When the water is falling by the force of gravity, its potential energy converts into kinetic energy. This kinetic energy of the flowing water then turns the blades of hydraulic turbine. The turbine turns the generator rotor which then converts this mechanical energy into electrical energy. Micro Hydro Power Pant (MHP) generates 5 KW to 100KW of power. These systems are run-off-river type and do not need reservoir or construction of dam. MHP can produce enough amount of energy out of a small water flow and runs 24 hours a day. MHP can be made entirely independent of the grid for the locations where it is really difficult to reach out through the grid. In situations where the resource exists reasonably close to the end use, MHP proves to be more economical than tapping other renewable sources of energy. Additional benefits of MHP involve ground level maintenance unlike the wind and solar based power plants. When it comes to reliable power supply its hard to beat Micro Hydro.

Small hydro power plants (up to 10MW capacity) are more capital intensive and include major political issues and decisions causing difficulties in various implementation phase of the plant. On the other hand, MHP are cost effective, small sized and can serve a small community with its ease of installation and implementation in the socio-political context.

Nepal has set the benchmark through Micro Hydro Power generation for water rich countries. Nepal has enough water to electrify the entire country of 27 million people. Since 1996 nearly 400 micro hydro power plants have been built in the most remote areas of Nepal bringing modern energy to 500,000 people. This simple technology proved to be long term solution to bring an end to various energy problems.

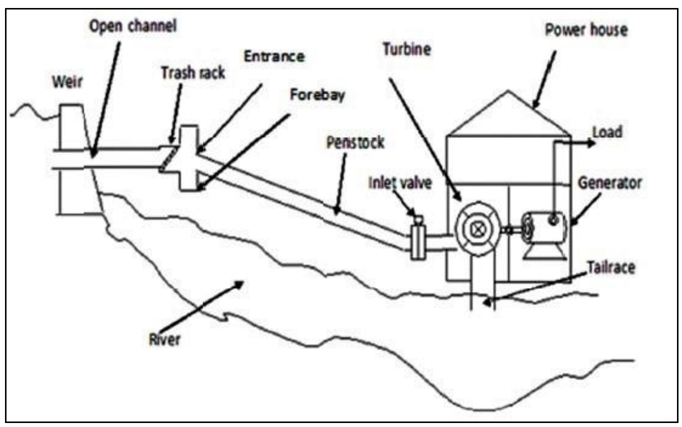


**Fig 1:** Schematic diagram of micro-hydroelectric power plant

## 2. Basic functional model of MHP

The complete block diagram of MHP is shown in figure 2. The water is first carried through an open channel from the running river stream to the penstock. Penstock is the pipeline used to create certain head (pressure) as per the required power generation. From the penstock the water is then fed into the hydro turbine via the gate or the guide vanes. The gate valve position can be controlled in order to control the mechanical power produced by the turbine.

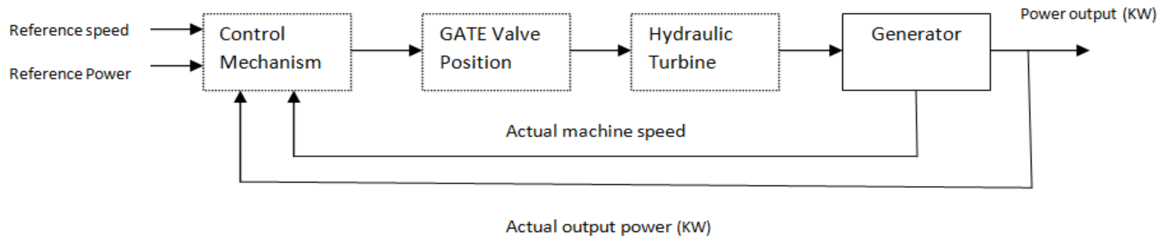


**Fig 2:** Functional Block Diagram of Micro Hydro Power Plant

The generator shaft is mechanically coupled to the turbine. The mechanical power output of the turbine is the input to the generator to produce rated electrical power. An appropriate control mechanism is required to operate and set the gate valve position to maintain the mechanical power output of turbine constant so that an optimum electrical power is generated by the generator. The two input to the controller are reference speed and reference power. The dashed blocks in figure 2 represent the speed governing system of the hydro plant. The speed governing system adjusts the speed of the generator rotor and generated active power to the optimum value based on the feedback signals of the deviations of both machine speed and power with respect to their reference settings. This ensures rated/optimum power generation from MHP.

## 3. Modelling of hydro turbine governor system

The block of Hydro Turbine Governor System is shown in figure 3. This block is created in Matlab using Simulink and it has the subsystem which explains its function. The input and output description of the HTG system is as follows:

Wref: Reference speed, in p.u.
We: Machine actual speed, in p.u.
Pref: Reference mechanical power, in p.u.
Pe: Machine actual electrical power, in p.u.
Pm: Mechanical Power for the synchronous generator block in p.u.

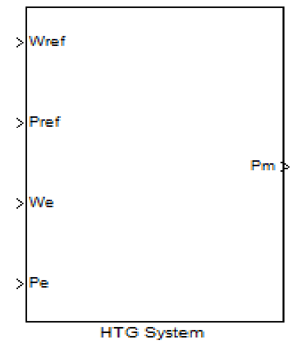


**Fig 3:** Hydraulic Turbine Governor System block

The subsystem of HTG block contains a controller (PID), Servo-motor and Hydraulic turbine as shown in figure 4.
The error in speed is fed as input signal to the PID controller and the controller tries to reduce the difference between the actual machine speed and the reference speed by adjusting the constants of the controller. The name of PID controller derives from three functions involved in calculating [1] the corrections and is accordingly sometimes called three term control: *P* stands for proportional, *I* stand for integrator and *D* stands for derivative [5] 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.

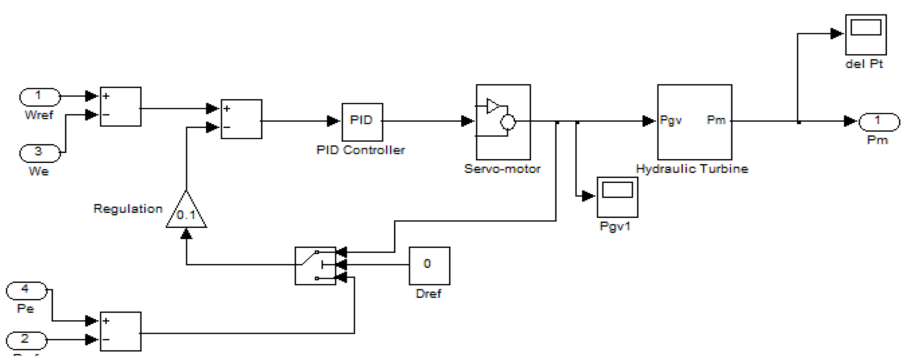


**Fig 4:** Subsystem of HTG block

The transfer function of the PID controller is shown below [4]:

$$K(s) = \frac{\vartheta(s)}{e(s)} = (K_p + \frac{K_i}{s} + K_d s)$$

Where,
E (s) is the controller input
$\upsilon$ (s) is the controller output

### 3.1 Modeling of Servo-Motor

Mechanical hydraulic governors or the conventional type of hydro governors are used in large hydro power plants. In case of small hydro power plants such as the MHP the servo motor serves the purpose of governor. The gate valve is operated by the servo motor. The gate opening position is controlled by the servomotor with the help of controller used for the plant. The servomotor requires specific sophisticated controller which can provide either digital or analog input signal for the position feedback.

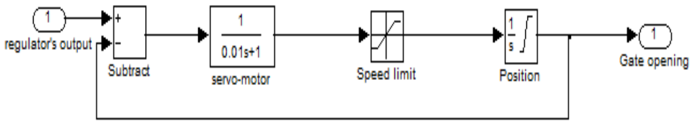


**Fig 5:** Model of Servo-motor

Here, the gate valve position is controlled by the servomotor when the PID controller receives the control signal through the feedback control loop as shown in figure 2. Thus, according to the change in synchronous speed of the generator at the shaft the complete control system maintains the electrical power constant. The transfer function required to develop the complete block diagram of the hydro electric servo system is given below [1, 3]:

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

Where Ka = K/(B+f) and $t_a$ = J/(B+f) are gain and time constant respectively.

### 3.2 Modeling of Hydraulic Turbine

The non-linear characteristics of the hydro turbine are neglected in the presented model. The equations related to the transient performance of the hydraulic turbine are described below. The water flow rate and the mechanical power produced at the shaft can be described by the following equations [2]:

$$Q = G\sqrt{H} \tag{1}$$

Where, Q is the water discharge or the flow rate in $m^3$/sec
G is the gate opening in rad and H is the net head in meters

$$P_m = A_t H(Q - Q_{nl}) \tag{2}$$

Where, $P_m$ is the mechanical power at the turbine shaft
$A_t$ is the turbine gain and $Q_{nl}$ is the no load flow rate.
The block diagram of the hydraulic turbine based on these equations is modeled in Matlab/Simulink and shown in figure 6.
The water flow in the penstock is described by the Eq. (3):

$$U = K_u G\sqrt{H} \tag{3}$$

Where, U is the velocity of water in penstock and $K_u$ is the proportional constant.
As the fluid discharge is also given by the equation

$$Q = AU \tag{4}$$

The acceleration of water in the penstock can be explained as:

$$\frac{du}{dt} = -\frac{ag}{L}(H - Ho) \tag{5}$$

Where, $a_g$ is the acceleration due to gravity and L is the length of the penstock.
The mechanical power output is given by:

$$P_m = (P - P_l) \tag{6}$$

Where, $P_l$ is the fixed power losses in the turbine due to friction and

$$P_l = U_{nl} H \tag{7}$$

And $U_{nl}$ is the no load speed.

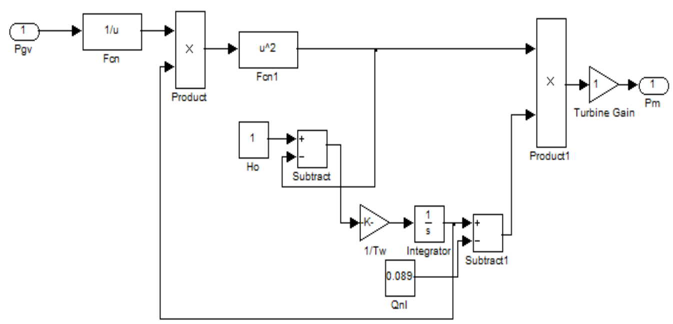


**Fig 6:** Model of Hydraulic Turbine

Here, in this model $P_{gv}$ is the gate valve position which acts as the input signal to the hydro turbine. The gate opening would vary the water flow inlet to the turbine and keeps the water discharge to the turbine constant to produce the desired mechanical power output at the shaft of the generator.

### 4. MATLAB/Simulink model of Micro Hydro Power Plant

The complete model of the micro hydro power plant as developed in MATLAB is shown in figure 7. Mechanical power output of the HTG system (as explained in the above section) is fed as input to the synchronous generator. The other input of the synchronous machine is the field voltage which is obtained from the Excitation system of the machine.

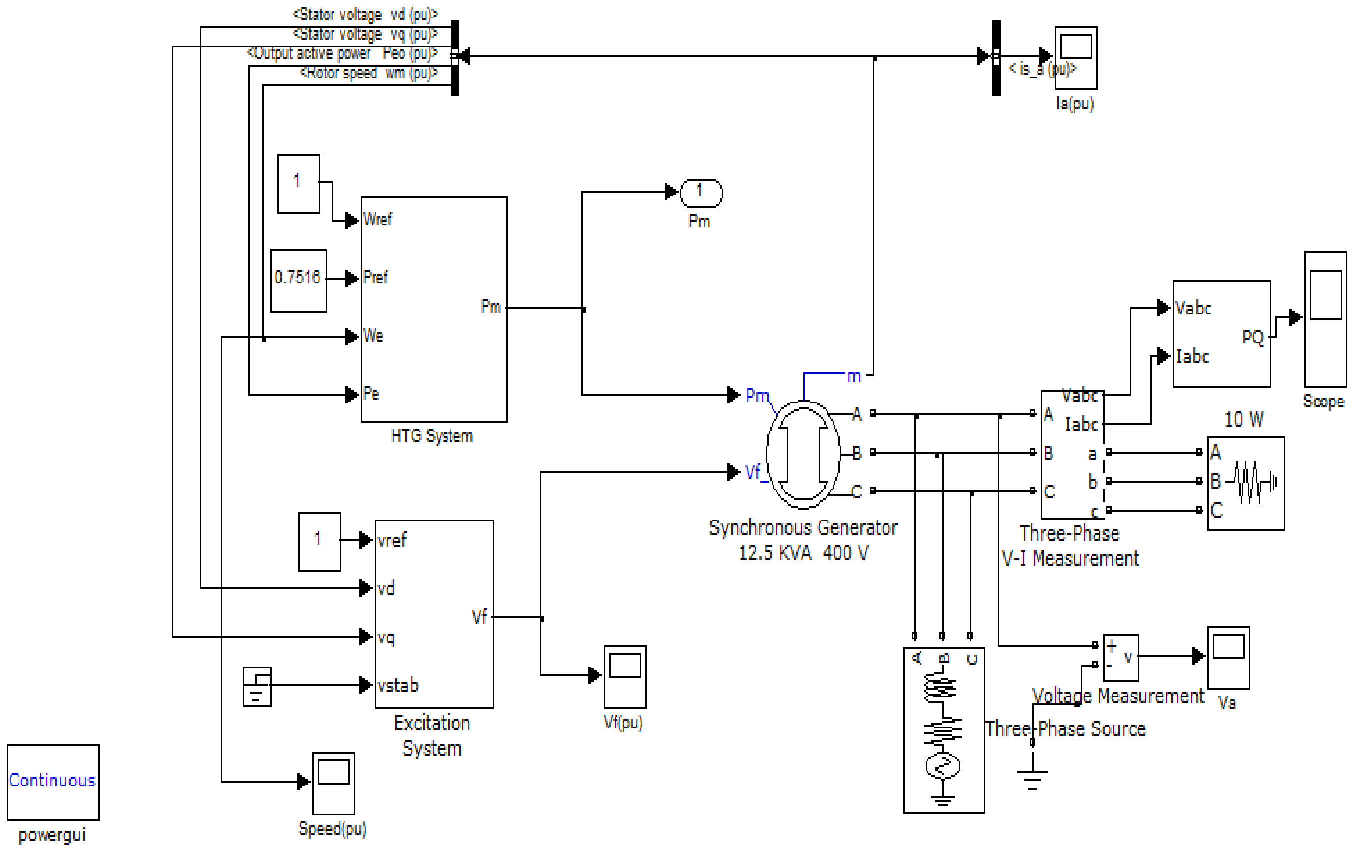


**Fig 7:** Simulink model of Micro Hydro Power Plant

## 5. Simulation results of MHP model

As shown in figure 12, The mechanical power output of the tubine increases with time and attains its steady state value at 0.9 p.u. within few seconds. This has become possible by optimum water discharge to the inlet of the hydraulic turbine. The inlet water flow rate is controlled by the appropriate opening/position of the gate valve which is shown in figure 11.

As a result the electrical power output of the plant is maintained constant to its maximum possible value of 0.6 p.u. as reflected in figure 8. The transient time period is around 14 sec. The transient behaviour of generated voltage and rotor speed are shown in the figures given below. The steady state error for allthe measured quantities is perfectly zero with settling time period of around 25 secs. The turbine effeciency is improved to 89.47% (normally varies between 80-90%) and the electrical efficiency of the MHP plant is maintained constant at 70.6%.

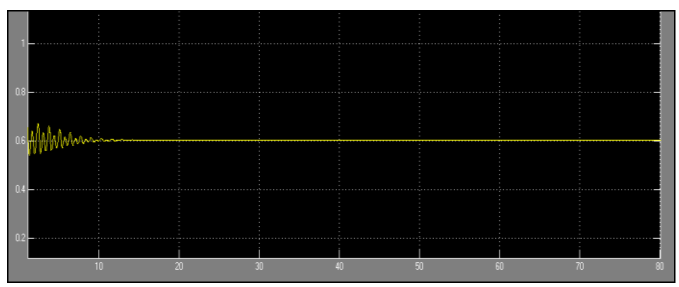

**Fig 8:** Electrical Power output (Pe) characteristics of the hydro power plant (in p.u.) with time (in sec)

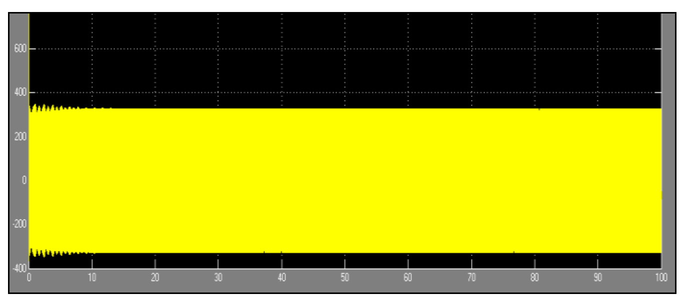

**Fig 9:** Phasor Voltage (Va) characteristics of the plant with time (sec)

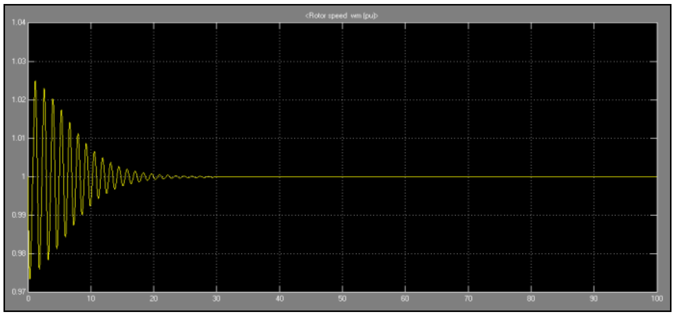

**Fig 10:** Characteristics of Synchronous Speed of the rotor (in p.u.) with time (in sec)

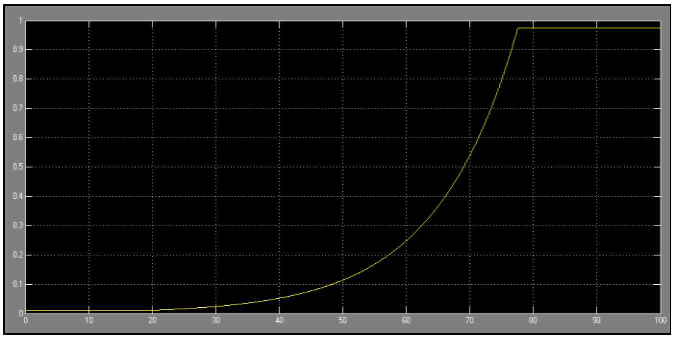

**Fig 11:** Gate Valve Opening (Pgv) characteristics with time (in sec)

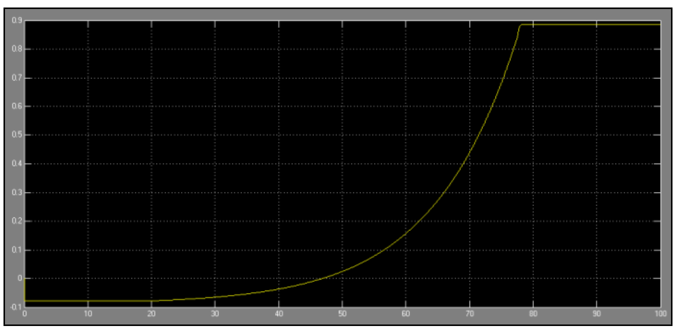

**Fig 12:** Characteristics of Mechanical power (Pm) output of turbine (p.u.) with time (in sec)

## 6. Conclusions

The proposed model of Micro Hydro Power Plant shows that even a low level of water discharge has enough potential to generate an optimal amount of electrical power. This paper approves that simulation of MHP with sophisticated controller can resolve the problem of fluctuations in power due to frequently variable flow rate. The controller mechanism would make the generated power and the entire system stable within a very short period of time. Both mechanical and electrical efficiency of the system is also improved.

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