CONTROL OF A SMALL HYDROPOWER SYSTEM FOR POWER SUPPLY IN A REMOTE COMMUNITY

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ABSTRACT : **The need to provide some neighbouring communities in the Boki Local Government area in Cross River State with a stable electric power supply from the Afi river compelled this work. Afi River has a water head of about 11.4m and a flow rate of about 13m^3/s which are used for the determination of the expected hydrological power, this helps in the choice of the appropriate turbine used. Non-linear models are used to represent devices required for the small hydropower plant (HPP). The control involves proportional integral derivative (PID) governor and power system stabilizer (PSS) to enhance the operation of the small hydropower system. Ziegler Nichols' turning method is adopted in selecting the right gain coefficient of the PID governor. The design is done using Matlab and simulation of the control system is carried out with Simulink. Matlab/Simulink is used to compare and model the response of the HPP when controllers are present and when they are absent. The results show that the controlled hydropower plant is able to regain stability after 3s when agitated by load variation. Also, the power system stabilizer (PSS) displayed the ability to improve the enhancement of the proposed hydropower plant. The hydropower plant has the prospect of producing over 1976kW approximately 2MW of energy. Load variation has little or no effect on the voltage of the system unlike in the active power and the speed. This is as a result of the inherent voltage regulator of the generator. The results further revealed that it is practically impossible to run a small hydropower system without the use of a speed controller. In terms of economic wise, hydropower is cheap to maintain and does not produce green house gas.**

Keywords: Small Hydropower Plant, Afi River, Power System Stabilizer, Turbine, Speed Control, PID Controller, Speed Response, Matlab/Simulink

1.0 INTRODUCTION

Hydropower is a zero-pollution and renewable energy source. Hydropower or hydroelectricity refers to the conversion of energy from flowing water into electricity. This is achieved by converting the gravitational potential or kinetic energy of a moving water source to produce power [1]

Hydropower is initially used for mechanical millings like crushing grains. Modern hydro plants use turbines and generators to generate electricity where mechanical energy is created when moving water spins a turbine's rotor [2]. When the turbine turns, an electromagnetic generator attached to it generates power. The most stable, economical, and environmentally friendly energy source in the country is hydropower, currently accounting for nearly two-thirds of all renewable energy generation in the country. It is also America's greatest source of clean electricity. In Nigeria, hydropower has the potential to increase significantly the energy profile with the proper Federal and State policies in place.

A hydropower project must satisfy a number of requirements, including minimal river flows, water quality, fish passage, watershed protection, threatened and endangered species, recreation, and curatorial protection in order to be identified as low-impact, according to the Low Impact Hydropower Institute (LIHI).

Electricity production via water resources is associated with instability in output power due to changes in weather conditions. The drought season is associated with the decline of water level thus determining the volume of water that can flow into the turbine. This greatly affects the speed that the turbine will attain over a given period. Because of this, it is necessary to devise a means of annulling negative effects to enable a small hydropower scheme to run at a nominal speed or frequency.

Epileptic power supply in Nigeria has forced industries and other businesses that bank on electricity to rely on private diesel engines to generate their electricity[3]. Turbines are easily affected when the water level in the dam changes, resulting in low-speed rotation of hydropower turbines. A hydropower automatic speed governor is used to controlling a turbine output when a sudden load change occurs. This is to avoid the rotation speed of the turbine and that of the generator to change sharply due to load reduction or increase[4]. Adjusting the water flow into the mini-hydro turbine makes the turbine output meet the change of external load. Due to the swiftness or fastness of the load changes in the generator, the artificial control method does not meet this requirement. This is why most hydropower stations are equipped with an automatic mechanical “governor” to regulate water flow through the penstock to the turbine blades.

There is a vast potential for the small hydropower in many developing nations. Small hydro can contribute to gains in productivity and the development of women by the powering of agro-industrial industries[5].

Over fifty pieces of equipment are designed and energized via hydroelectric power. Selecting the appropriate type of hydro turbine for a particular situation often depends mainly on the amount of the available head and water flow rate in the location[6].

The water turbine is powered by potential energy in water that is created when there is a head in a river, according to current small hydropower (SHP) technology. Based on this current technology, the potential of generating electricity and mechanical power from small scale hydropower systems is qualitatively stated to be enormous in many countries in the world due to its geographical features such as the presence of perennial rivers locations, as seen in Buanchor Community in Boki L.G.A, Cross River State of Nigeria[7]. It should be pointed out that Boki Local Government Area has a complete up-to-date national inventory of the potential sites for the installation of the Small hydropower (SHP) systems in terms of head, flow rate, firm power output, and unit power investment cost.

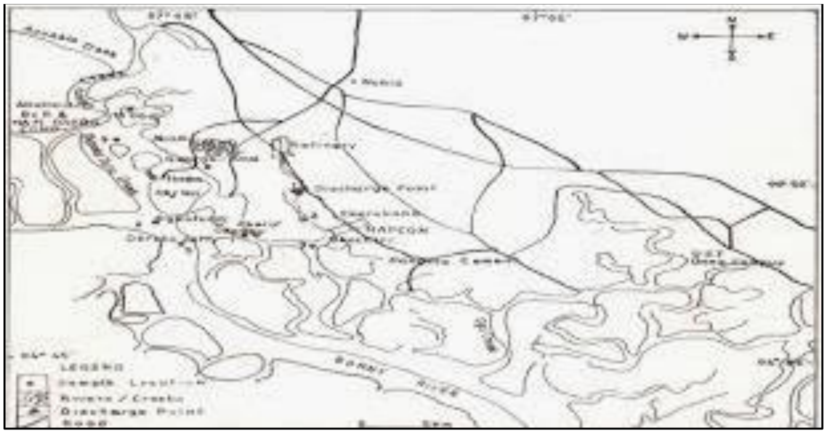


Plate 1: Map of Buanchor, Afi River and nearby Communities
Source: https://www.researchgate.net/figure/

Specific speed is the main numerical category for a hydro turbine. The fluid flow parameters and intended shaft output speed can be used to calculate the specific speed, which enables the best turbine design to be selected. A specific speed is employed in order to successfully scale an old design to a new size with the corresponding performance. Mathematically, the specific speed can be determined as a function of either the flow rate discharge and the net head or as a function of the maximum power and the net head (represented as Ns). (expressed as nq) [8-9]. For the first case, the specific speed Ns is the turbine turning speed (r.p.m) working under a fall of 1m and producing a power of 1 kW as given by

$$N_s = \frac{N * \sqrt{Pt}}{H_n^{5/4}} \tag{1}$$

Where,

N = Turbine speed in (***r.p.m***)

H_s = Net water head in (***m***)

P_i = Turbine output power in (***kW)***

For the second case, the specific speed n_q is the turbine turning speed (*r.p.m*) at work under a fall of 1m and a flow of 1m^3/S as specified below

$$n_q = \frac{N * \sqrt{Q}}{H_n^{3/4}} \tag{2}$$

Where,

$Q =$ Worker discharge (m^3/S)

The relationship between N_s and n_q is expressed as:

$$N_s \approx 3 * n_q \tag{3}$$

Once the type, specific speed, and net head are identified, the turbine's core dimensions can be assessed. Every turbine has a distinct shape and construction. There will therefore be several dimensionality equations based on the design and functionality of the turbine[8 & 9].

The main specifications of this type are the runner diameter, runner length, and jet thickness or nozzle width.

$$D_r = \frac{40*\sqrt{Hn}}{N} \tag{4}$$

$$L_r = \frac{0.81*Q}{D_r*\sqrt{Hn}} \tag{5}$$

$$t_j = \frac{0.233*Q}{L_r*\sqrt{Hn}} \tag{6}$$

Where:

D_r =Runner diameter in meter

L_r =Runner length in meter

t_j =Jet thickness or nozzle width in meter

The exit and inlet diameters are the primary dimensions in this type. The net head, rated turbine speed, and specific speed are used to formulate them.

$$D_3 = 84.5\left(0.31 + 2.488\frac{Ns}{995}\right) * \frac{\sqrt{Hn}}{N} \tag{7}$$

$$D_1 = \left(0.4 + \frac{94.5}{Ns}\right) * D_3 \tag{8}$$

$$D_2 = \frac{D_3}{0.96+3.8*10^{-4}*Ns} \tag{9}$$

where:

D_3 =Outlet diameter in meters

D_1 =Inlet diameter in meters.

D_2 =Inlet diameter in meters for Ns >163,

If Ns < 163 then $D_1 = D_2$

This type covers a wide range of specific speeds, going from 30 to 400 corresponding to the high and low heads.

The primary dimensions of this type are represented by the runners' outer and inner diameters.

The net head, rated turbine speed, and specific speed are used to formulate them.

$$De = 84.5(0.79 + 1.60 * 10^{-3}Ns) * \frac{\sqrt{Hn}}{N} \qquad (10)$$

Where:

De =Outer diameter of the runner in meters

D_1 = The hub (inlet) diameter of the runner in meters

Generally, the Kaplan turbines exhibit much higher specific speeds than Francis types. The right turbine type is chosen based on the water head and flow parameters that are available. The turbine's efficiency curves is a function of the rated head, runner diameter, turbine specific speed, and design/manufacturer coefficient. Numerous manufacturing efficiency curves for various water heads and flow circumstances can be used to infer the efficiency equations for various types of turbines[10].

The turbine efficiency, nq, can be computed using the following equation:

$$n_q = 0.79 - 0.15\left(\frac{Q_p - Q}{Q_p}\right) - 1.37\left(\frac{Q_p - Q}{Q_p}\right)^{14} \qquad (11)$$

Where $Q_p$is the peak efficiency flow which can be computed as $Q_p = Q_d$ and $Q_d$is the design flow (flow at the rated head and full gate opening in m^3/S).

A significant factor for comparing different turbine types is their relative efficiencies at both design points (peak efficiency, $\hat{\eta}_p$) and reduced flows, q. The peak efficiency can be computed using

$$\hat{\eta}_p = \left(0.919 - \hat{\eta}_{nq} + \hat{\eta}_d\right) - 0.0305\_0.005R_m \qquad (12)$$

$$\hat{\eta}_{nq} = \left(\frac{(\eta_q - 56)}{256}\right)^2 \qquad (13)$$

$$\hat{\eta}_d = \left(0.081 + \hat{\eta}_{nq}\right)(1 - 0.789d^{-0.2}) \qquad (14)$$

Where

$\hat{\eta}_{nq}$ =Specific speed adjusted to peak efficiency;

$\hat{\eta}_d$ =Runner size adjusted to peak efficiency;

D = Runner size of Francis turbine in meters.

R_m =Turbine manufacture/design coefficient

The efficiency at reduced flow can be computed as:

$$\eta_q = \left\{1 - \left[1.25\left(\frac{Q_p - Q}{Q_p}\right)^{(3.94-0.0195nq}\right]\right\}\hat{\eta}_p \qquad (15)$$

where,

Q_p =Peak efficiency flow which can be computed as$Q_p = 0.65 Q_d {n_q}^{0.05}$

Q_p =The design flow (flow at the rated head and full gate opening in m^3/S)

The peak turbine efficiency can be computed as:

$$\hat{\eta}_p = \left(0.905 - \hat{\eta}_{nq} + \hat{\eta}_d\right) - 0.0305 + 0.005 R_m \qquad (16)$$

$$\hat{\eta}_{nq} = \left(\eta_q + \frac{170}{700}\right)^3 \qquad (17)$$

$$\hat{\eta}_d = \left(0.905 + \hat{\eta}_{nq}\right)(1 - 0.789 d^{-0.2}) \qquad (18)$$

Where,

$\hat{\eta}_{nq}$ = Specific speed adjusted to peak efficiency;

$\hat{\eta}_d$ =Runner size adjusted to peak efficiency;

d =The runner size of Kaplan turbine

The efficiency at reduced flow can be computed using the following equation:

$$\eta_q = \left\{\left[103.5\left(\frac{Q_p - Q}{Q_p}\right)^6\right]\right\}\eta_p \qquad (19)$$

where,

Q_p =Peak efficiency flow which can be computed as. $Q_p = 0.75\ Q_d$

1.1 Voltage and frequency control

When the SHP system is in on-grid mode, the grid controls both the active and reactive power; however, when the system is in off-grid mode, the generator terminals' frequency and voltage must be maintained throughout speed fluctuations. Consequently, a variety of control techniques are needed to keep the frequency and voltage within acceptable ranges[11-13].

1.2 Control methods of SG

The SGs are suitable for modest hydro-power plants and can function in an isolated mode. By altering the SG's excitation, the voltage is managed[14]. The excitation system consists of protective elements, controllers, and regulators to control the field current. The acceptable limits are typically within ±10% [11 &12]

The generator's voltage and speed are controlled by the governor. The governor controls the active power and frequency (P-f) for islanding operation, while the exciter controls the reactive power and voltage (Q-V) [15]. According to the generator swing equation, islanding state could change the electric load and cause a frequency deviation[12]. The problem of frequency deviation is a huge one. It can be under/over frequency relays and consequently stop the generator. The speed governor should be able to maintain the frequency within acceptable limits and fulfil the system resynchronization requirements[14 &16]. The relation between the active power and the speed of the SG can be expressed by the swing equation as:

$$2H\Delta\omega_s = \Delta P_m - \Delta P_e \qquad (20)$$

where H is the inertia of the generator, *Pm* is the changes in mechanical power, *Pe* is the changes in electrical power, and *s* the variations in generator speed. It is clear from (20) that changes in active power are inversely correlated with changes in generator speed. The water flow valves are opened or closed to control the mechanical power[14].

1.3 Control methods of IG

Self-Excited Induction Generators (SEIG), Doubly Fed Induction Generators (DFIG), and Permeant Magnet Induction Generators are the three different forms of IGs (PMIG). The IGs struggle to keep the frequency and voltage within their permitted ranges. To regulate the voltage, they are frequently equipped with capacitors or Automatic Voltage Regulators (AVRs) [17]. Small hydropower systems are discovered to be the most suitable for the SEIGs. Direct Voltage Control (DVC) method to regulate the frequency and voltage of a standalone wind-driven SEIG with changeable loads has been studied [18]. A lead-lag corrector, a proportional-integral (PI) controller, and a feed-forward compensator made up the controller.

This study is aimed at providing a small hydropower system with the view of enhancing the electricity power supply for a remote community. The objectives of this study are to :

- ascertain that the generator operates at or near nominal speed at all times.
- optimize the stability response of the hydroelectric power scheme by integrating a supplementary controller in the system.

This work focuses on modelling and control of a hydropower system basically at the generation level. MATLAB/SIMULINK software is used in demonstrating the models and the control techniques

2.0 MATERIALS AND METHODS

2.1. Materials

- Matlab/Simulink Software
- Data are collected from the Cross River Basin Development Authority (CRBDA)
- laptop

In modelling of SHPPS, element like the turbine and the governor, synchronous generator are essential to study the electric power scheme characterize during any perturbation of the system dynamic characteristic of a turbine and its governing systems when the system perturbs influence power system performance. Figure 1 shows the block model of the turbine governor system etc.

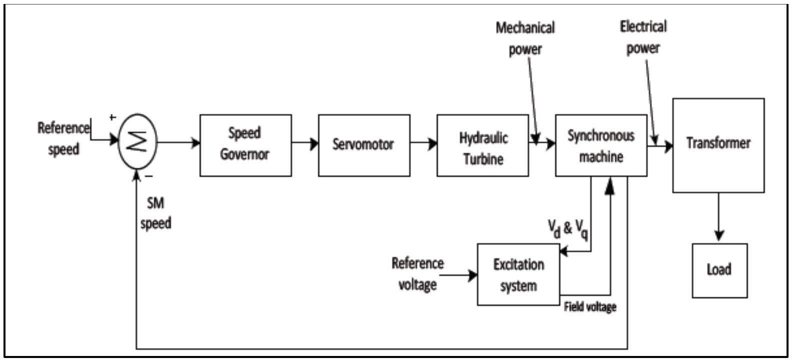


Figure 1: Block diagram for hydropower plant
Source: [19]

2.2. Method

The Small Hydropower plant us modelled in Matlab/Simulink software. The governor receives the reference speed, and the servo motor controls the gate valve based on the signal from the PID controller. This causes the measured generator speed to be fed backwards until it reaches the speed signal's starting value. By comparing the reference speed and generator speed, the speed deviation is obtained and fed into the PID as input Error. PID starts the control signal, which causes the gate position to change. The generator that produces the electrical energy as an output is driven by the turbine-like device, which intelligently generates a starting torque. The speed governor, or PID, continuously monitors a process' variance [19].

2.2.1 Modelling of proportional integral derivative (PID)

The PID is employed as the speed governor; by changing its constants, it lowers the speed error given into its input. PID as shown in figure 2, lessens the difference between the real speed and the reference PID Controller's speed. PIDs are also referred to as three-term controllers. The terms P, I, and D, respectively, denote integrator, proportional, and derivative. P, I, and D are reliant on the present, previous, and potential faults, respectively. The PID output response is depicted in equation 21

$$\theta(t) = k_p e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \quad (21)$$

Equation 22, is gotten by applying the Laplace scheme.

$$\theta(s) = k_p E(s) + k_i \frac{E(s)}{s} + k_d\, sE(s) \quad (22)$$

The PID transfer function is given as

$$C(s) = \frac{Q(s)}{E(s)} = k_p + \frac{k_i}{s} + k_d s \quad (23)$$

Where $\theta(s)$represents the output response of the PID.

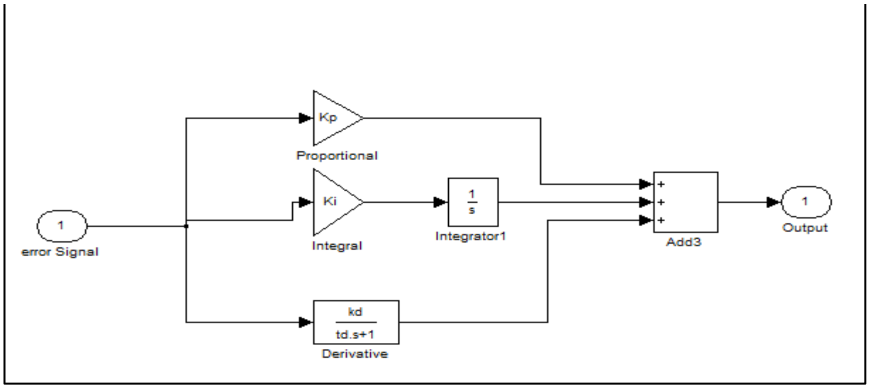


Figure 2: Block Model showing PID Controller in Simulink
Source: [20]

2.2.2 Integration of Power System Stabilizer in the HPP model

A power system stabilizer (PSS) helps in supplying the rotor speed deviation to the excitation system regulator input, it also reduces the instability of the system which is characterized by a swinging response.

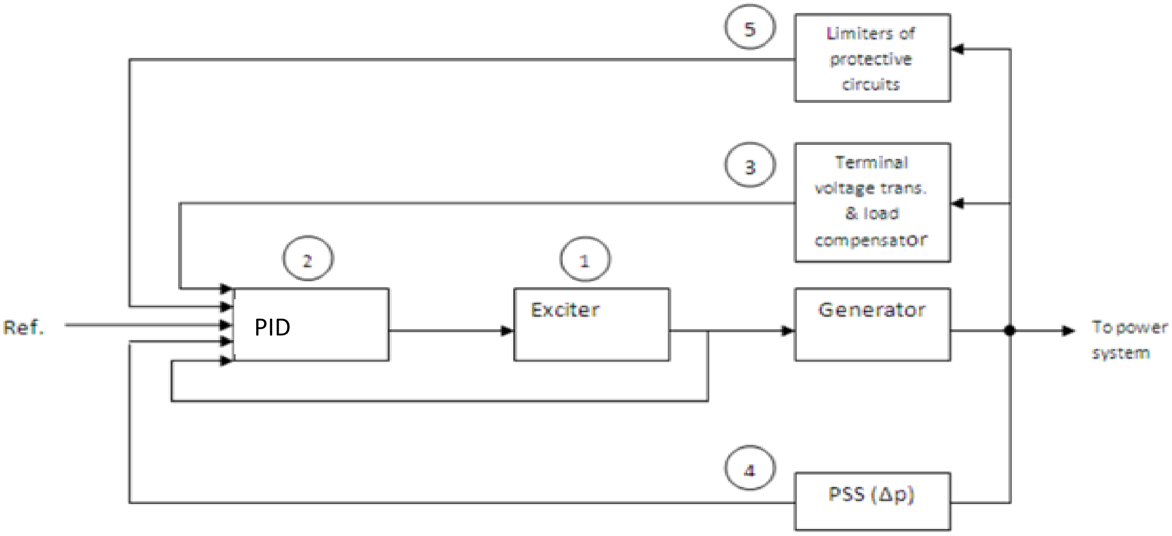


Figure 3 Block diagram showing the addition of PSS to the circuit

The output of the generator is a function of the mechanical torque created by the turbine. This torque can be altered by changing the excitation value. A PSS senses the generator output power, controls the excitation system value and declines the rapid fluctuations

3.0 RESULTS AND DISCUSSION

The simulation experiment of the PSHPP is carried out under ordinary co without any controlling element, normal condition with a PID controller, normal conditio PID and PSS controllers, under 50% load increment with PID and PSS controllers, ar er 50% load decrement with PID and PSS controllers.

The simulation consists of rotor speed and active power and this enables the response of the SHPP to be perceived during different cases of perturbation. The simulation arrangement for a normal condition is shown in figure 4 while for RLC load variation is shown in figure 5. The circuit breaker block is connected to the load bus as shown, the simulation time is 20 seconds.

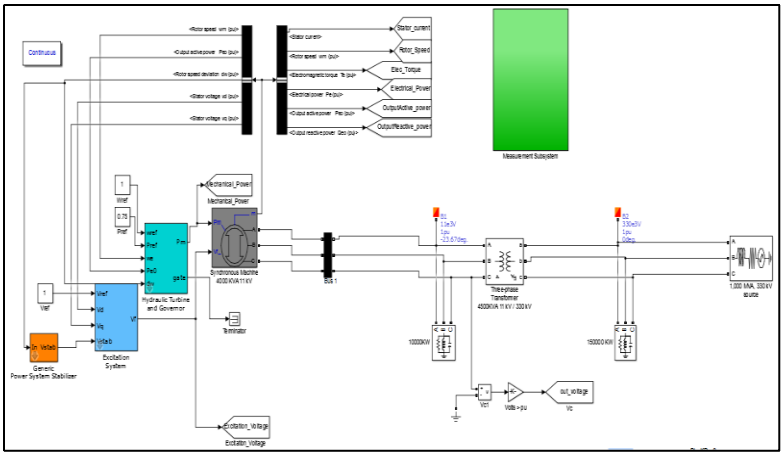


Figure 4 : Simulink Design of the PHPPS at normal operation condition

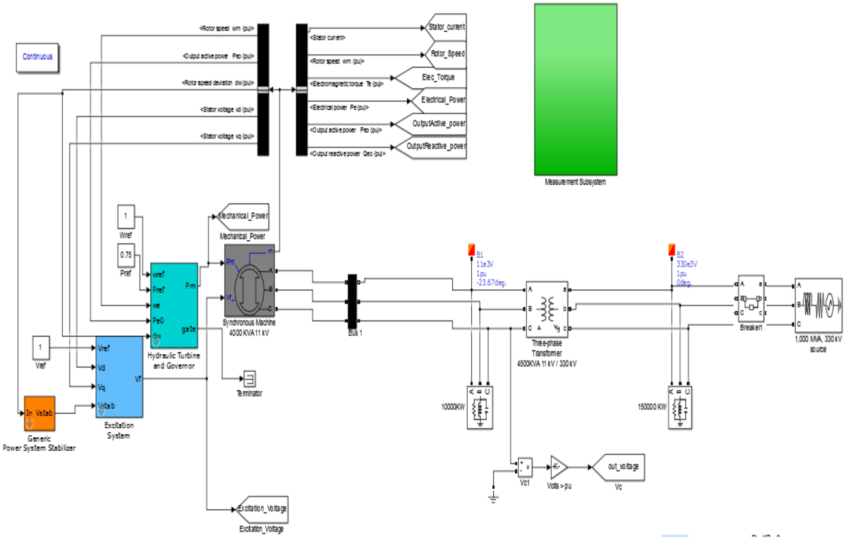
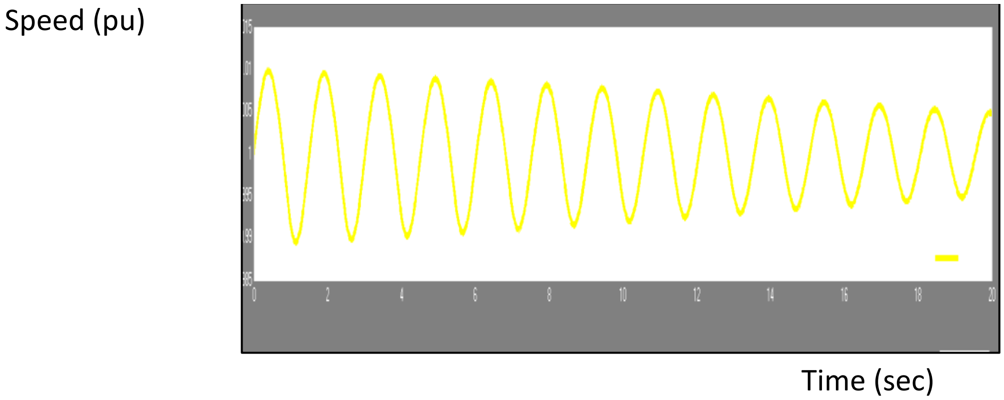


Figure 5: Simulink design of the PHPPS during load variation

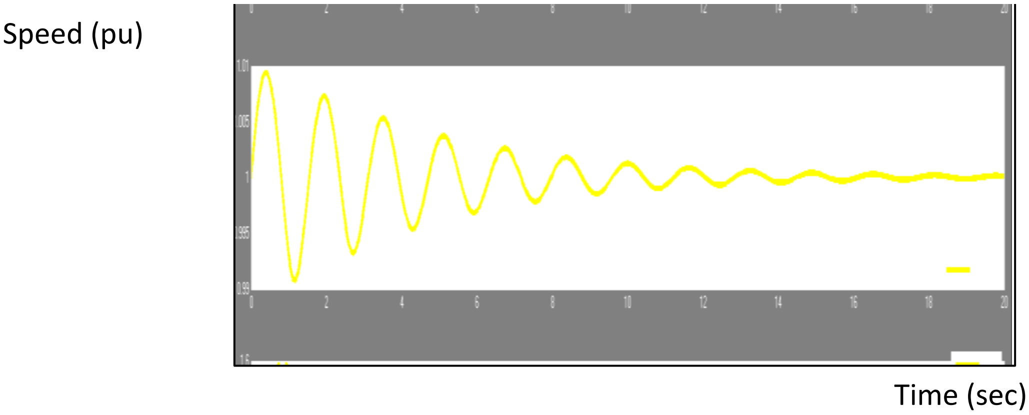
The model outcomes are graphically shown as waveforms of the different measured output parameters. The outcome is shown in different cases from case 1 to 5 which represents different operating conditions. The parameters considered are speed and output power as shown on the graphs. The magnitude of the parameters is on the vertical axis and all the parameters are measured per unit (Pu) while time in (sec) is on the horizontal axis. The first waveform represents the speed and the last represents the active power in all the different cases.

3.1 Comparison of speed

Case1: Running without a controller



Case2: Running only with a PID controller



Case: 3 Running with a PID and a PSS controller

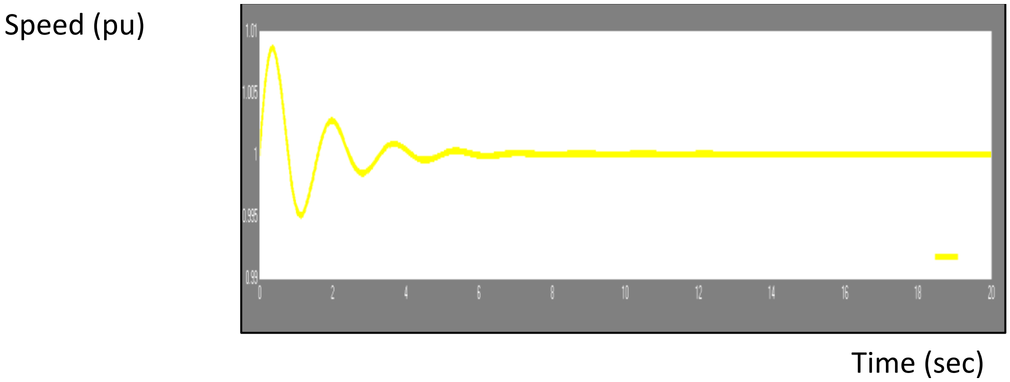


Figure 6 Comparison of the speed response at different operating conditions.

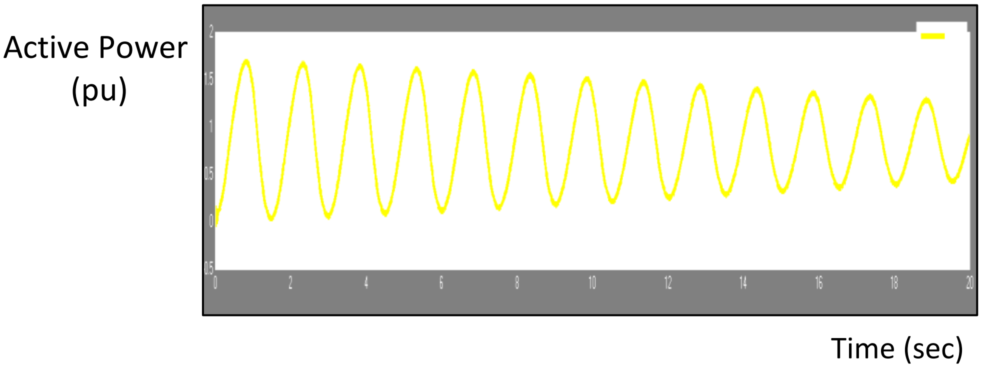
In figure 6, case 1 represents the response of the hydropower plant during the uncontrolled condition. It is observed that repeated oscillation occurred in the speed of the system, this repeated oscillation lasted throughout the operation of the system. The speed of the plant oscillated between 0.89pu and 1.089pu which shows a significant deviation from its normal reference setting of 1pu. This high repeated oscillation signifies instability in the system. This reveals that it is practically impossible to run a small hydropower system without a speed controller. The system will run under an unrelated speed and frequency which will cause adverse effects on the appliance of the consumers.

In case 2, during the initial period, there is a heavy starting oscillation in the speed of the plant, this is an implication that the plant needs some time to run before it stabilizes. The periodic oscillation lasted for about 10s before the speed started becoming stable and the heavy oscillation started dying out gradually because of the presence of the speed governor (PID controller). The system stability is far better compared to when there is no speed governor.

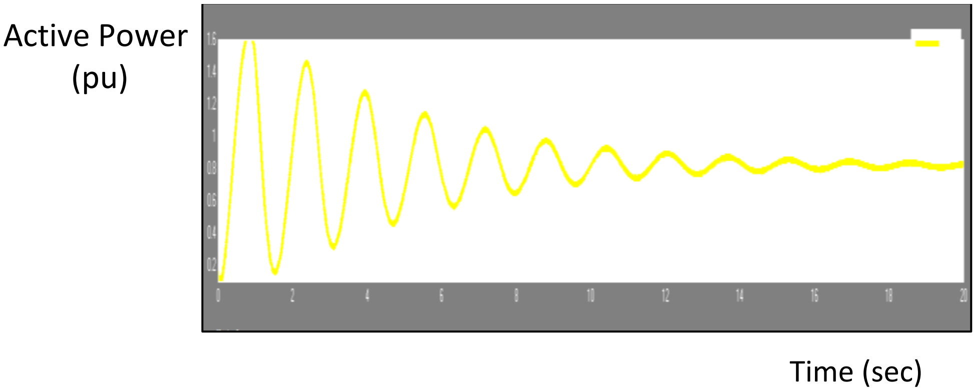
Case 3 shows the presence of PID and PSS in the small hydropower system. It reveals that the heavy oscillations in the case1 above are damped but noticeable only from 0s to 4s and the system stabilizes throughout the whole period of operation. After the period of 4s, the speed is running at the reference setting of 1pu. The PSS acts as a supplementary controller. At the integration of the PSS, the system becomes very stable with almost zero oscillation and the periodic signal that are present in the previous cases are eliminated apart from the initial starting oscillation that lasted for about 4s.

3.2 Comparison of Active power

Case 1: Running without a controller



Case 2: Running only with a PID controller



Case: 3 Running with PID and PSS controller

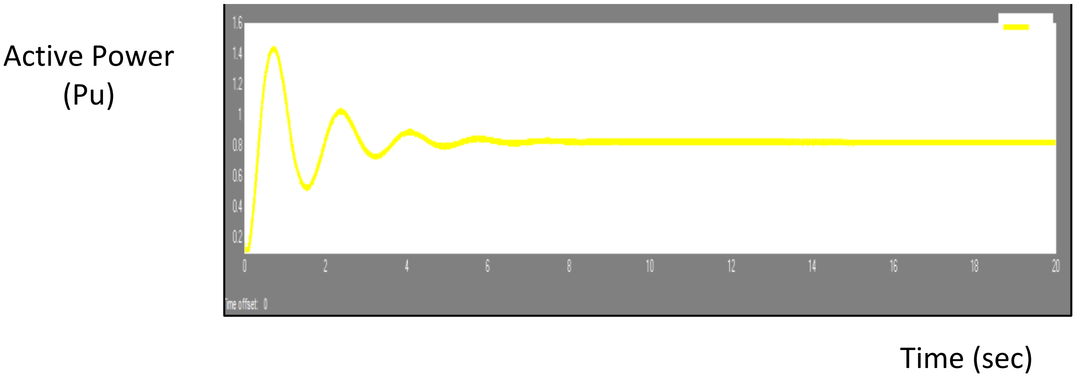


Figure 7 Comparison of the active power response under different conditions

In figure 7**,** Case 1 shows the response of active power of the hydropower plant during the uncontrolled condition. During this period there is repeated oscillation throughout the operation and the repeated oscillation signifies instability in the system. The result signifies that it is practically impossible to run a small hydropower system without a speed controller. The quality of power generated in an unregulated power system will cost huge financial loss to the consumers.

Case 2 represents the response of active power when PID is used as a speed controller. The result reveals that there is heavy starting oscillation in the output power plant. This oscillation lasted for about 10s before the system becomes stable and the heavy oscillation starts dying out.

Case 3 shows the presence of PID and PSS in the small hydropower system. It reveals that the heavy oscillations in the case1 above are damped but noticeable only from 0s to 4s and the system stabilizes throughout the whole period of operation. The PSS works as a supplementary controller, and the system becomes very stable with almost zero oscillation and the periodic signal that are present in the previous cases are eliminated apart from the initial starting oscillation that lasted for about 4s. This is an indication that a power system stabilizer is very much needed when the system stability is a matter of concern.

Case 4: Running under 50% of load demand increment with PID and PSS Controllers

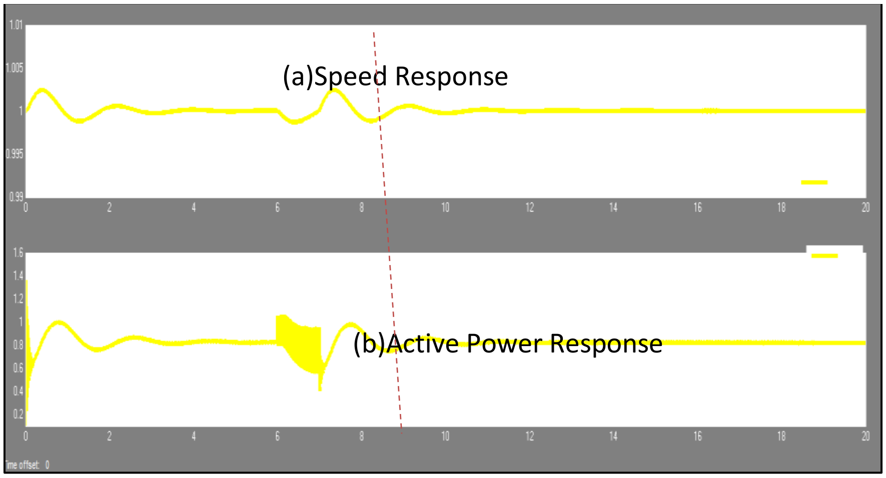


Figure 8 Response of the planned hydropower plant during load addition of 50% using PID and PSS controllers.

The speed is shown in figure 8a. A considerable initial oscillation is seen at the period of 0s to 2s, and it stabilized from 2s to 6s before the system is upset by a load increment of 50%, which causes the plant's speed to drop below the reference value of 1Pu. The plant's speed decreased at the 6s mark as a result of the load escalation. Despite a load increase of 50%, the system oscillated for 2 seconds before returning to stability. It is noticed that this stability persist during the entire operation. Figure 8b shows that the active power of the system follows the same trend as the speed, peaking at 6 seconds.

Case 5: Running under 50% of load demand decrement with PID and PSS controllers

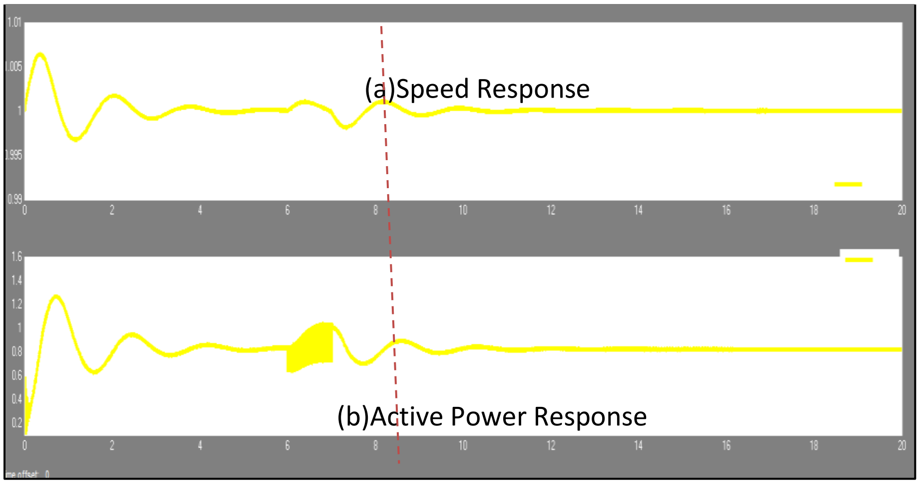


Figure 9 Response of the planned hydropower plant during load decrement of 50% using PID and PSS controllers

When the system is agitated by load reduction, as shown in Figure 9a, a prominent initial oscillation is seen at the period of 0s to 2s and becomes steady from 2s to 6s. The plant's speed becomes high at 6s as a result of the load reduction. The system oscillated for 2s before quickly returning to stability. The active power of the system, represented by the last waveform, is found to follow the same pattern as the speed. At 6 seconds, the output power increases, and after a brief period of oscillation, it regained stability and remains in the steady-state for the duration of the measurement.

Figure 8 is a representation of load RLC load increment, the HPP is running at a steady-state, at 6s the resistive load is increased by 50% from 1130kW to 1695kW. This change is achieved with the use of a breaker line in the Simulink. At the start of the simulation, the breaker is an open circuit and when the time is at 6s, it closes and then opens again at 6.2s. It is observed that the speed suddenly falls below the nominal value which leads to a drop in the rated frequency of the system which may have adverse effect in the appliances of the consumer. This sudden fall in speed is an indication that it is inversely proportional to an increase in load of the system. In the case of the output at the period of 6s, the active power suddenly declined from 0.8737*pu* to 0.8657*pu* while the speed is reduced below the reference setting of 1pu but later stabilizes after 4s. This stabilization is as a result of the presence of the control elements in the system.

Figure 9 is a representation of load RLC load decrement, the HPP is running at a steady state. The steady-state is altered during the period at 6s when the resistive load is decreased by 50% from 1130kW to 565kW. This change is achieved with the use of a breaker line in the Simulink. At the start of the simulation, the breaker is an open circuit and when the time is at 6s, it closes and then opens again at 6.2s. It is noticed that there is a sudden spike in the magnitude of active power and the speed at the period of 6s when the load decrement occurred. The increment of inactive power indicates that the plant is under loaded; the increase in speed shows an increase in frequency which is unhealthy for the plant and the electrical appliance of the end-users. This implies that for the smooth running of small hydropower plants there must be a balance between the generation and distribution of electric energy. In the case of the output at the period of 6s, the active power suddenly increased from $0.8737pu$ to $0.922pu$. This is an indication that the plant cannot give out more than what it produces.

4.0. CONCLUSION

A nonlinear model assuming an inelastic water column is established on the inelasticity of the pipe and incompressibility fluid. The surge tank riser helps to suppress the water hammer and its tank provides the water storage function. The PID parameters are separately adjustable; the proportional term reduces the steady-state error. Hence, the designed hydropower system (HPS) which centres on a non-linear system is achieved. Lowering the value of K_p gives a stable response and great steady-state error. Increasing the value of K_p gives a better steady-state performance but poorer transient response. The steady-state error can be minimized to zero by the K_i but such performance is at risk of stability expense of the system since it raises damping oscillation amplitude and settling time. From the foregoing, the generator has the capacity to operate at a nominal speed at all times. Lastly, the trial and error in conjunction with Ziegler – Nichols Turning Techniques for PID is adopted. To improve the proficiency and steadiness of the hydropower plant, a power system stabilizer (PSS) block is incorporated into the scheme. Consequently, a simulation of the hydropower plant is done under the various working condition, the result reveals that the PSS block enhances the steady-state response with a minimal oscillation in the system amplitude. Therefore, the hydropower plant has the prospect of producing over 1975kW; such an amount of power can boost the electricity supply of the host community and neighbouring communities respectively thereby bringing development and economic value to them. The simulation outcome after the integration of the power system stabilizer (PSS), shows great enhancement in the stability. The result reveals that a PID controller is necessary for speed control and stability control of hydropower systems.

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