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# Advanced Control And Development of Hydro and Diesel Generator Hybrid Power System Models for Renewable Energy Microgrids

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**Abstract**

*The Nigerian power problem resulted to incessant and erratic supply of electricity which has destroyed many industrial processes in the country. It has reduced productivity and has increased unemployment rates in the country to over 50million (over 70% of Nigerian youths). This has led many of the youths in the country to crime. As of 2016, the electricity energy consumption in the world from the world fact book revealed that the average power per capita (watts per person) in the United States is 1,377 Watts. In South Africa, it is 445 and in Australia, average power per capita is as high as 1,112 Watts. Whereas, the average electricity consumed in watts per person in Nigeria is just 14 Watts putting the country in a rank of 189 out of 219 countries estimated. In this research work, a Hybrid Electric Power System (HEPS) which comprises Hydro Electric Power Plant (HEPP) and Diesel Generator (DG) was modelled and a control algorithm was established to improve the performance of the system. Hybrid power system mathematical and Simulink models were developed. The output power of the developed Simulink model was be optimized using optimum power point optimization techniques and control algorithms. Simulink models of the two components of the Hybrid Electric Power System were produced using MATLAB/Simulink software. The results obtained revealed that the problems associated with conventional methods of power generation was overcomed by the development of this Hybrid Electric Power System (HEPS) models.*

## Introduction

The major objectives of hybrid electric power system are to combine two or more energy resources in order to reduce power production cost to the barest minimal, reduce power purchase from the grid, increase efficiency of the power system, reduce emission of gases and increase the reliability of the system. Owusu & Asumadu-Sarkodie (2016) A review of renewable energy sources, sustainability issues and climate change mitigation, Cogent Engineering, Norway . It is becoming popular all over the world due to advancements in renewable energy technologies and substantial rise in prices of fossil fuel. It provides economical, reliable and sustainable energy for human and industrial development. It is beneficial in terms of reduced transformer and line losses. It has no environmental impacts as it is pollution free. It has long-term cost advantage, higher system reliability, improved power quality and increased overall efficiency. Srivastava & Banerjee, (2015) Hybrid Renewable Energy Systems & their Suitability in Rural Regions, India.

In the case of renewable and non-renewable energy resources like Hydro Electric Power Plant (HEPP) and Diesel Generator (DG), variation in output voltage and current affects the stability, efficiency, output power and installation cost of the system. Whenever different



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output Voltage - Current characteristics are obtained due to occurrence of transient faults and variation of loads, extracting maximum power becomes difficult). This reduces efficiency, reduces reliability of the system and increase installation cost. Jawaid et al. (2019) Hybrid Renewable Energy System for Electrification, A Review, Science Journal of Circuits, Systems and Signal Processing, New York, USA.

In this research work, Simulink Models were developed for the Hydro Electric Power Plant (HEPP) and Diesel Generator (DG) systems. Also, Control Algorithms were established in order to maximize output power and improve the performance of the system. The final output characteristics of the developed model show that the model is suitable for the production of reliable and efficient power supply to the consumers.

**Principle of operation of HEP Station**

Hydro-electric power stations require the utilization of energy in falling water and the rotor situated in an alternator for the rotation of water turbine and the generation of electricity. They are generally located in hilly areas where dams can be built conveniently and large water reservoirs can be obtained. In a hydro-electric power station. Water head is created by constructing a dam across a river or lake. From the dam, water is led through the penstock to the water turbine shown in figure 2.1. The water turbine captures the energy in the falling water and changes the hydraulic energy (i.e., product of head and flow of water) into mechanical energy at the turbine shaft. The turbine drives the alternator which converts mechanical energy into electrical energy. (Metha & Metha, 2008). The mechanical power (Pm) that can be transferred to the generator shaft from the Francis turbine is a function which is related to the flow rate (q), hydraulic pressure which is strongly dependent on hydraulic head available (h), density of water (ρ ) and acceleration due to gravity (g).

Hence, mechanical power of the turbine, $P_m$,

$= \eta \rho \quad q_c g h$

where,

$Pm$ is the mechanical power of the turbine (W);

$\eta$ is the efficiency factor of the turbine;

ρ is the density of the water (kg/m3);

q is the flow rate (m3/sec);

g is the gravitational constant (m/s) and

h is the hydraulic head of the turbine (m).

While developing the penstock model, it is assumed the water channel in the penstock is a solid mass. Hence, the force on the water mass is given by equations 2.1 – 2.3

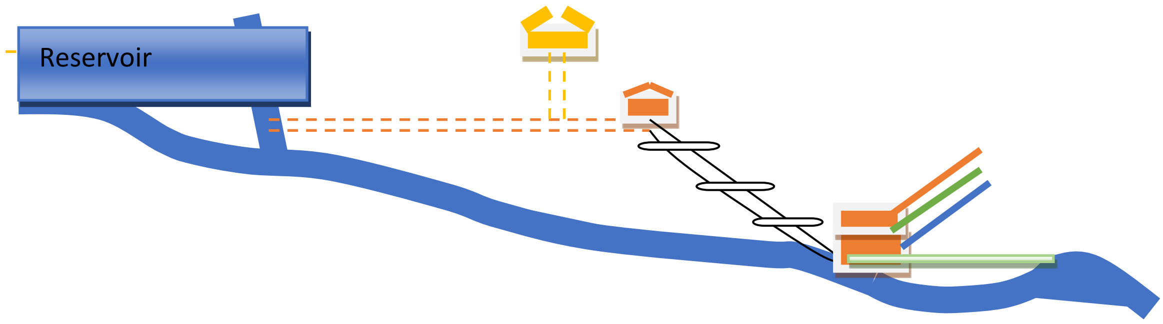


*Figure 1. Hydro Electric Power Plant*



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Force on water mass = $[h_s - h - h_1]$ ρ $q_c A$ ……………………. 2.1

Force on water mass = ρ $A L g$ = ρ $A L \frac{dV}{dt}$ …………………....2.2

Hence, $[h_s - h - h_1]$ ρ $q_c A$ = ρ $A L \frac{dV}{dt}$

$$\frac{dq}{dt} = [h_s - h - h_1] \frac{qA}{L} \qquad \text{……………………2.3}$$

where,

$h_s$ is the gross head (m);

h is the head at the turbine admission (m)

$h_1$ is the head loss due to friction (per unit);

$\rho$ is the density of water (kg/m3);

$q_c$ or q = discharge rate in $m^3$ per sec

g is the gravitational acceleration constant (m/s2);

A is the cross-sectional area of the penstock (m2);

L the length of the penstock (m) and

V denotes the speed of the water column in the penstock (m/s).

$\frac{dq}{dt}$ can be written in per unit by multiplying by $h_{base}$ and dividing by $q_{base}$ as shown in equations 2.4 and 2.5.

$$\frac{\bar{dq}}{dt} = [1 - \bar{h} - \bar{h}_1] \frac{h_{base}\, q\, A}{q_{base}\, L} \qquad \text{……………………… 2.4}$$

$$\frac{h_{base}\, q\, A}{q_{base}\, L} = \frac{1}{T_W} \qquad \text{……………………......... 2.5}$$

i. $\bar{dq}$ is the per unit rate of flow

ii $\bar{h}_g$ is the per unit static head

iii . $\bar{h}$ is the per unit head at the turbine admission (m)

iv. $\bar{h}_L$ is the head loss due to friction (per unit);

v. L the length of the penstock (m) and

vi. V denotes the speed of the water column in the penstock (m/s).

vii. $T_w$ = water time constant or water starting time

viii. A is the cross sectional area of the penstock (m2);

ix. g is the gravitational acceleration constant (m/s2);

x. $\rho$ is the density of water (kg/m3

This research work established the modeling and simulation of hydroelectric power plant and a Diesel Generator with the objective of increasing the efficiency and stability of the generating plant. The Hydroelectric power plant model was developed using MATLAB/Simulink software. The designed model consists of the speed governor (which uses a PID (proportional–integral–derivative control system), servomotor, hydraulic turbine, Synchronous generator and an excitation system. The speed governor controls the hydraulic turbine (Nanaware et al., 2012). It comprises the control mechanism, the motor and sluice gate which serve as actuator and regulate the flow of water, which in turn regulates the speed and output power of the generator in case of any electrical disturbance as shown in figure 2.2.



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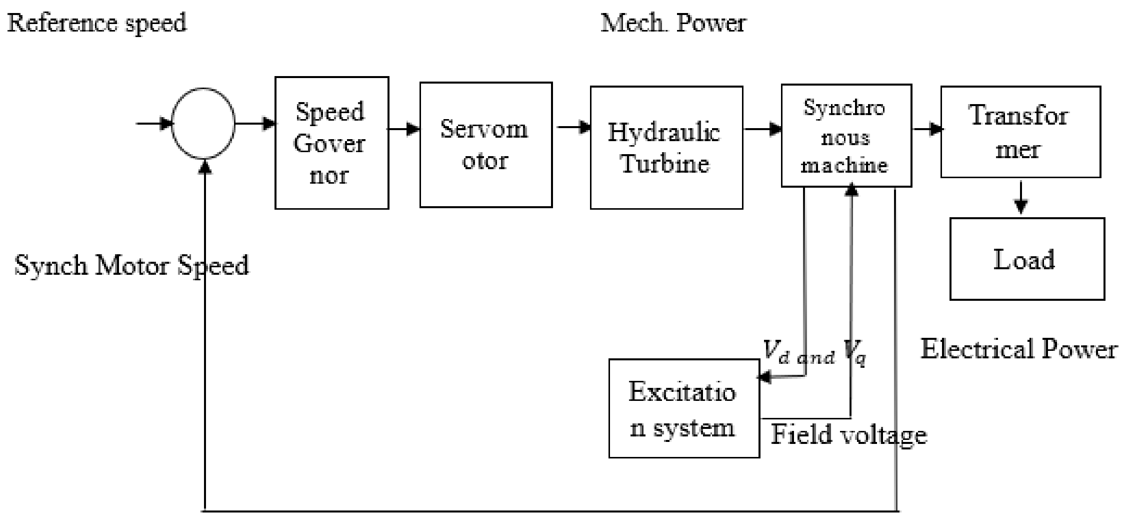


*Figure 2. Block Diagram of a Hydro Power Plant*

## Methods

### Modelled 6MW Hydro-Electric Power Plant Using MATLAB/Simulink

A Simulink model of a proposed 6MW Hydro Electric Power Plant along Ikere River in Oyo State shown in figure 3.1 is developed using MATLAB Simulink software. The Hydro Electric Power Plant model comprises the pressure channel, Pelton or Francis hydraulic turbine, excitation system and synchronous generator (Acakpovi et al., 2014).

In order to produce a Simulink model for the power station, a total load of 5MW was placed on the power station. The terminal voltage was set to 5.4kV with active power 5MW and reactive power 1.2 MW. The initial field voltage was set to 0.8 per unit and the initial voltage set at 1.0 pu. The Simulink model obtained is presented figure 3.1

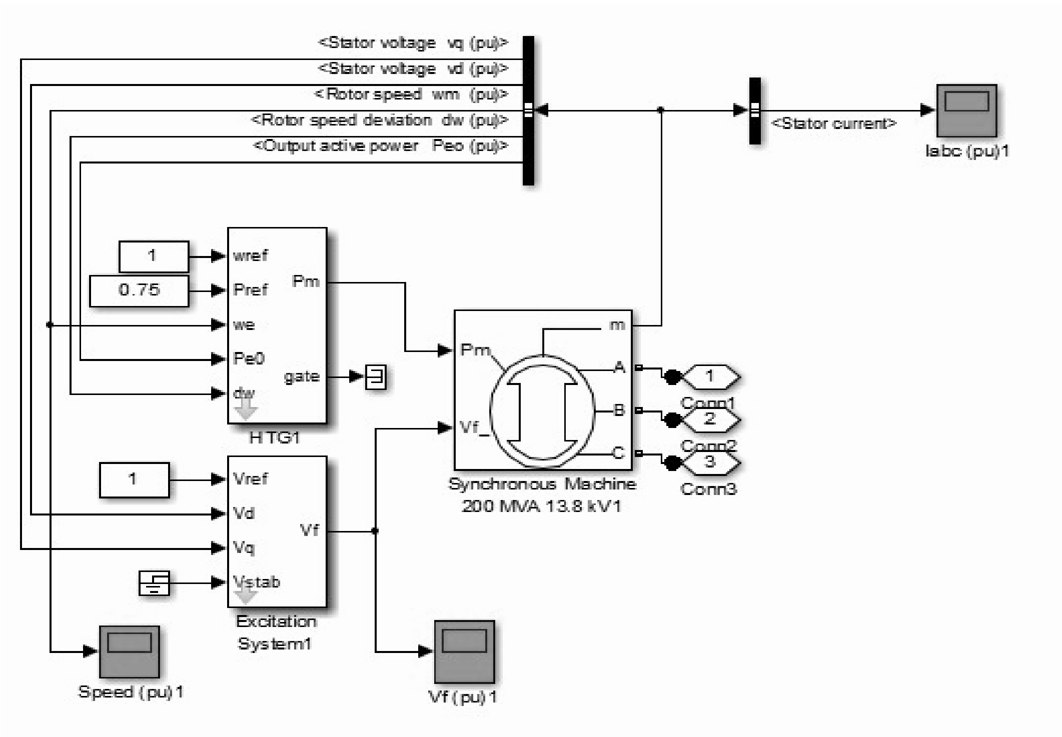


*Figure 3. The Simulink model 6MW Hydro-Electric Power Plant*



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### Modelling of the Diesel Generator

Practically, a diesel generator consists of the diesel engine which converts the energy in the atomized fuel and current from the ignition coil (through combustion process at high temperature and pressure) into mechanical energy. The crankshaft rotates and the rotor rotates around the magnetic field at a speed above the critical speed in order to induce output current on the stator windings (Laiho et al., 2008). The magnetic field can be produced using permanent magnet or through the use of external exciter. The speed governor regulates the intake of fuel in order to control the speed of the generator and the output power. The speed governor keeps the machine running at the rated speed by controlling the supply of fuel into the combustion chamber through its throttle outlet in the events of fault and under the variation of loads (Heywood, 2018). The flowchart used in this research work is presented in figure 3.2 and 3.3.

### Data Acquisition for the Diesel Generator (DG)

A 500 kVA Diesel Power Generator in Elizade University, Ilara-Mokin, Ondo State is taken as reference generator in this research work. The data obtained from the generating unit is presented in table 3.1.

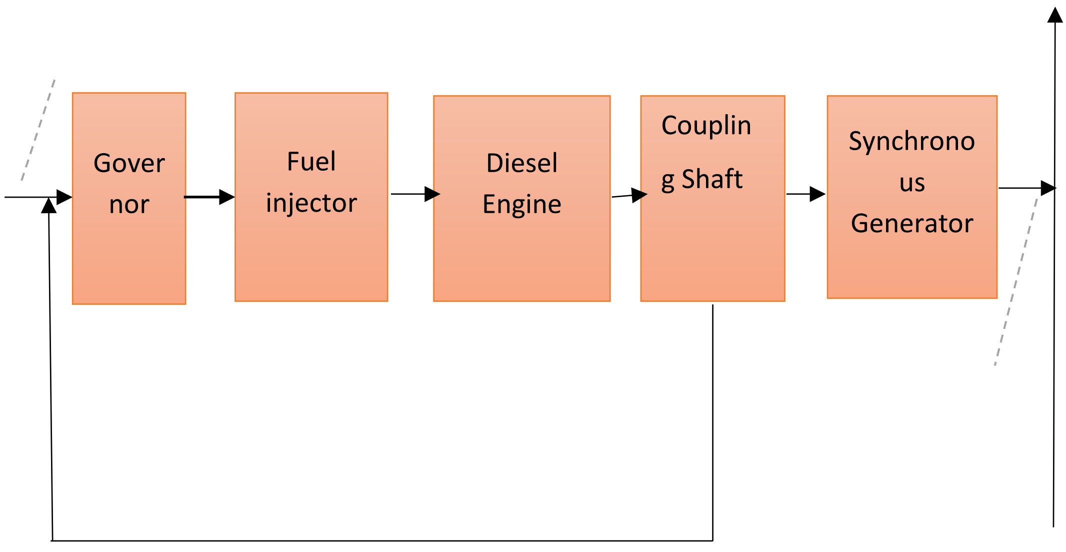
Table 1. Parameters of the 500 kVA Diesel Power Generator

| S/N | Load Connected to generator (kVA) at 0.9 p.f | Output Voltage (V) | Full load Current (A) | Rate of fuel injection Kg/sec | Maximum Generator speed (rpm) |
|---|---|---|---|---|---|
| 1 | 300 kVA | 415 V | 463.75 | 0.0025 | 2400 |

### Diesel Generator Simulink Model

The Diesel Generator Simulink Model was developed using MATLAB Simulink Sim Power System Environment. The model takes the mechanical power aspect (P_m) and the excitation system as input

As discussed earlier, the mechanical aspect is completed by the process of atomized fuel combustion process. The electrical aspect employs the theory of electromagnetic induction for the generation of electrical energy as shown in figure 3.4.




Measured voltage

*Figure 4. Components of Diesel Generator*



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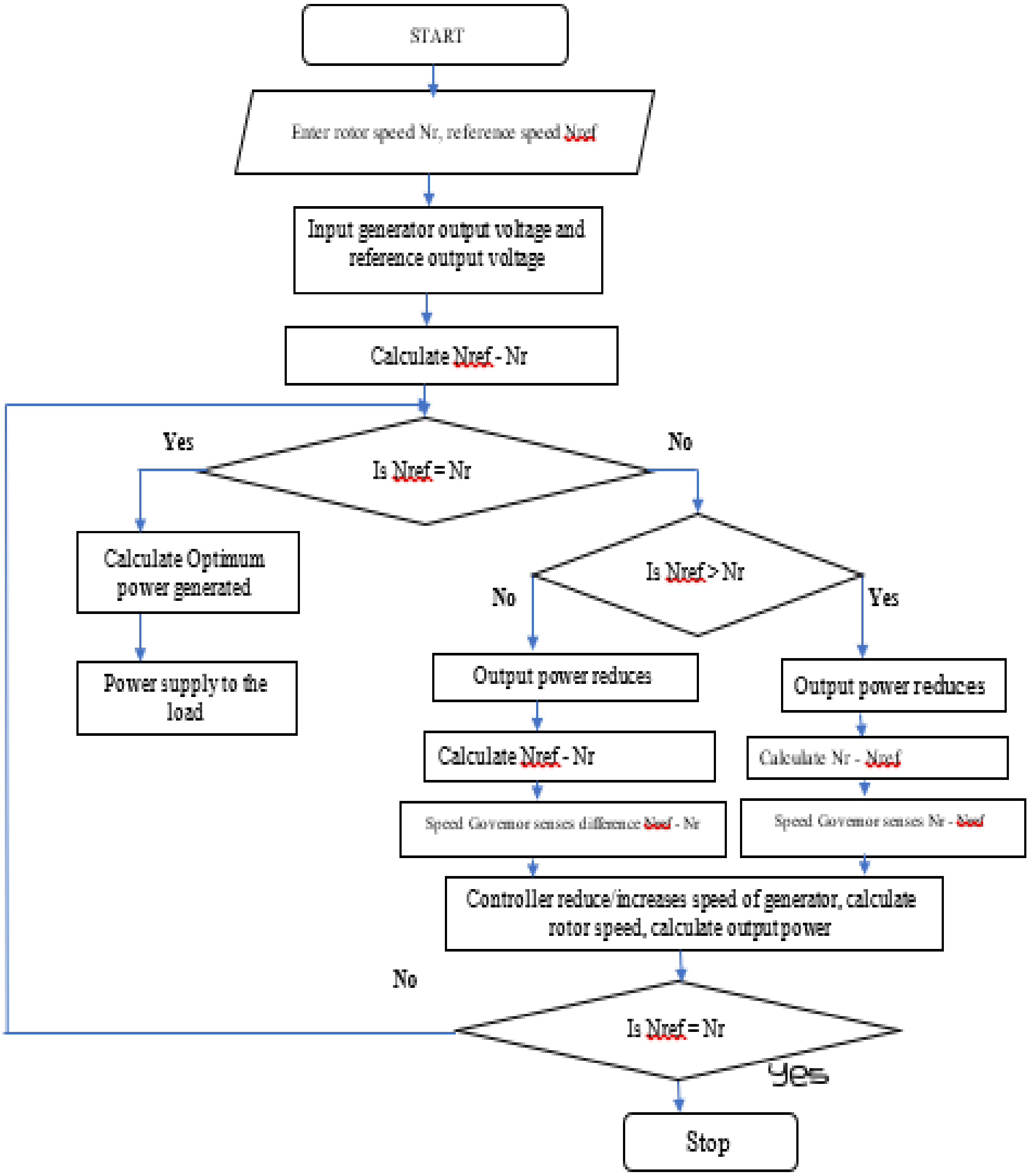


*Figure 5. Flow Chart of the Control Algorithm/Optimization Process of The Hydro-Electric Power Plant in the Events of Variation of Loads*



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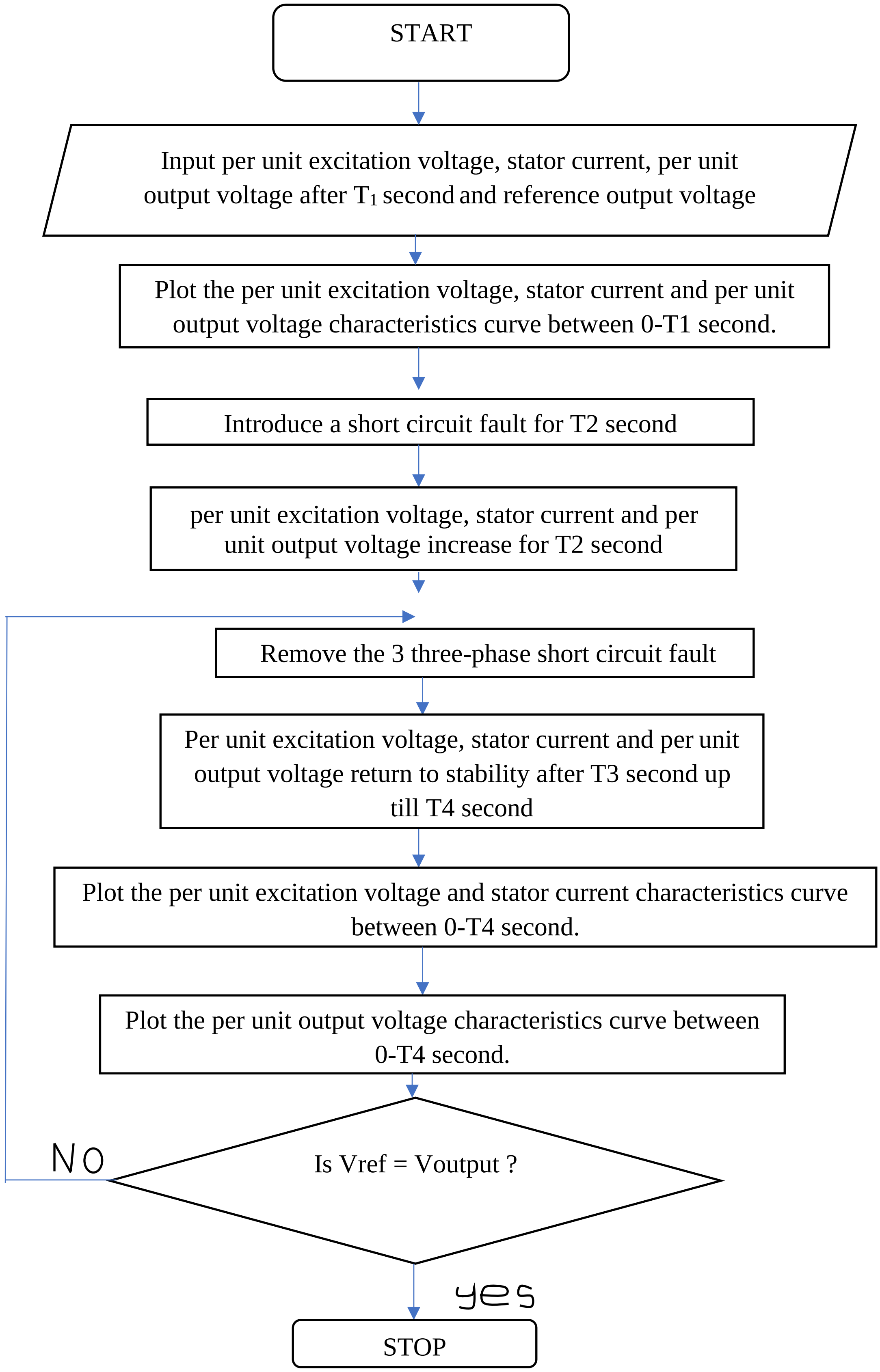




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*Figure 6. Flow Chart of Control Algorithm for the Hydro Electric Power Plant in the events of faults*

The Simulink model comprise of the Proportional Integral Derivative based Governor (PID) which control the inflow of atomized fuel, the compression process and the combustion process. The synchronous machine and the excitation system are shown in figure 3.5

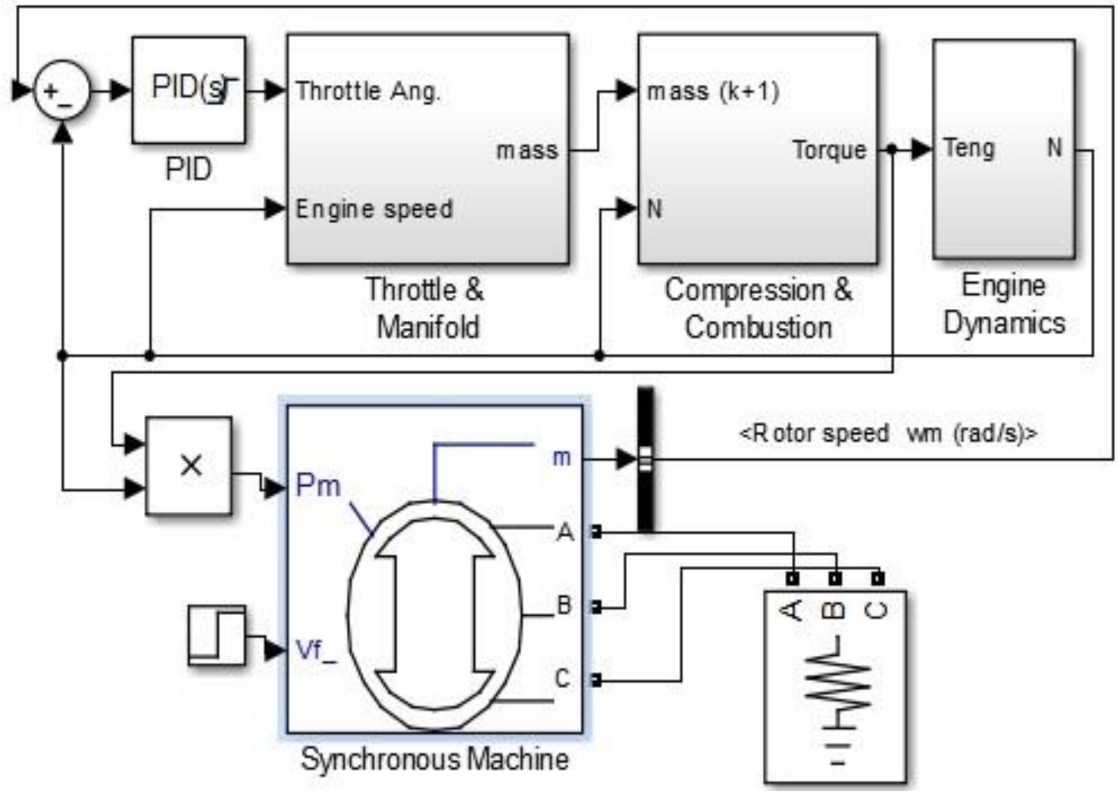


*Figure 7. Diesel Generator Simulink Model*

The Simulink model which analyses the variation of supply of fuel, rotor speed, excitation current, output current, voltage and power was developed. The model shows that the generated power is a function of the variation of supply of fuel, combustion process, mechanical power of the engine, excitation current, magnetic field and rotor speed. The flow chart which shows the diesel generator control algorithm is presented in figure 3.6



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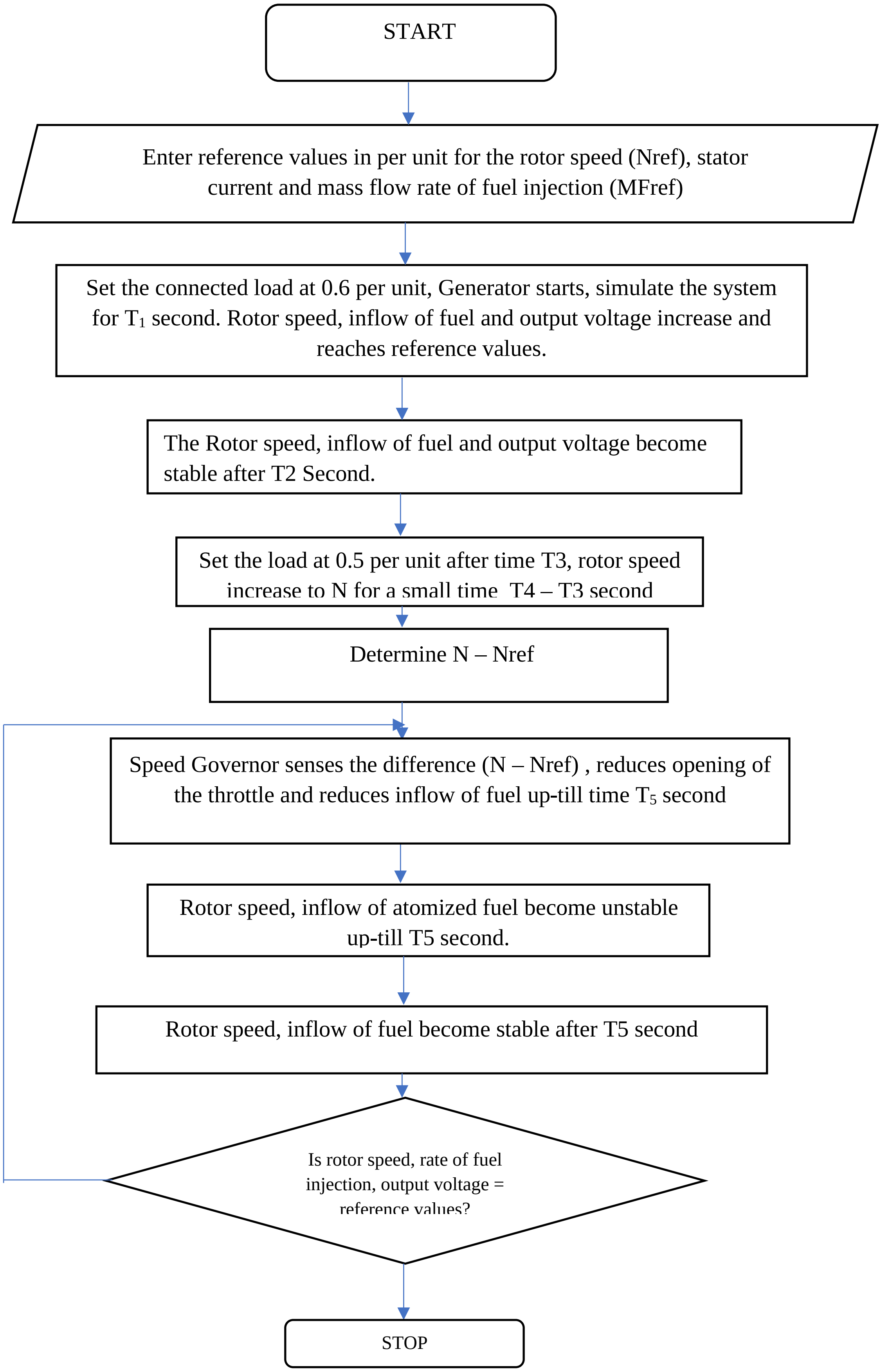


*Figure 8. Flow Chart of The Diesel Generator Simulation Process*



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## Results and Discussion

This chapter presents the results of the analysis, simulation and optimization processes carried out for the development and establishment of the Hybrid Power System Model. It presents the results of the feasibility assessment of the renewable energy resources. It also shows the results of the advance control of the Hybrid power system using Optimum Power Point Tracking Techniques. Table 4.1 shows the power production from the hydro power plant for year 2019. The discharge rate and the output power of the Hydro Electric Power Plant is shown in tables 4.1 - 4.2, and figures 4.1 - 4.2

Table 2. Proposed power production from the hydro power plant for year 2019

| **Power Generated from the Modelled Hydro Electric Power Generating Plant** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Months** | **Density of water** | **Discharge rate in meter-cube/sec** | **Acc (g) x Turbine Eff (0.92)** | **Hs** | **H** | **h1** | **hs-h-h1** | **Power Gen. in kW** |
| January | 1000 | 15.4 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 3024.3136 |
| Februay | 1000 | 13.8 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 2710.0992 |
| March | 1000 | 16.3 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 3201.0592 |
| April | 1000 | 25.2 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 4948.8768 |
| May | 1000 | 28.8 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 5655.8592 |
| June | 1000 | 30.2 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 5930.7968 |
| July | 1000 | 31.6 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 6205.7344 |
| August | 1000 | 30.7 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 6028.9888 |
| September | 1000 | 31.8 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 6245.0112 |
| October | 1000 | 25.1 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 4929.2384 |
| November | 1000 | 16.8 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 3299.2512 |
| December | 1000 | 15.6 | 9.025 | 30 | 7.2 | 1.04 | 21.76 | 3063.5904 |

Table 3. Discharge Rate and Output Power of the Proposed Hydro Electric Power Plant

| **MONTHS** | **DISCHARGE RATES(METER-CUBE/SEC)** | **OUTPUT POWER (KW)** |
|---|---|---|
| January | 15.4 | 3024.31 |
| February | 13.8 | 2710.1 |
| March | 16.3 | 3201.06 |
| April | 25.2 | 4948.88 |
| May | 28.8 | 5655.86 |
| June | 30.2 | 5930.8 |
| July | 31.6 | 6205.73 |
| August | 30.7 | 6029 |
| September | 31.8 | 6245.01 |
| October | 25.1 | 4929.24 |
| November | 16.8 | 3299.25 |
| December | 15.6 | 3063.59 |



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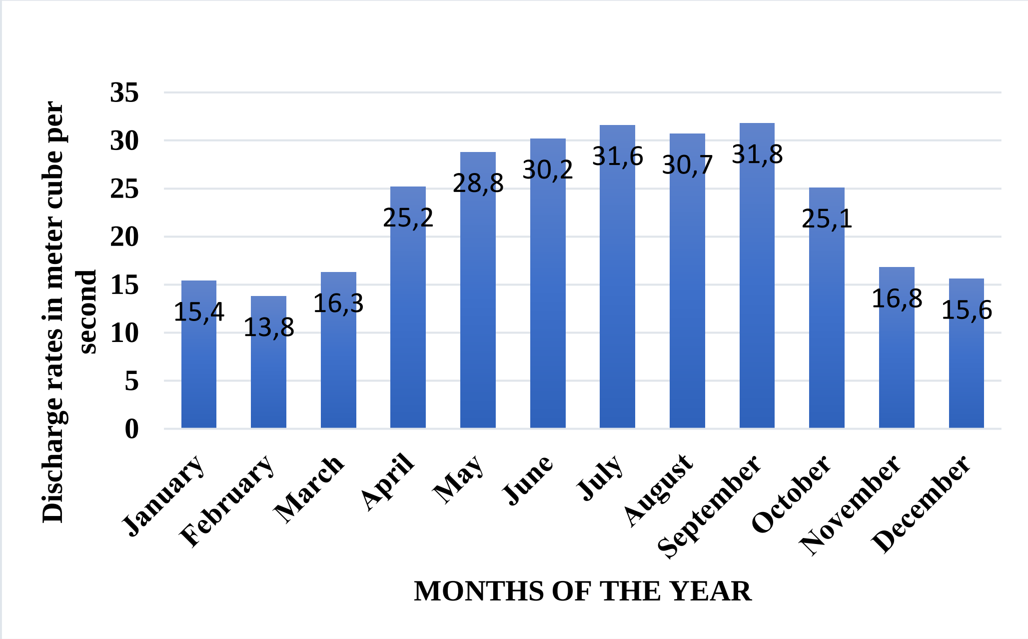


*Figure 9. Discharge rate of Ikere River for the proposed hydro- Electric power plant during year 2019.*

Table 4.3 shows the Output Power Generated from the Hybrid Power System

Table 3. Output Power Generated from the Hybrid Power System

| S/N | Months | Average Power Generated from the Diesel Generator (x 100 Watts) | Average Power Generated from the Proposed Hydro Electric Power Plant (x 10 kW) |
|---|---|---|---|
| 1 | January | 416 | 302.43 |
| 2 | February | 448 | 271.01 |
| 3 | March | 450 | 320.11 |
| 4 | April | 452 | 494.89 |
| 5 | May | 282 | 565.59 |
| 6 | June | 456 | 593.08 |
| 7 | July | 452 | 620.57 |
| 8 | August | 446 | 602.90 |
| 9 | September | 245 | 634.50 |
| 10 | October | 242 | 492.92 |
| 11 | November | 240 | 329.93 |
| 12 | December | 208 | 306.36 |

Table 9 Output Power Generated from the Hybrid Power System comprising Hydro-Electric Power Plant and Diesel Generator



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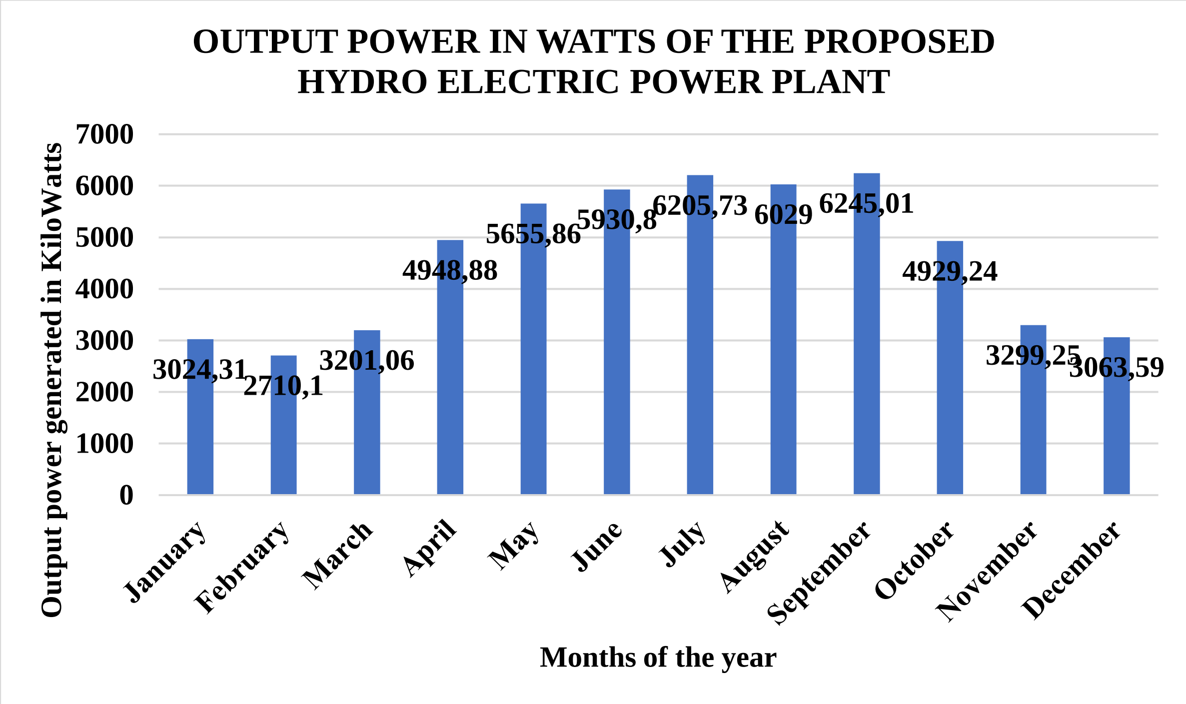


*Figure 10. represents the Output Power of the Proposed Hydro Electric Power Plant*

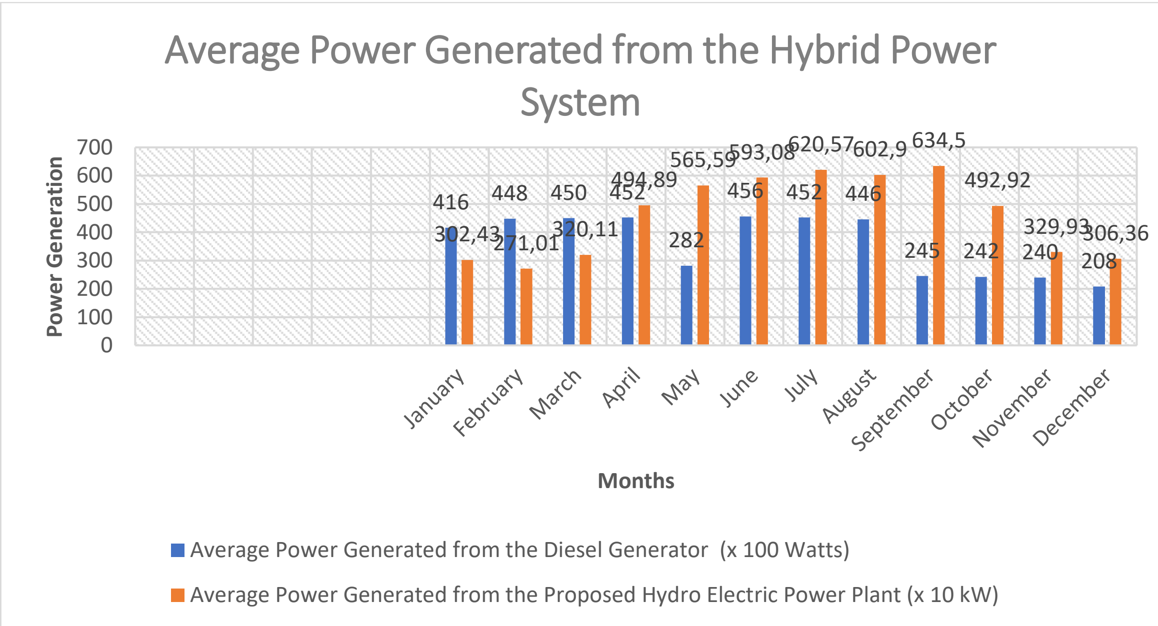


*Figure 11. Average Power Generated from the Hybrid Power System*

## Performances of the Diesel Generator under the Events of faults and Variation of Loads

### *Performances under the Variation of Loads*

Before the occurrence of fault, the system experienced normal steady state condition at 0 – 0.2 second. During this normal condition, the rotor speed is 1.0 per unit, stator current is 0.9 per unit, excitation voltage is 1 per unit, rotor speed is 0.96 per unit. The system became unstable after the introduction three phase fault for 0.4 second. The introduction of this three-phase fault, increases the magnetic flux around the field winding. This led to increase in rotor speed to 4.1 per unit and consequently the generated voltage and the stator fault current increased to 4.1 and 6.2 per unit respectively. The system returns to stable state after the removal of fault at exactly 0.6 second.



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Comparison of the Terminal Voltage of the generator, fuel supply and Rotational Speed of the Generator

The Simulink model shown in Table 4.13 was simulated for 80 seconds and the following results were obtained.

At time t = 0, a total load of 20 kW is connected and the generator is started

Table 4.12 shows the simulation results of variation of generated speed and inflow of fuel with various loads

The speed of the generator became unstable and it increased from 0 to 2400 rpm (n = 40rps) for 5 seconds i.e., during the startup process. After 5 seconds, the speed of the generator became stable at 1860 rpm (31rps) up till the 49.9the sec after which the load on the system is reduced to 15 kW. After 50 seconds, the load decreased to 15 kW and observation revealed that the generator speed increased from 1860 rpm to 2000 rpm. Hence, the system became unstable for another 2 seconds. The speed governor observed the sudden increase in speed. It then reduced the opening of the throttle valve in order to reduce the flow of atomized fuel. This reduction in rate of flow of atomized fuel reduces the speed of the rotor. Hence, the output power is reduced and it reaches stability point after 0.02 sec

***Performance of the Generator with the Variation of inflow of fuel***

At time t = 0, a total load of 20 kW is connected and the generator is started. The speed of the generator became unstable and it increased from 0 to 2400 rpm (n = 40rps) during the startup process. The rate of flow of fuel became unstable and increases up to 2.2 kg/sec. After 5 seconds, the speed of the generator became stable at 1860 rpm (31rps) up till the 49.9the sec. The rate of flow of fuel became stable up till the 50th second.

After 50 seconds, the load decreased to 15 kW and observation revealed that the generator speed increased from 1860 rpm to 2000 rpm. The speed governor observes the sudden increase in speed. It then reduces the opening of the throttle valve in order to reduce the flow of atomized fuel with the help of the PID based governor. The inflow of fuel became unstable for another 2 second. The inflow of fuel became stable after 2 seconds at exactly 52nd second

***Performance of the Generator with the Variation of Generated voltage***

At time t = 0, a total load of 20 kW is connected and the generator is started. The speed of the generator became unstable and it increased from 0 to 2400 rpm (n = 40rps) during the startup process. Hence the generated voltage increases to 415 V three phase. After 5 seconds, the speed of the generator became stable at 1860 rpm (31rps) up till the 49.9the second and the generated voltage became stable after 0.02 second. After 50 seconds, the load decreased to 15 kW and observation revealed that the generator speed increased from 1860 rpm to 2000 rpm. The generated voltage increased slightly for 0.02 second and it enters into stability after 0.02 second.

Table 4. shows the results of the response of the hydro-electric power plant to three phase short circuit Fault

| **Time** | **Stator Current (P.U)** | **Rotor Speed (P.U)** | **Excitation Voltage (P.U)** | **System Voltage (P.U)** | **Results: Stable/ Unstable States** |
|---|---|---|---|---|---|
| 0-0.2 | 0.9 | 0.96 | 1.0 | 1.0 | System stability state |
| 0.2-0.3 | 6.2 | 4.1 | 3.0 | 4.1 | Three phase short circuit transient fault |
| 0.3 | 5.2 | 3.3 | 2.4 | 3.4 | Unstable state |
| 0.4 | 3.0 | 2.3 | 1.5 | 2.5 | Unstable state |
| 0.5 | 2.3 | 1.5 | 1.2 | 1.4 | Unstable state |



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| | | | | | |
|---|---|---|---|---|---|
| 0.6 | 0.9 | 0.96 | 1.0 | 1.0 | System stability state |
| 0.7 | 0.9 | 0.96 | 1.0 | 1.0 | System stability state |
| 0.8 | 0.9 | 0.96 | 1.0 | 1.0 | System stability state |
| 0.9 | 0.9 | 0.96 | 1.0 | 1.0 | System stability state |
| 1.0 | 0.9 | 0.96 | 1.0 | 1.0 | System stability state |

Table 4.4: results of the response of the hydro-electric power plant to three phase short circuit fault.

Figure 4.4 shows the Stator Current – before, during and after the occurrence of faults in per unit.

Figure 4.5 shows the per unit rotor speed of the Hydro Electric Power Plant during the events of faults.

Figure 4.6 represents diesel Generator Speed under the variation of Loads.

Figure 4.7: Generator Rate of Fuel Consumption under the variation of Loads and

Table 4.5 shows the results of the variation of generated speed and inflow of fuel with various loads.

| **Time (Seconds)** | **Load (kW)** | **Generator speed, N, Rev/min** | **Inflow of fuel x $10^{-3}$ kg/sec** | **Generated Voltage** |
|---|---|---|---|---|
| 0-5 | 20 | 0-2400 | 0-2.2-1.05 | 0-415 |
| 5-49.9 | 20 | 1860 | 1.05 | 415 |
| 50 | 15 | 1860-2000 | 1.05 | 415 |
| 50-50.02 | 15 | 1860-2000 | 1.05 | 415 |
| 50.02-52 | 15 | 1824 | 1.05-0.92 | 415 |
| 52-60 | 15 | 1824 | 0.92 | 415 |
| 60-80 | 15 | 1824 | 0.92 | 415 |

Table 4.5: simulation results of variation of generated speed and inflow of fuel with various loads

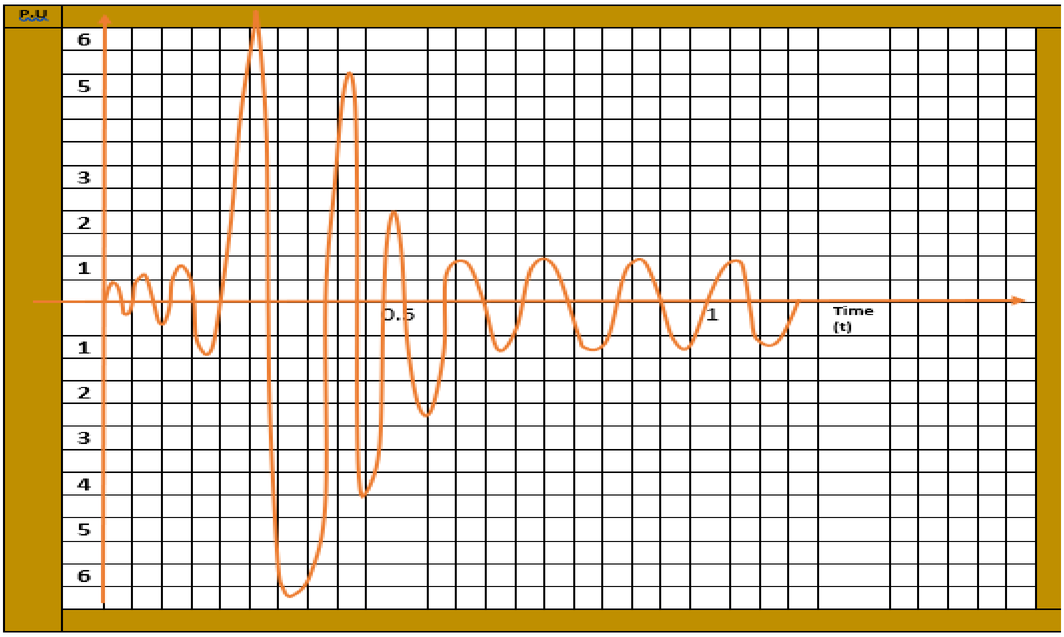


*Figure 12. Stator Current – before, during and after the occurrence of faults in per unit*



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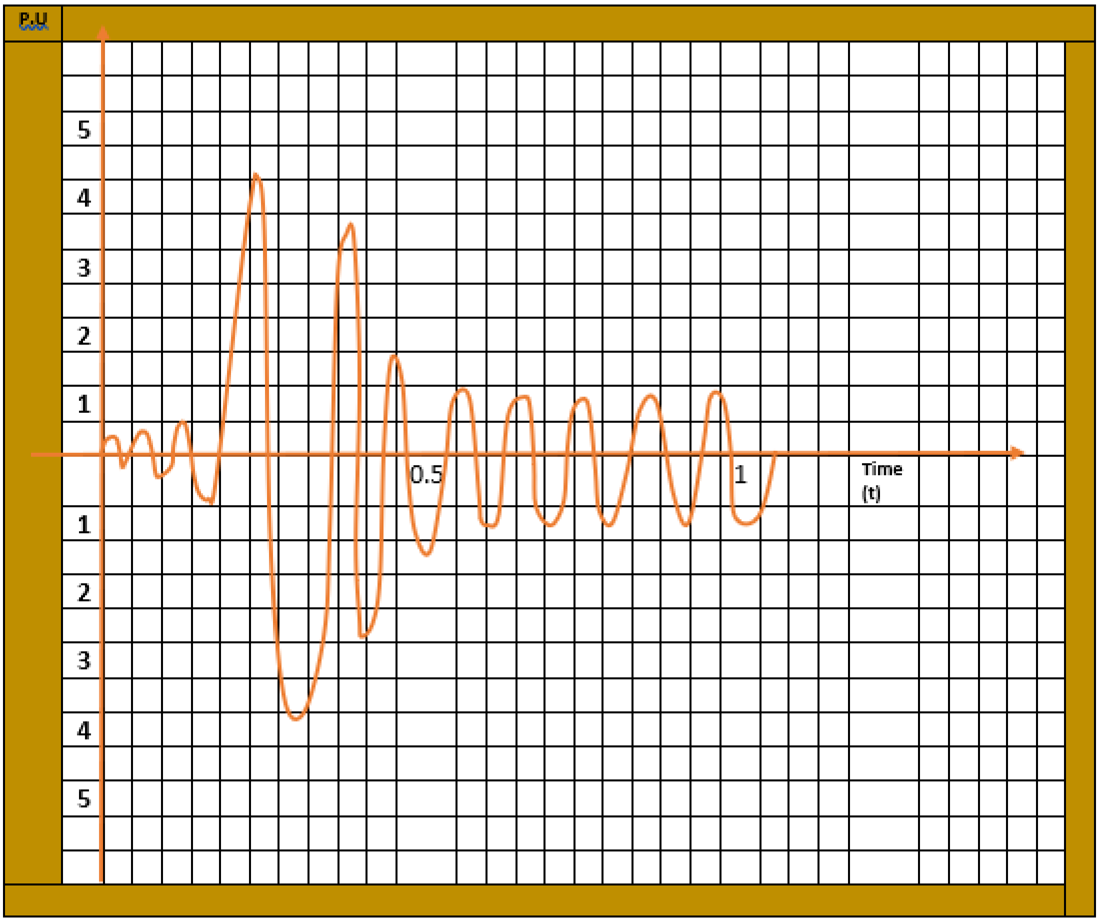


*Figure 13. H.E.P.P Rotor Speed, before, during and after the occurrence of faults in per unit*

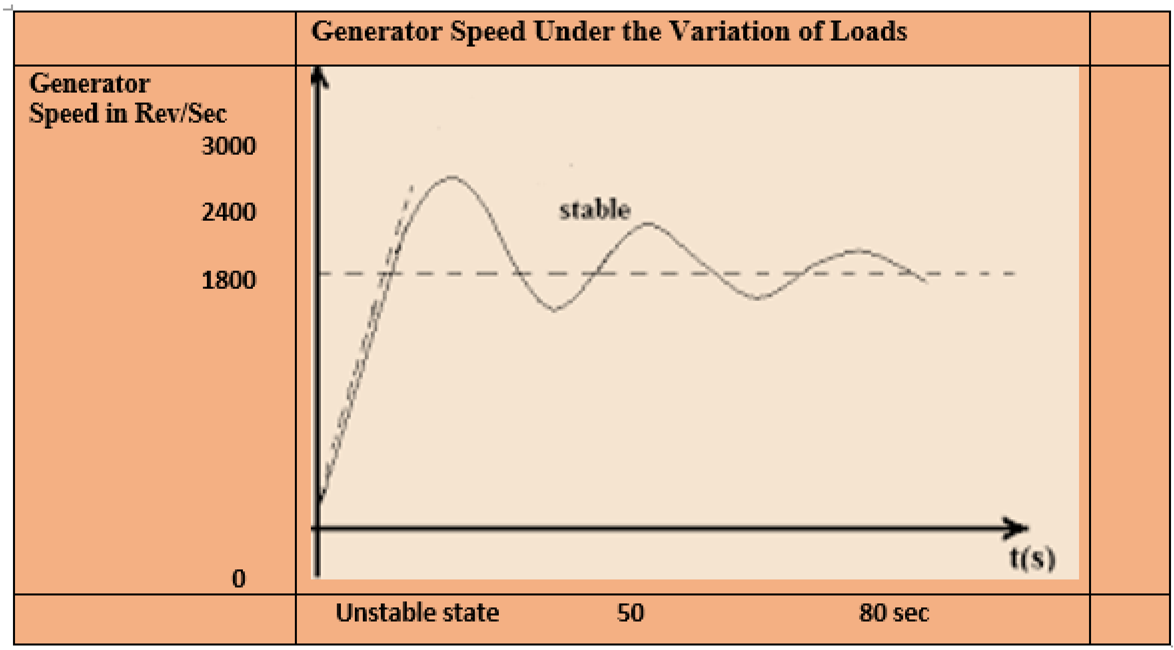


*Figure 14. Diesel Generator Speed under the variation of Loadsk*



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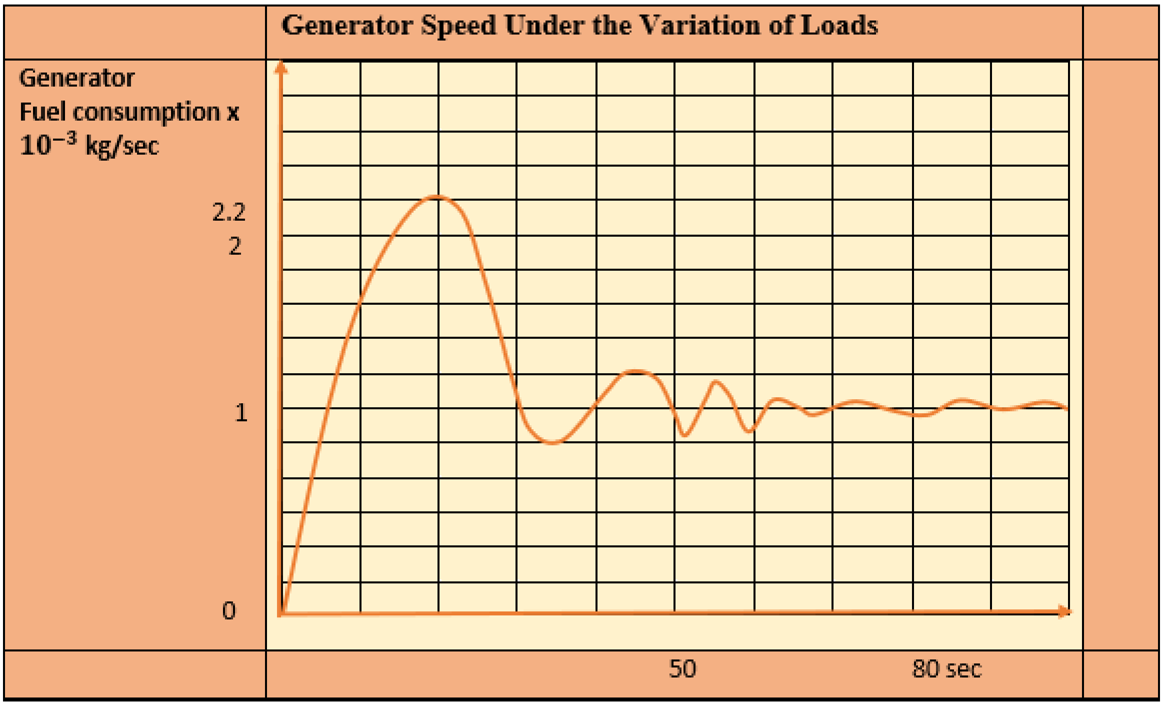


*Figure 15. Generator Rate of Fuel Consumption under the variation of Loads*

## Conclusion

The Proposed Hybrid Electric Power System Models developed in this research work provide adequate solution to the problems of incessant power supply in the rural community. The proposed power Plant has generating Capacity of 4,948.88 kW to 6,245.01 kW during the rainy season as shown in tables 4.1 to 4.3 and figures 4.1 to 4.3. The discharge rate of Ikere River in Iseyin Community, Oyo State, where the proposed Hydro-Electric Power Plant will be located ranges between 13.8 m^(3 )/second in the month of February to 31.8 m^(3 )/second in the month of September. Output power developed during this period ranges between 4,948.88 kW and 6,245.01 kW. The results obtained from the control algorithm for Hybrid Electric Power System provide reliable, efficient and stable power supply even in the events of faults and variation of loads. The performances of the Hydro Electric Power Plant and the Diesel Generator revealed that the problems associated with other conventional methods of power generation was overcomed by the development of these renewable and non-renewable energy resources Hybrid Electric Power System (HEPS) models. Hence, when these models are implemented, it will be possible to supply adequate and continuous Power Supply to the consumers in any rural or urban community.

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