DYNAMIC MODELING AND SIMULATION OF SHIRORO HYDROPOWER PLANT IN NIGERIA USING MATLAB/SIMULINK

Gbadamosi S. L and Ojo O. Adedayo

Abstract— Hydroelectricity is an important component of world renewable energy supply and hydropower remains a major source of electricity generation due to its environmental friendly nature. This paper aimed at modeling and simulating hydropower plant with a view of increasing the efficiency and stability of the generating station. The hydropower plant model was developed using Matlab/Simulink software. The designed model comprises: Hydraulic turbine (PID governor, servomotor and turbine), Synchronous generator and an excitation system. The dynamic response of the system to the disturbances on the system network was studied. A three phase fault was introduced in the SHPP model at 0.1 sec and cleared at 0.2 sec. The simulated result shows that the generated voltage quickly regained its stability on the removal of the fault, the stator currents went into transient after the fault was cleared and become stable at 0.4 sec. The excitation voltage also regains its stability but it was slower and the speed of the rotor was out of stable after the occurrence of the disturbance on the system. The simulated result shows an improvement in the static and dynamic behavior of SHPP and an increase in the generating performance of the generating station.

Index Terms— Electricity, Efficiency, Governor, Modeling, Turbine

◆

1 INTRODUCTION

Today, global warming is a major problem in the world. The generation of electricity using renewable hydro-energy resource is an essential nature protection and resource saving technology. Among all renewable energy sources, water has the lowest cost and is most reliable resource [2]. Hydroelectricity is an important component of the world's renewable energy supply. Electricity generation in the world has been on the increase over the last few decades especially in the developing nations where hydropower remains the major source of electricity generation [8].

The modern power system is increasing very rapidly in size and complexity due to the high load demands from power energy consumers, therefore it is necessary to produce electricity in large scale and economically [4 & 11]. Technological advancement has resulted into most power utilities to be interconnected into a single power grid in order to maximize efficiency of the generating stations. Due to increased load demands from consumers which may cause power system network to be in highly stressed conditions, the need for increasing the efficiency of the generating station is arising. The possible means of increasing this efficiency is to model and simulate the generating stations, which aid in describing the static and dynamic behavior of the whole network. These evaluations aim to assess the behavior of the power system in isolated operation, reserve capabilities and the stability analyzes in the whole power system through modeling and simulating of hydropower plant (SHPP).

Hydropower plants convert the potential energy of water head to mechanical energy by using a hydraulic turbine [1]. Hydro-turbines are in turn connected to a generator that converts the mechanical energy to electric energy as shown in Figure 1.

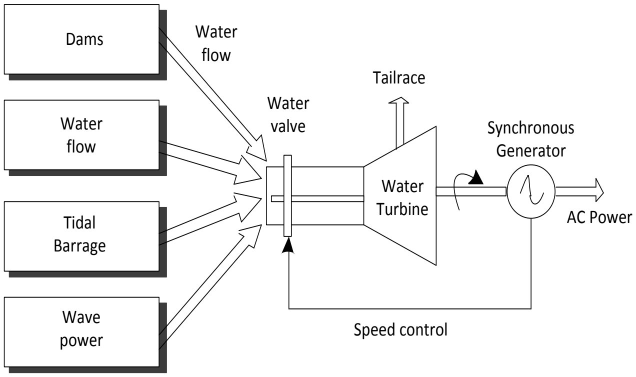

Figure 1: Hydro Electric Generation. [8]

The main components of a hydropower plant are illustrated in Figure 1. The hydropower plant is basically made of a generator, a turbine, a penstock and wicket gates. The water drives the turbine-generator set and the rotating generator produces electricity. At the initial stage, the stored water with clear hydraulic head possesses potential energy. As it flows through the penstock it gradually loses potential energy and gain kinetic energy before reaching the turbine. A critical look at the process of energy generation by hydropower plant shows that hydropower plant models are highly influenced by

---

- *Gbadamosi S.L. is also a lecturer in the Department of Electronic Electrical & Computer Engineering, College of Engineering, Afe Babalola University, Km 5454, Afe Babalola way, Ado-Ekiti, Nigeria. Email:gbadamosisl@abuad.edu.ng*
- *Ojo O. Adedayo is a lecturer in the Department of Electronic Electrical & Computer Engineering, College of Engineering, Afe Babalola University, Km 5454, Afe Babalola way, Ado-Ekiti, Nigeria. Email:ojoao@abuad.edu.ng*

the penstock-turbine system, the electric generator and numerous control systems [1].

In the recent time, studies have shown that most of the hydro-electric generating stations in Nigeria are operating below their installed capacity as compared to the International Standard Organization (ISO) ratings [8]. This poor electric power generation has hindered industrial development and contributed immensely to the poor economic state of Nigeria. Ever since the resumption of democratic government, improving power generation in Nigeria has been a top priority of Nigerian government. Despite all efforts and funds put in place, generation of sufficient electric power to drive the economy is far from being a reality. Apart from insufficient number of power generation plants, existing ones are facing declining output due to ageing, neglect and ineffective maintenance. The Shiroro hydropower plant (SHPP) in Niger State, Nigeria, which started operation in 1990 is not an exception, this system has been plague by multi-faceted deficiencies with causes that are financial, structural and socio-political, none of which are mutually exclusive. This has resulted into declining output from the SHPP.

Shiroro hydropower plant is situated in the Shiroro Gorge on the Kaduna River, approximately 60 km from Minna, capital of Niger State, in close proximity to Abuja, Nigeria's federal capital. The plant has an installed capacity of 600MW from four generating units rated at 150MW each. The operational capacity of SHPP for over a decade now has been below 65% of installed capacity. Therefore, it becomes expedient to model and simulate SHPP in order to overcome insufficient generating capacity constrained. This is a concern because of rapidly growing of Nigerian power system. Increase in generating capacity is crucial to provide stable electricity supply and avoid fluctuating energy prices.

For planning of safe and reliable operation in the future it's very important to have current simulation models, which can describe the static and dynamic behavior of the whole network including any elements [5].

In this paper, simulation is applied for the dynamic modeling of the hydropower plant components: the hydro turbine governor, excitation and the generator. The detailed mathematical representation of these component are presented. In this stage, simulation has been proved to be an effective tool when modeling the dynamics of the hydropower plant using basic function blocks in Matlab/Simulink software. For effective modeling, differential equations of the synchronous machine and the hydro turbine are needed to be considered.

Figure 2: Shiroro Hydro Power Plant with Dam in Nigeria. (Source: Google map).

2. MODEL OF HYDROPOWER PLANT

An ideal modeling of SHPP components, such as synchronous machine, turbine and its governing system is necessary to analysis the power system response during any disturbance on the system. Power system performance is affected by dynamic characteristics of hydraulic turbine and its governor system during any disturbance, such as presence of a fault, harmonics on the network, rapid change of load and loss of a line. The block diagram of the Hydraulic Turbine with governor, servomotor, synchronous machine and the generator excitation is shown in Figure 3.

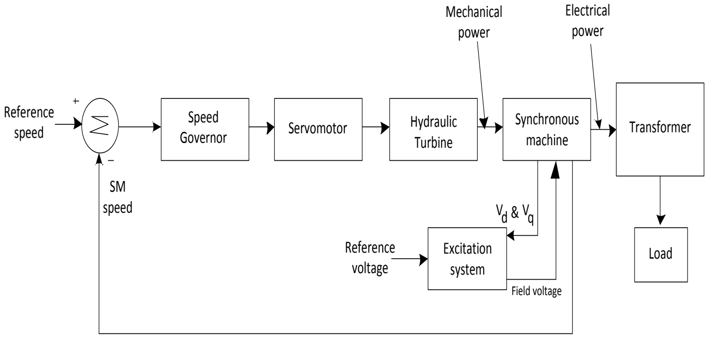

Figure 3: Block Diagram of Hydro Power Plant.

The model of SHPP is developed using existing Simulink blocks contained in the SymPowerSystems blockset. In this simulation model, the reference speed signal is obtained from the kinetic energy of the falling water through the penstock. The measured synchronous machine speed is fed back to compare with the reference speed signal. The speed deviation produced by comparing reference and synchronous generator speed is used as input for PID

- *Gbadamosi S.L. is also a lecturer in the Department of Electronic Electrical & Computer Engineering, College of Engineering, Afe Babalola University, Km 5454, Afe Babalola way, Ado-Ekiti, Nigeria. Email:gbadamosisl@abuad.edu.ng*
- *Ojo O. Adedayo is a lecturer in the Department of Electronic Electrical & Computer Engineering, College of Engineering, Afe Babalola University, Km 5454, Afe Babalola way, Ado-Ekiti, Nigeria. Email:ojoao@abuad.edu.ng*

based speed governor. PID is used as turbine governor because this control has simple structure, stability, strong robustness and non steady state error. The governor produces the control signal, causing a change in the gate opening. The turbine in turn produces the torque, driving the synchronous machine that generates the electrical power output. The speed governor constantly checks speed deviation to take action [3].

2.1 MODELING OF HYDRAULIC TURBINE

The turbine and penstock characteristics are determined by four basic relations between the turbine mechanical power, velocity of water in the penstock and turbine inlet and the acceleration of the water column [7]. The mechanical power (Pm) that can be transferred to the generator shaft from the Francis Turbine is a nonlinear function related to the flow rate (q) and hydraulic pressure which is strongly dependent on hydraulic head available (h). The nonlinear relationship of the mechanical power of a turbine is expressed as in equation (1) [6, 10 and 4].

$$P_m = \eta q \rho g h \tag{1}$$

where,

P_m is the mechanical power of the turbine (W); η is the efficiency factor of the turbine; q is the flow rate (m^3/sec); ρ is the density of the water (kg/m^3); g is the gravitational constant (m/s) and h is the hydraulic head of the turbine (m).

The output power of the Francis turbine is adjusted by changing the opening of wicket gates, hence the amount of water flowing into the runner blades. As the opening of the wicket gate changes, the effective flow area of the water changes; therefore, the inlet water velocity in the penstock, hence the inlet water flow to the turbine runner changes [4]. This relationship in per unit is as expressed in equation (2).

$$q = A\sqrt{h}\ \text{(p.u)} \tag{2}$$

where,

q is the flow rate (m^3/sec); A is the he effective flow area (per unit) and h is the hydraulic head of the turbine (m).

The nonlinear relationship relating mechanical power output with water flow and hydraulic head is as expressed in equation (3)

$$P_m = f(qh) \tag{3}$$

where,

P_m is the mechanical power of the turbine (per unit); f is the nonlinear function relating mechanical power to water flow; q is the flow rate (m^3/sec) and h is the hydraulic head;

While developing the penstock model, it is assumed the water channel in the penstock is a solid mass, the change in the flow rate in the penstock is related to the pressure of the water. Hence, the force on the water mass is given in equation (4);

$$(h_g - h - h_l)\rho g A = L A \rho\, {dv}/{dt} \tag{4}$$

where,

h_g is the gross head (m); h is the head at the turbine admission (m); h_l is the head loss due to friction (per unit); ρ is the density of water (kg/m3); g is the gravitational acceleration constant (m/s^2); A is the cross sectional area of the penstock (m^2); L the length of the penstock (m) and v denotes the speed of the water column in the penstock (m/s).

Assuming turbulence does not occur during the flow of water because the area of the penstock is constant. To determine the rate of flow of water in the penstock, the speed of the water channel multiplied with the area of penstock.

$$ {dq}/{dt} = (h_g - h - h_l)\frac{gA}{L} \tag{5}$$

This can also be written in per unit,

$$\frac{d\bar{q}}{dt} = (1 - \bar{h} - \overline{h_L})\frac{h_{base} g A}{L q_{base}} \tag{6}$$

$$\frac{d\bar{q}}{dt} = \frac{(1 - \bar{h} - \overline{h_L})}{T_w} \tag{7}$$

$$T_w = \frac{L q_{base}}{h_{base} g A} \tag{8}$$

where,

$\bar{q}$ is per unit water flow; $\overline{h_g}$ is the per unit static head h is per unit head at the turbine admission; $\overline{h_L}$ is per unit head loss due to friction and T_w is the water time constant or water starting time

The nonlinear Hydraulic Turbine and Governor block implements an hydraulic turbine model, a PID governor system, and a servomotor as described in Figure 3.

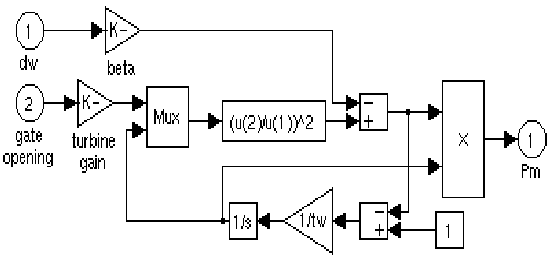

Figure 4: Model of Nonlinear Hydraulic Turbine.

2.2 MODELING OF SYNCHRONOUS MACHINE

The synchronous machine block operates in the generator or motor modes. The positive operating mode of the machine indicated by the sign of the mechanical power shows the machine is on generator mode. The electrical part of the machine is represented by a sixth-order state-space model. The input signals are excitation voltage and turbine power P_T, the inertia of the generator turbine set is also included in the generator model. The output signals are active power and reactive power. The parameters of the generator were taken from the power plant documentations. The model takes into account the dynamics of the stator, field and damper windings. The equivalent circuit of the model is represented in the rotor reference frame (qd). All rotor parameters and electrical quantities are shown from the stator. The electrical mode of the machine is presented in Figure 5 with the following equations.

$$V_d = R_s i_d + \frac{d}{dt}\phi_d - w_R \phi_d \quad (9)$$

$$\phi_d = L_d i_d + L_{md}(i_{fd} + i_{kd}) \quad (10)$$

$$V_q = R_s i_q + \frac{d}{dt}\phi_q + w_R \phi_q \quad (11)$$

$$\phi_q = L_q i_q + L_{mq}(i_{fq} + i_{kq}) \quad (12)$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\phi'_{fd} \quad (13)$$

$$\phi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i'_d + i'_{kd}) \quad (14)$$

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\phi'_{kd} \quad (15)$$

$$\phi'_{kd} = L'_{kd} i'_{kd} + L_{md}(i'_d + i'_{fd}) \quad (16)$$

$$V'_{kq} = R'_{kq} i'_{kq} + \frac{d}{dt}\phi'_{kq} \quad (17)$$

$$\phi'_{kq} = L'_{kq} i'_{kq} + L_{md} i'_q \quad (18)$$

The model assumes currents flowing into the stator windings. The measured stator currents returned by the synchronous machine block (i_a, i_b, i_c, i_d, i_q) are the currents flowing out of the machine.

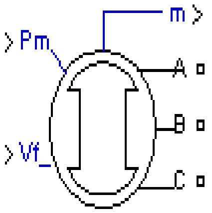

Figure 5: Model of Synchronous machine under Matlab/Simulink

2.3 MODEL OF THE EXCITATION

An excitation system block is used to generate the excitation voltage that supplies the synchronous generator. Feedback systems are used through PID controllers to regulate both the generated excitation voltage as well as mechanical power produced by the turbine. Figure 6 present the model of excitation system, which utilize a direct current generator with a commutator as the source of excitation system. The exciter is represented by the following transfer function between the exciter voltage V_{fd} and the regulator output e_f[9]:

$$\frac{V_{fd}}{e_f} = \frac{1}{K_e + sT_e} \quad (19)$$

where, V_{fd} is the exciter voltage; e_f is regulator output; K_e is the feedback gain and T_e is time constant.

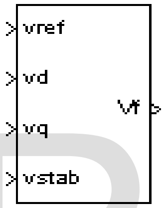

Figure 6: Model of Excitation System.

3. METHODOLOGY

The model of SHPP using Matlab/Simulink is presented in Figure 8, the generating station consists of four generating units of 150 MW each. The model consists of hydraulic turbine, synchronous machine and excitation system blocks. SHPP model is a 600 MW station with 210 MVA, 15.5kV three phase generator with a speed of 1500 rpm that is connected to a 330 kV network through a Δ-Y 210 MVA transformer. In the model, the synchronous generator is driven by mechanical power generated by the hydraulic turbine block. In addition, an excitation system is used to generate the excitation voltage that supplies the synchronous generator. The generated excitation voltage from the excitation system block and the mechanical power produced by the turbine are both regulated through the PID controller employed in feedback systems. Each of the generating unit has an output of 150 MW as shown in figure 9, and each unit generator has an output voltage of 15.5 kV which is fed to a step up transformer that feeds 330 kV transmission line. A fault simulation block was developed on the network and likewise a load of 12 MW was added. The desired terminal voltage parameter is set to15.5 kV and the active power is 120 MW. The initial terminal voltage and field voltage is set to 1.2 and 1.3 per unit respectively for the excitation system block.

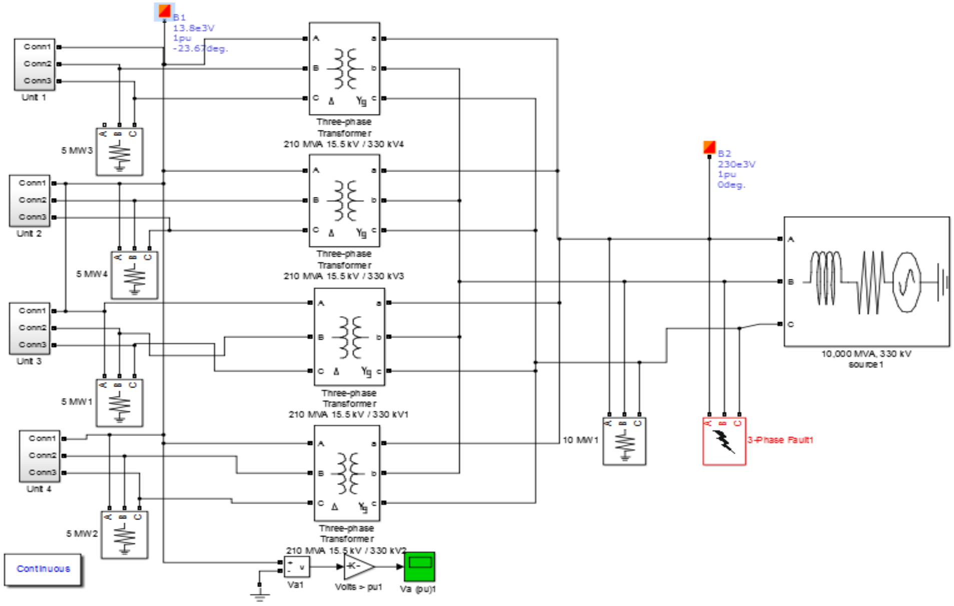

Figure 7: Model of Shiroro Hydro Power Plant using Matlab/Simulink.

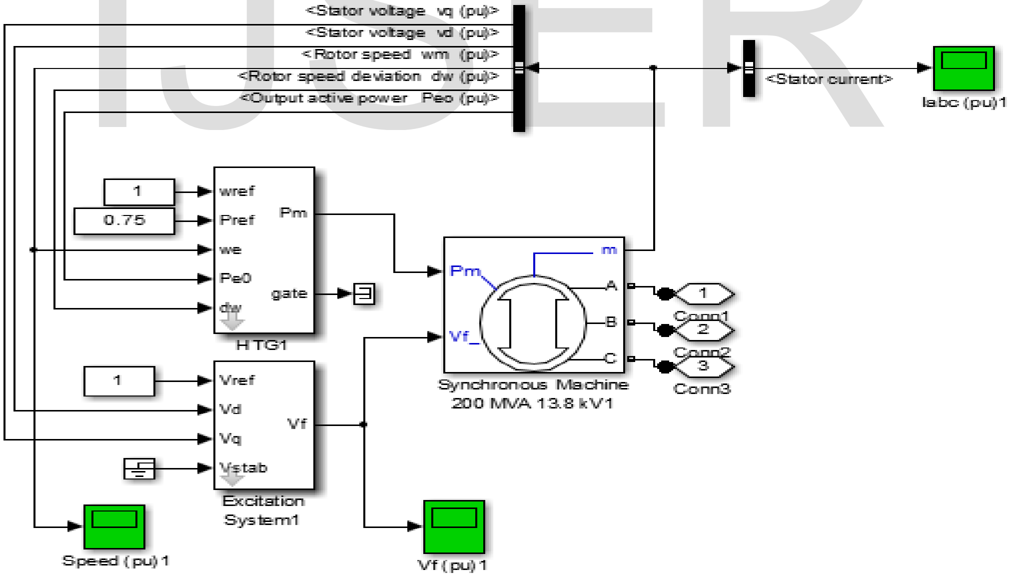

Figure 8: Model of Generating Unit using Matlab/Simulink

4. RESULT AND DISCUSSION

The results of evaluation of the simulated model of SHPP are analyzed. Four different graphs have been plotted from the modeled SHPP: the speed characteristics, the voltage output characteristics, the excitation voltage and the stator current. A three phase short circuit fault was introduced into the SHPP model in order to determine the response of the system during and after fault conditions and how effectively the entire

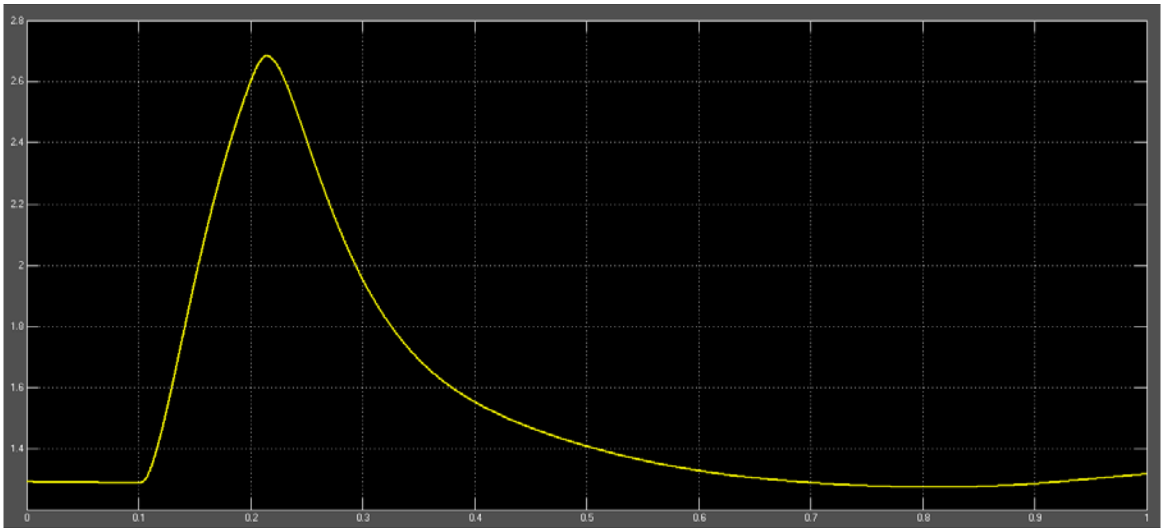

Figure 9: Waveform of Excitation Voltage (Vf) in per unit.

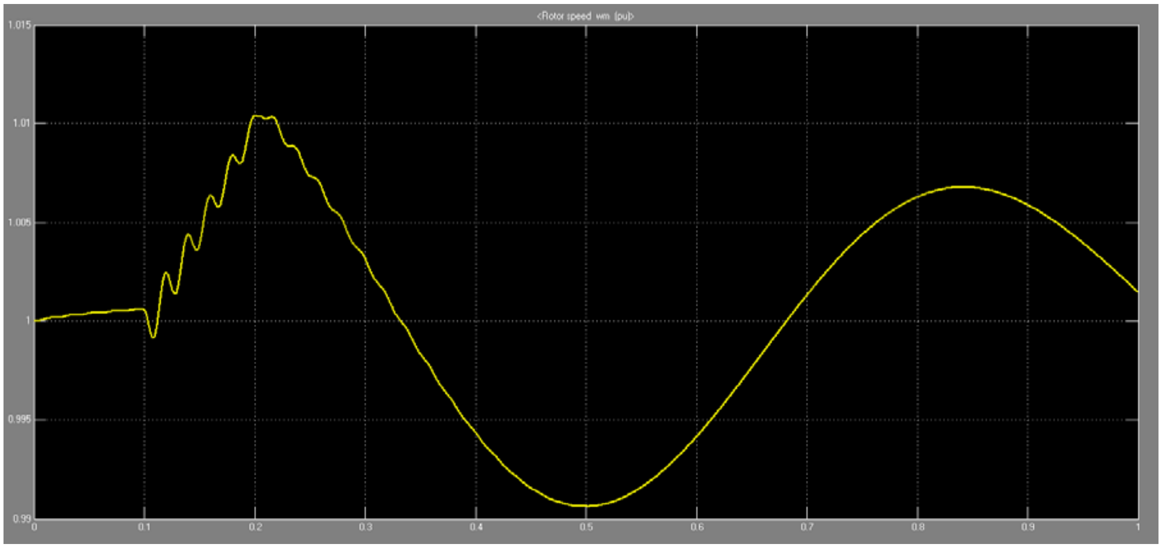

Figure 10: Waveform of the Speed of the Rotor in per unit.

system network can regain its stability after the three phase fault occur. The simulation time for all the models is 1sec. Figures 9, 10, 11and 12 present the waveforms of the excitation voltage (Vf) with respect to time in per unit, the speed of the rotor, the stator currents (I_{abc}) of the generator and the generated voltage (Va) respectively. A three phase to ground fault was introduced into the model at a time of 0.1 sec. It was observed from the graphs in Figures 9, 10,11 and 12 the system experienced a steady state condition at the initial stage of the simulation with excitation voltage of 1 pu, an output voltage of about 1.1 pu, the nominal speed of amplitude of 1 pu and the stator currents of about 0.8 pu. A three phase fault was

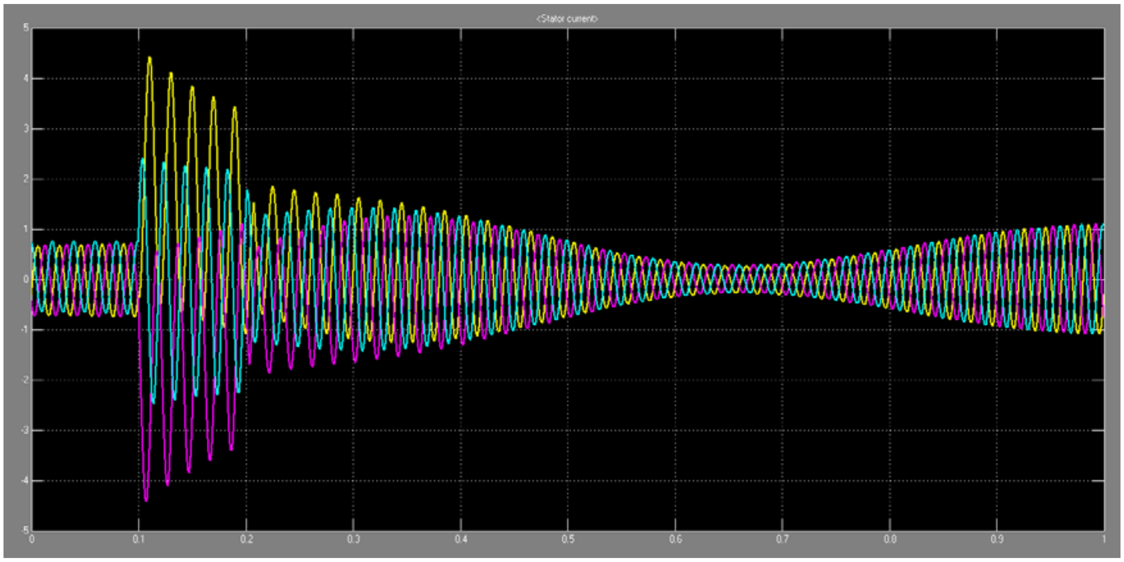

Figure 11: Waveform of Stator Currents (I_{abc}) in per unit.

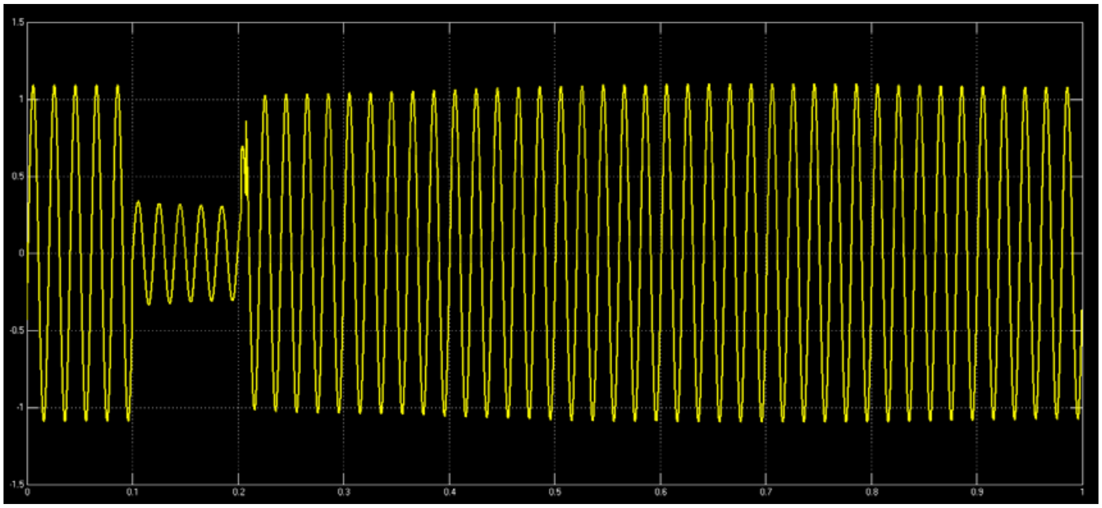

Figure 12: Waveform of the Generated Voltage (Va) of the generator in per unit.

introduced at 0.1 sec and the fault lasted for another 0.1 sec, bringing the system back to stable state at 0.2 sec. The system experienced a significant drop in the amplitude of the output generated voltage to 0.3 pu and the generated voltage (Va) become stable at 0.2 sec. In addition, there was an increment in generator stator current to 4.2 pu and the generator stator currents enters a transient state at 0.2 sec and it becomes stable at 0.4 sec. Furthermore, the excitation voltage of the system modeled increased drastically to a value of 2.7 pu and the speed likewise increased to 1.01 pu. It was observed that the introduction of fault into the system result into an increase in the flux value of the generator thereby increasing the terminal voltage, and an increased in the terminal voltage leads to increasing in the speed of the generator. Therefore an increase in flux will have effect of bringing the terminal voltage back to its initial value as it was highly reduced by the fault. The oscillation of the speed did not return to its initial state as a result of the rate of valve opening and closing of the governor system of the hydraulic turbine. Therefore, the speed of the rotor become unstable during and after the introduction of three phase fault whereas excitation voltage return to stable state after a long period at 0.5 sec.

5. CONCLUSION

In this paper, the simulation for analyzing the SHPP has been developed using Matlab/Simulink software. The simulated model consists of three subsystems: the hydraulic turbine which comprises the PID governor, servomotor and the turbine, the synchronous generator and the excitation system. In order to analyze the stability of SHPP, a disturbance was introduced on the line by creating three-phase to ground fault on the transmission at 0.1 sec with a load of 12 MW on the generator.

The modeling and simulation of SHPP in Nigeria, if fully operational, could be replicated for other generating stations (thermal, nuclear, wind etc) in Nigeria or other developing nations for the sole aim of improving the generating performance of each generating stations and to deepening the current understanding of the dynamics and control of structurally weak electric power networks.

REFERENCES

[1] Acakpovi, A., Hagan, E. Ben, & Fifatin, F. X. (2014). Review of Hydropower Plant Models. International Journal of Computer Applications, 108(18), 33–38.

[2] Jasa, L., Priyadi, A., & Purnomo, M. H. (2014). An Alternative Model of Overshot Waterwheel Based on a Tracking Nozzle Angle Technique for Hydropower Converter. INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH, 4(4), 1013–1019.

[3] Nanaware, R. A., S.R, S., & Jadhav, B. T. (2012). Modeling of Hydraulic Turbine and Governor for Dynamic Studies of HPP. International Conference in Recent Trends in Information Technology and Computer Science (ICRTITCS), 6–11.

[4] Nassar, I. (2010). Improvements of Primary and Secondary Control of the Turkish Power System for Interconnection with the European System. PhD thesis submitted to Faculty of Computer Science and Electrical Engineering, Rostock University, Turkey.

[5] Prillwitz, F., Al-ali, S. E., Haase, T., Weber, H., & Saqe, L. (2007). SIMULATION MODEL OF THE HYDRO POWER. 6th EUROSIM Congress on Modelling and Simulation.

[6] Sattouf, M. (2014). Simulation Model of Hydro Power Plant Using Matlab / Simulink. 6th EUROSIM Congress on Modelling and Simulation, 4(1), 295–301.

[7] Gencoglu, C. (2010). Assessment of the Effect of Hydroelectric Power Plants Governor Settings on Low Frequency Inter-area Oscillations, Ms Thesis, Middle East Technical University.

[8] Gbadamos S.L., Ojo A.O., and Nnaa. L (2015). Evaluation of Operational Efficiency of Shiroro Hydro-Electric Plant n Nigreia. International Journal of Science and Engineering Investigations, 4(42), 33–38

[9] Sridhar P and Prasad K.B (2014). Fault Analysis in Hydro Power Plant Using Matlab / Simulink. International Journalof Electrical Engineering & Technology, 5(5), 89–99.

[10] Bhoi R and Ali. S. M (2014). Simulation for Speed Control of the Small Hydro Power Plant using PID Controllers. International Journal of Advanced Research in Electrical and Instrumentation Engineering, 3(4), 8392–8399.

[11] Izuegbunam. F. I, Ubah C. B and Akwukwaegbu I. O (2012). Dynamic Security Assessmen of 330 kV Nigeria Power System. Academic Research International, 3(1), 456–466.