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Development of Wind and Diesel Generator Hybrid Power System Model for Urban Electrification

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Abstract

The progress and prosperity of any nation depend on the amount of electrical energy consumed in the country. But African countries produce and consume the lowest amount of electricity in the world. This has led to the present incessant, unstable and unreliable power supply system in African Countries which has grounded many activities and has destroyed many industrial processes. This has also increased unemployment rate and increased crime rates in the continents. In order to satisfy the high energy demand in the residential and industrial environments in this continent, and provide solution to these problems, electrical energy should be reliable, affordable, effective, and sustainable.

Introduction

There is an immediate need to set up a renewable hybrid power supply system that makes use of cutting-edge control algorithms and techniques for Maximum Power Tracking in order to guarantee a consistent, predictable, and efficient flow of power. This is a task that must be completed as quickly as possible. This is an unavoidable need that can in no way be avoided. As a consequence of this, the objective of this inquiry was to determine whether or not it would be possible to set up a Hybrid Power System (also known as an HPS) in the region that was the subject of this investigation (the Iseyin Community in Oyo State, Nigeria).

With the assistance of the MATLAB/Simulink 8.1064 (2020a) software, the HPS Simulink models were constructed. Their operating parameters as well as their performances were analyzed. Both models of wind turbine generators and models of diesel generators were employed in the process of developing the model of the hybrid power system (HPSM). A simulation was performed on each and every one of the Simulink models that were built. Optimum Power Point Tracking (OPPT) Techniques and Genetic Algorithms were used when the optimization procedure was being carried out (G.A). The hybrid power system's output power has undergone extensive research, development, and regulation to ensure that it is both consistent and effective over the whole of the system (Wang & Singh, 2009).

The power factor correction (MPPT) techniques and control algorithms for the HPS were developed in order to provide a reliable and constant power supply that is unaffected by faults as well as variations in load. This was done in order to fulfill the standards that were outlined in the HPS. In spite of the existence of faults and changes in the load, the multipoint PV tracker (MPPT) methodologies and control algorithms created for this study proved to be very robust and reliable. We are now in a position to provide our customers a dependable source of electricity that is not only kind to the environment but also very efficient as a direct consequence of the results that we acquired via the usage of Simulink and the validation. In conclusion, the HPS model that was established during the course of this study proved to be of great assistance in the process of creating hybrid power plants and supplying consumers with electricity that is dependable and constant.

Aim and Objectives of the Research

The primary objective of the project is to develop optimum power point monitoring algorithms for renewable energy micro grids and to construct hybrid wind and diesel power system models for use in such grids. Additionally, the project aims to build models of power systems that can be used in such grids. During the course of the study, we shall be successful in achieving both of these objectives.

The following is a list of some of the goals that the study aims to accomplish: (2) to create Simulink models of the HPSM in MATLAB/Simulink 8.1.0604 (2020a) version software; (3) to create an efficient Hybrid Power System model with peak performance via OPPT techniques; (4) to determine the design procedure and control algorithms necessary for the creation and efficient operation of the Hybrid Power System Model; (HPSM).

Maximum Power Point Techniques (MPPT) in A Wtg

Adjusting the amount of power that is generated by the generator of a wind turbine may be accomplished via the use of control strategies known as Tip Speed Ratio (TSR). In order to accomplish this objective, the Tip Speed Ratio of a variable speed generator has to be kept at the value that gives it the best results. As a consequence of this, the objective of the Maximum Power Point Techniques (MPPT) is to locate the optimum TSR by calculating it based on the wind speed and rotor speed that are determined through the application of the mathematical model equation that is presented further down in this paragraph. The optimal TSR can then be utilized to generate the maximum amount of power.

$$\text{The Tip Speed Ratio} = \frac{R\omega}{V} \qquad 2.1$$

Where R = Radius of the turbine (m), ω = angular speed of the tip of a blade in rad/sec

V = average wind speed in m/s

Maintaining the TSR at its optimum level ensures that the generator on the wind turbine is operating at its maximum efficiency (Abdullah et al. 2011; Kumar et al. 2017). In wind turbine generators, the tip speed ratio (TSR) is defined as the ratio between the speed of the wind and the product of the turbine's radius and the angular or rotational speed of the blade's tip. Another way to say this is that the TSR is the ratio of the wind speed to the angular or rotational speed of the blade's tip to the (Bhandari et al. 2014; Kumar et al. 2017).

The optimum tip speed ratio λ_{opt} is attained when the coefficient of performance C_p of the WTG is maximum as shown in the figure 1. For Wind Turbine generator, coefficient of performance C_p is less or equal to 0.593.

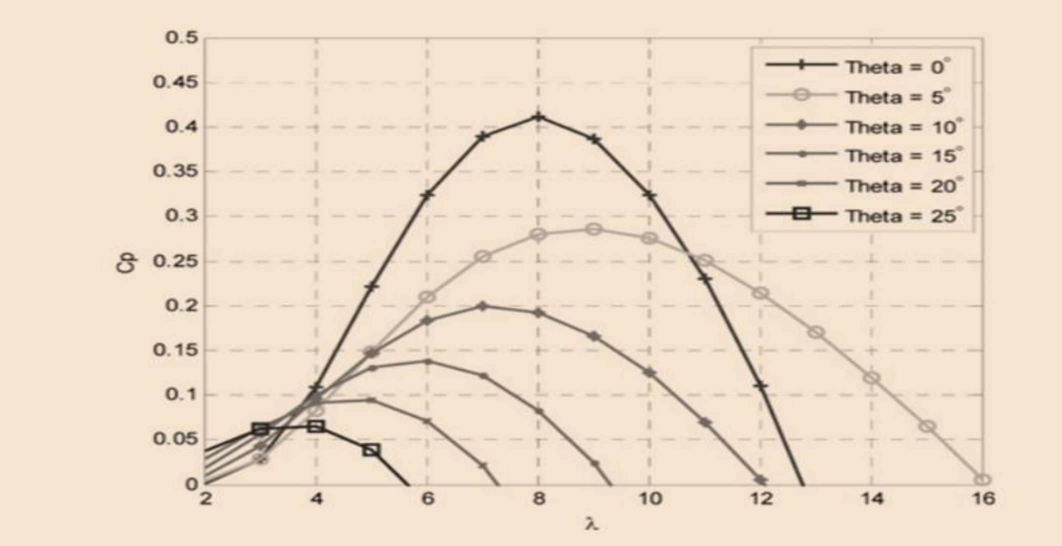

Figure 1. showing the coefficient of performance, C_p, and the Tip Speed Ratio λ

Bhandari et al. (2014), Kumar et al. (2017).

The maximum rotor speed of the wind Turbine generator can then be obtained.

Optimum rotor speed = $\omega_{optimum} = \frac{\lambda_{optimum}}{R} V_{windspeed}$ 2.2

Hence, the maximum Power Point is obtained when the rotor is running at optimum rotor speed ($\omega_{optimum}$). Maximum Power Point is obtained when the turbine shaft (ω_r) is optimum as shown in figure 2.

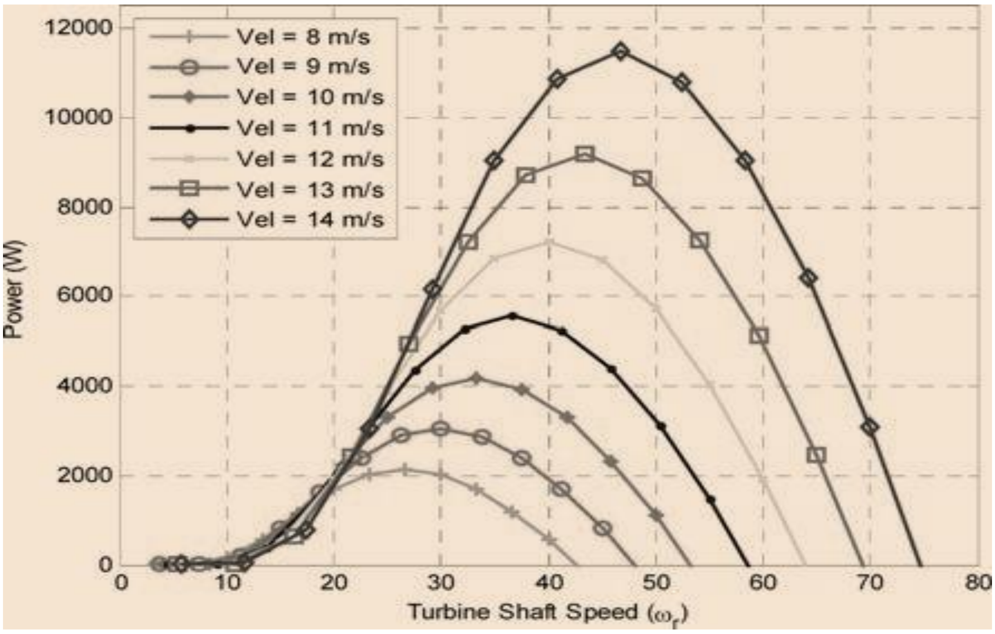

Figure 2. Wind Turbine Power Curve

Therefore, the main objective of Maximum Power Point Tracking (MPPT) in Wind Turbine Generator is to determine the maximum coefficient of performance (C_P) under the condition of varying wind speed and then the optimum tip speed ratio 9 (Lu et al., 2002). This is because maximum power point can be obtained in a varying wind speed by keeping the Tip Speed Ratio (λ) at its optimal value.

The optimum rotor speed or optimum turbine shaft speed $\omega_{optimum}$ can then be determined. The corresponding power at this optimum turbine shaft speed is the maximum power produced.

The mechanical power of an induction machine like wind turbine generator is given as

$$P = \omega T \tag{2.3}$$

Where

a. P = mechanical power

b. ω = angular speed of the machine in rev/sec

c. T = Torque

The model equation for wind power system is shown below:

$$P_{wind} = \frac{1}{2}\ C_p\ \lambda \rho\ A\ \ V^3 \tag{2.4}$$

Maximum Power Point in a WTG

The optimum Tip Speed Ratio λ_{opt} is obtained when the value of turbine power efficiency coefficient is maximum.

$P_{wind} = \frac{1}{2}\ C_p\ \lambda \rho\ A\ \ V^3$ (optimum Tip Speed Ratio $is\ optimum\ when\ C_p\ is\ maximum$)

(P) = Power Output of the wind turbine in kilowatts

(ρ) = Air Density, measured in kilogram per cubic meter

(A) = intercepting area of the rotor blade in square meter

(V) = Wind Speed, miles/seconds

λ = Tip Speed Ratio (TSR)

(Cp) = Turbine power efficiency coefficient or Bertz coefficient which is a maximum of 0.593

Then, the optimum generator speed which gives the maximum output power can be determined.

Hence, $\omega_{opt} = \frac{\lambda_{opt}\, V}{R}$ 2.5

If the angular velocity of the turbine shaft is already lower than the speed at which it generates the greatest power, then the angular velocity of the turbine shaft has to be increased in order to maximize the amount of power that is generated by the turbine. It is recommended that the angular speed be raised if it is lower than the speed of the turbine shaft at the point where the greatest amount of power is generated. "Maximum power point tracking" refers to the process of modifying the speed at which the rotor of the turbine spins in order to achieve the highest possible level of power output.

Wind Turbine Generator Output Power and Simulation Procedure

Figure 3 shows the flow chart of the wind turbine generator simulation procedure. The maximum rotor speed of the wind turbine generator generates maximum power was determined using equation 3.1

Optimum rotor speed = $\omega_{optimum} = \frac{\lambda_{optimum}}{R}\ V_{windspeed}$ ……………….3.1

Hence, the maximum Power Point was obtained when the rotor is running at optimum rotor speed ($\omega_{optimum}$). Maximum Power Point was obtained when the turbine shaft (ω_r) is optimum as shown in figure 4.

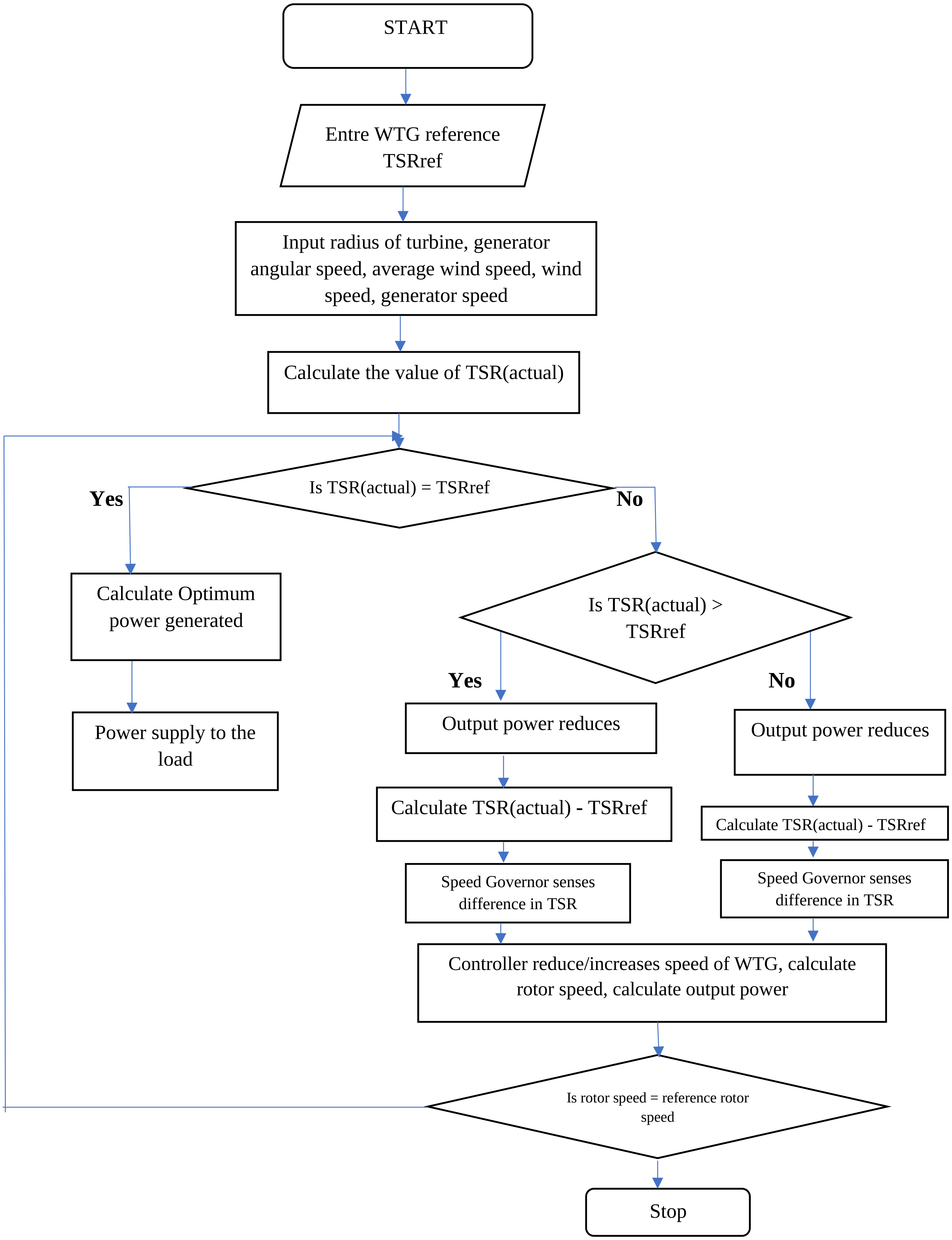

Figure 3. Flow Chart of The Wind Turbine Generator Simulation Procedure

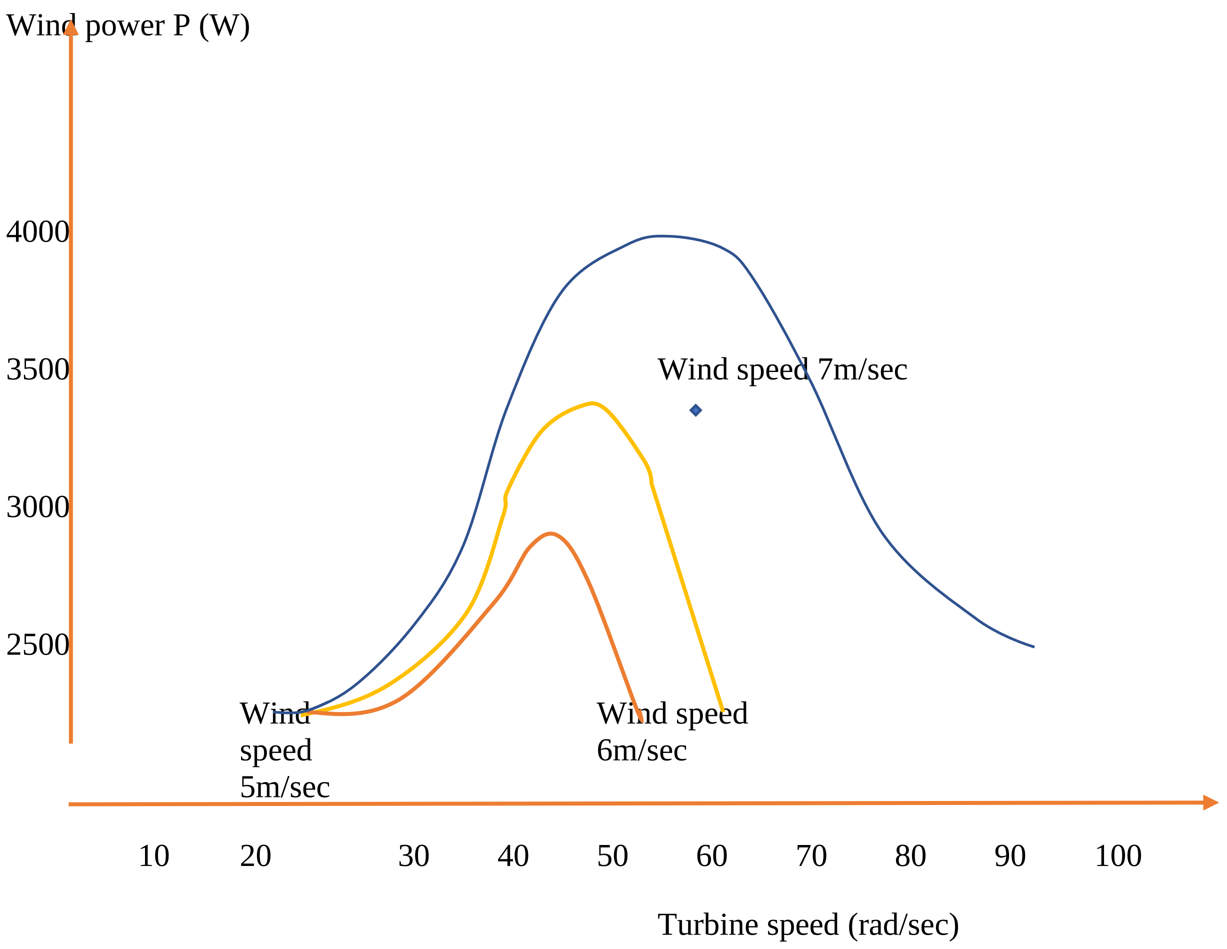

Figure 4. Wind Turbine Power- Rotor angular speed Characteristics

If the current angular speed is greater than the reference or goal turbine shaft speed at which maximum power can be generated, then the angular speed should be slowed down in order to obtain the maximum output power that is possible. This will ensure that the turbine generates the maximum amount of power possible. It is recommended that the angular speed be raised if it is lower than the speed of the turbine shaft at the point where the greatest amount of power is generated. The point of maximum power in the process of adjusting the angular speed of the turbine in order to produce the most amount of output power feasible is referred to as "tracking," and it is denoted by the phrase. A tachometer is used in order to determine the speed at which the blade is rotating. A device known as an anemometer may be used to determine the velocity of the wind at a particular location. The TSR value that was determined as a result is then compared to the ideal TSR value that had been set by the generator earlier on in the process. This is carried out on a continual basis, and the resulting deviation is sent back into the controller in order to effect a change in the speed of the WTG. This assures that the TSR will continue to be maintained at a number that is as near to its optimal level as is feasible. When looking at Figures 1, 2, and 4, it becomes clearly clear that a Wind Turbine Generator operates at its most productive and efficient levels when the Turbine Speed Ratio (TSR) is kept at its optimal setting. This is shown by the fact that it generates the largest amount of power.

In this research work, a 3.5 kW wind turbine generator is being proposed in Lagos State, Nigeria. The radius of the turbine blade is 1.12m. Average wind speed is 7m/s. Maximum Bertz-coefficient of performance, C_p, is 0.5. Air density = 1.3 kg/m^3.

Optimum Tip speed ratio , λ_{opt} is obtained when C_p is maximum. Optimum rotor speed, ω_{opt} is obtained during this Optimum Tip speed ratio.

$$\text{Optimum Tip Speed Ratio} = \lambda_{opt} = \frac{2P}{C_p \; \rho \, A \; V^3}$$

$$= \frac{2 \; x \, 3{,}500}{0.5 \, x \;\, 1.3 \, x \, 3.94 \, x \, 7^3} \quad = 7.9688$$

The Optimum rotor speed, ω_{opt} was obtained for the proposed wind turbine generator as follows:

$$\text{Optimum Rotor Speed Ratio} = \omega_{opt} = \frac{\lambda_{opt} \;\, x \, V}{R}$$

$$= \frac{7.9688 \, x \, 7}{1.2} \quad = 49.805 \text{ rad/sec}$$

The tip speed ratio, angular rotor speed and output power generated is presented in table 1.

Table 1. Tip speed ratio, angular rotor speed and output power of the wind turbine generator

S/N	Radius of blade(m)	$\boldsymbol{\omega}$	V	R$\boldsymbol{\omega}$	Tip Speed Ratio	Power Output
1	1.12	30	7	33.6	4.8	2,540
2	1.12	40	7	44.8	6.4	3,200
3	1.12	50	7	56.0	8.0	3,400
4	1.12	60	7	67.2	9.6	3,150
5	1.12	70	7	78.4	11.2	2,500

The characteristics of the rotor speed and the output power generated is presented in figure 5.

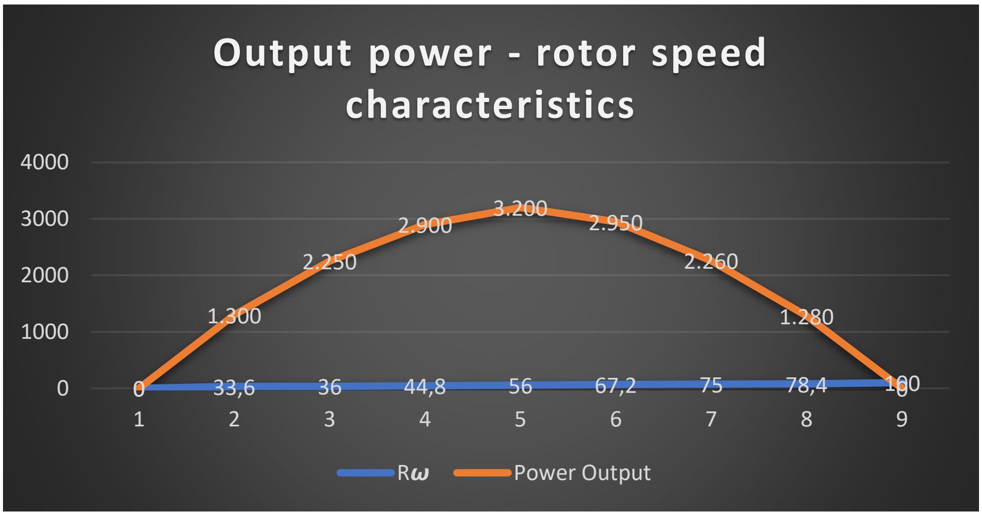

Figure 5. characteristics of the rotor speed and the output power generated in a wind turbine generator

Optimum Tip Speed Ratio Control Method

Tip Speed Ratio, also known as TSR for short, is a way that may be used to manage the amount of power that is created by a wind turbine generator. This method was given its name since it is a ratio that measures the speed of the blade tips. As the ultimate goal of this optimization technique, finding the TSR that is most efficient should be your top priority. Starting with the best TSR is the best place to be in order to compute the perfect angular rotor speed. A particular wind turbine generator will, at all times, have a TSR that is optimal for that generator, regardless of how quickly the wind blows. This is the case even when the wind speed is quite high. Consequently, maintaining the TSR at an optimum level will guarantee that the angular rotor speed is at an optimal level and that the generator of the wind turbine is operating at its maximum power point. You are going to want not only an anemometer but also a tachometer in order to correctly measure the speed of the wind as well as the rotational speed of the turbine.

The ideal TSR value that had been previously recorded by the power system will then be compared to the TSR value that was recently produced by the power system. The difference between the two values of TSR is sent to the controller, which subsequently alters the angular speed of the generator in order to guarantee that the maximum amount of power is created, as seen in figure 6.

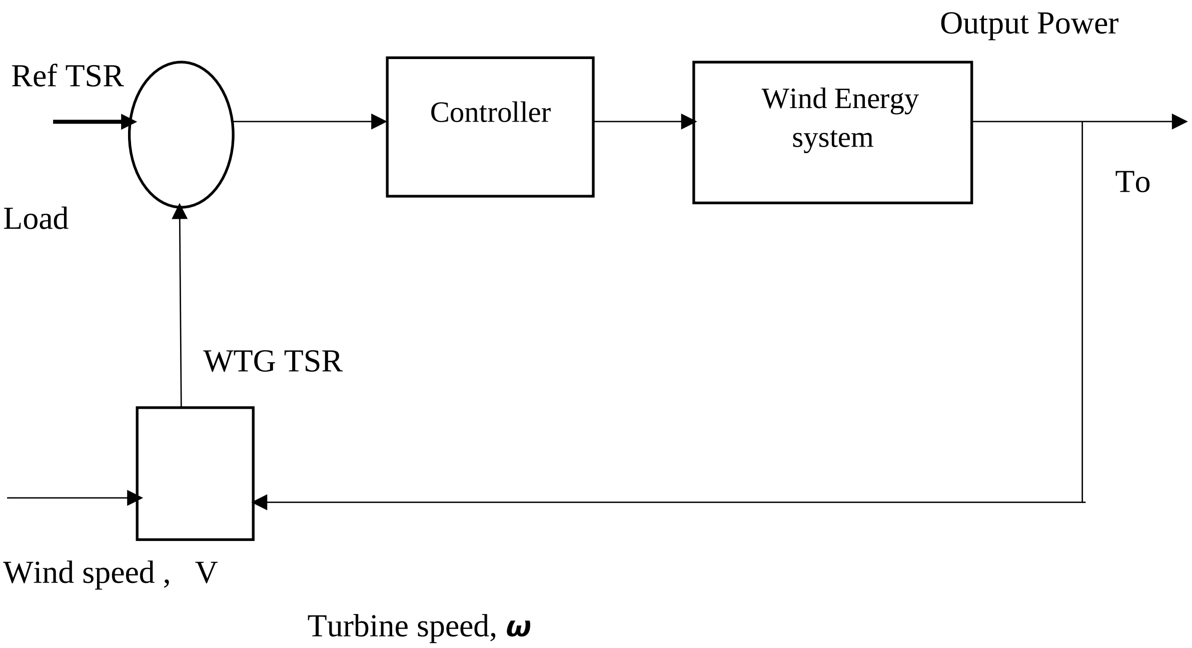

Figure 6. Working principle of TSR control techniques

Diesel Generator Simulink Model

Matlab Simulink Sim Power System Environment was utilized in order to build the Diesel Generator Simulink Model. This environment was developed by Simulink. Both the mechanical power, which is represented by the symbol P m, and the excitation system are regarded as inputs into the model. The same as what was said before. An procedure that includes the combustion of atomized fuel is what puts the finishing touches on the mechanical component. The application of the concept of electromagnetic induction, which is seen in figure 7, is what makes it possible for the electrical element to produce electrical energy.

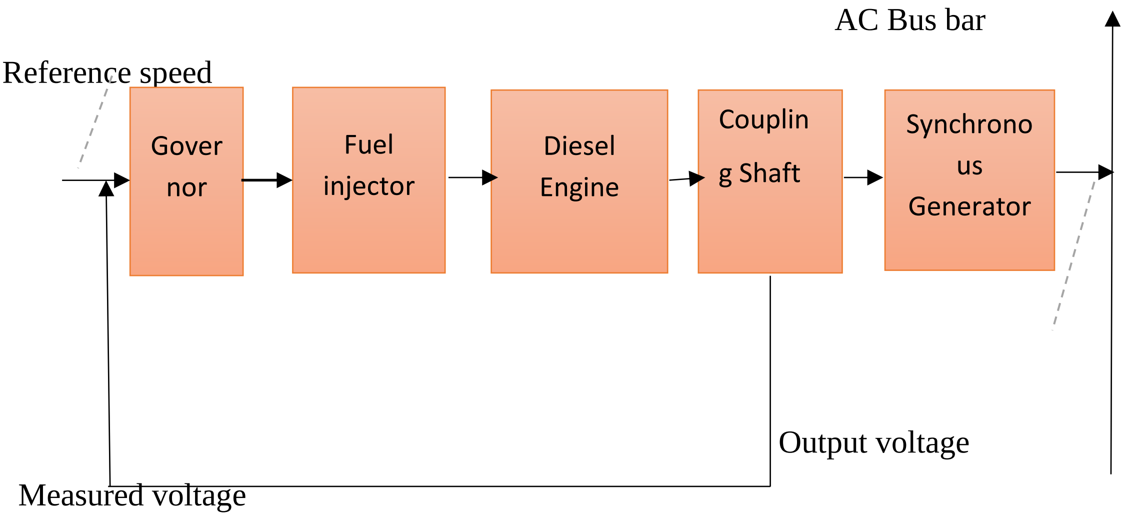

Figure 7. Components of Diesel Generator

Characteristics of the Fuel Supply System and the Rotor Speed

Figure 8 shows the relationship between the reference speed of the generator (N_{ref}), actual generator speed (N_{gen}), and the fuel supply system of the generator.

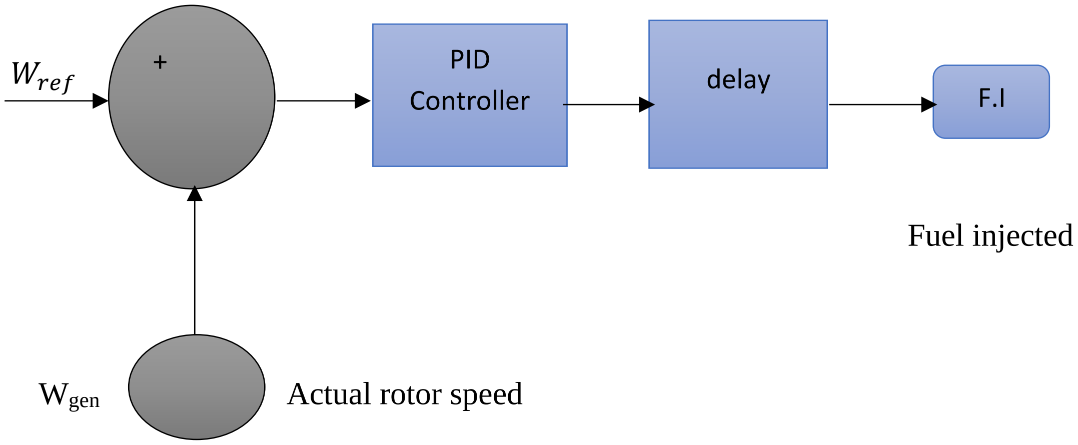

Figure 8. Relationship between the reference speed of the generator (N_{ref}), actual generator speed (N_{gen}), and the fuel supply system of the generator.

In order to get further knowledge about the functioning of the system, an investigation in the form of a simulation was carried out so that the investigation could be carried out. A few examples of appropriate inputs for the Simulink model are the amount of excitation voltage, the rate at which fuel is fed, and the rotor speed. Because this component is responsible for supplying both the current and the voltage at the output of the stator, the output characteristics of this component include both of these variables. Specifically, the current and the voltage. Throughout the whole of the experiment, the load on the system was held at 0.6 per unit, the excitation voltage was maintained at 0.9 per unit, and the generator speed was held at 0.8 per unit. These values were all held constant. The whole amount of time needed to carry out the simulation procedure is about two seconds.

The load that is being supplied to the generator is decreased to 0.5 per unit after a certain amount of time has elapsed, and during a condensed period of time, the speed of the rotor that is contained inside the generator rises. This difference in speed between the reference speed and the speed of the rotor is picked up by a component known as the speed governor, which then alerts the control system to the fact that there is a discrepancy in speed between the two speeds. As a consequence of this, the speed governor will limit the amount of air that is allowed to pass through the throttle, which will, in turn, lessen the amount of fuel that is introduced into the combustion chamber. This will be a consequence that is directly related to the scenario. The quantity of fuel that is still available will have a direct correlation to the rate at which the spinning of the generator's blades will start to slow down. As a direct consequence of this, the output stator current dropped, and the system's output voltage became stable after only a very small fraction of a second, as can be seen in figure 9 of the simulation flowchart. This occurred as a direct result of the system's output stator voltage becoming stable. This was all possible as a result of the fact that the system was able to keep the input voltage at a consistent level. This was completely the consequence of the output stator current being dropped, which was the only mechanism that could have brought this about.

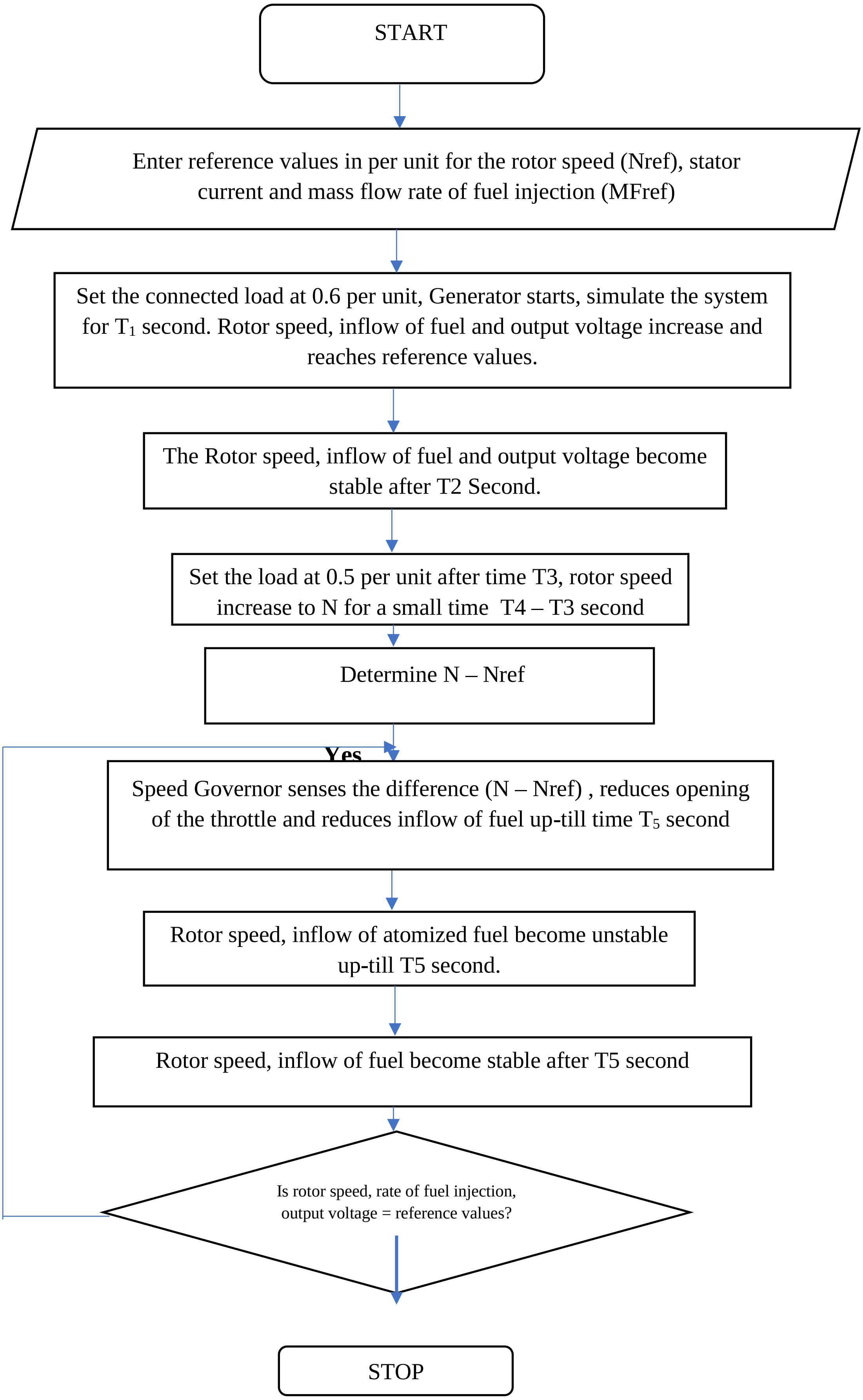

Figure 9. Flow Chart of The Diesel Generator Simulation Process

Results and Discussion

Data Acquisition for the Wind Turbine Generator (WTG)

A 3.5 kW wind turbine generator proposed in Lagos State, Nigeria is taken as reference. The radius of the turbine blade is 1.12m. Average wind speed is 7m/s. Maximum Bertz coefficient of performance, C_p, is 0.5. Air density = 1.3 kg/m^3.
Optimum Tip speed ratio , λ_{opt} is obtained when C_p is maximum. Optimum rotor speed, ω_{opt} is obtained during this Optimum Tip speed ratio.

Optimum Tip Speed Ratio = $\lambda_{opt} = \frac{2P}{C_p\ \rho\ A\ V^3} = \frac{2\ x\ 3{,}500}{0.5\ x\ 1.3\ x\ 3.94\ x\ 7^3} = 7.9688$

The Optimum rotor speed, ω_{opt} was obtained for the proposed wind turbine generator as follows:

Optimum Rotor Speed Ratio = $\omega_{opt} = \frac{\lambda_{opt}\ x\ V}{R} = \frac{7.9688\ x\ 7}{1.2} = 49.805\ \mathrm{rad/sec}$

The tip speed ratio, angular rotor speed and output power generated is presented in table 2

Rω	0	33.6	36	44.8	50	56	60	67.2	75	78.4	100
Power Output (Watts)	0	1060	2100	2400	3100	3200	3100	2800	2200	1200	0

The tip speed ratio, angular rotor speed and output power generated is presented in table 3.

Table 3. Tip speed ratio, angular rotor speed and output power generated

S/N	**Radius of blade**	ω	**V**	**Rω**	**Tip Speed Ratio**	**Power Output**
1	1.12	30	7	33.6	4.8	1,060
2	1.12	40	7	44.8	6.4	2,400
3	1.12	50	7	56.0	8.0	3,200
4	1.12	60	7	67.2	9.6	2,800
5	1.12	70	7	78.4	11.2	1,200

The characteristics of the rotor speed and the output power generated is presented in figure 10.

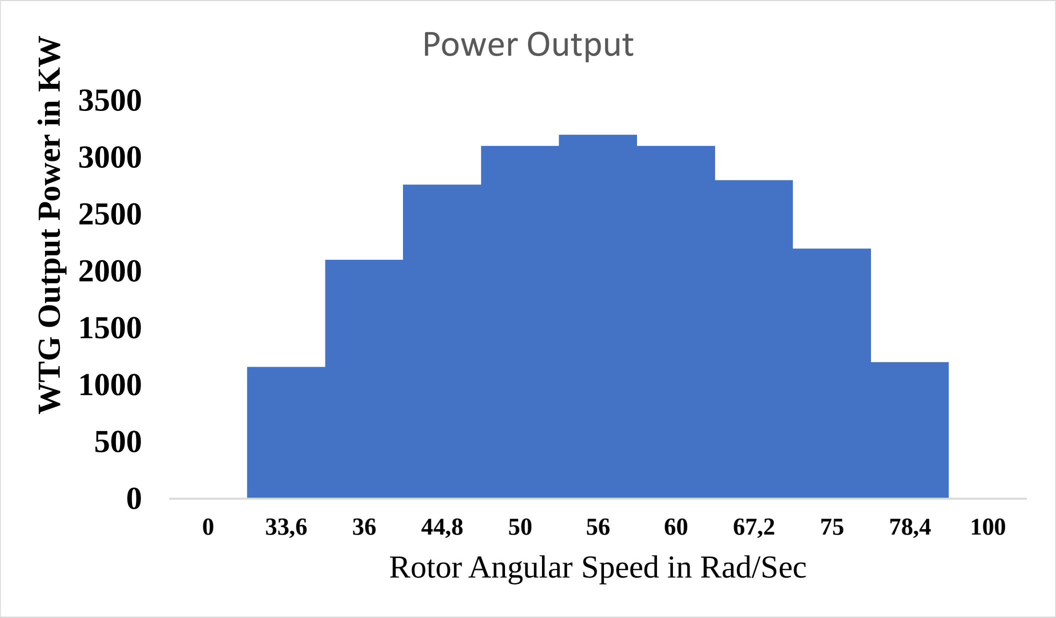

Figure 10. characteristics of the rotor speed and the output power generated from the wind turbine generator

Table 4. Parameters of the proposed 50 kVA Diesel Power Generator

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)
40 kVA	415 V	81.84	0.0025	2400

Figure 11 shows the developed model for the Diesel Generator.

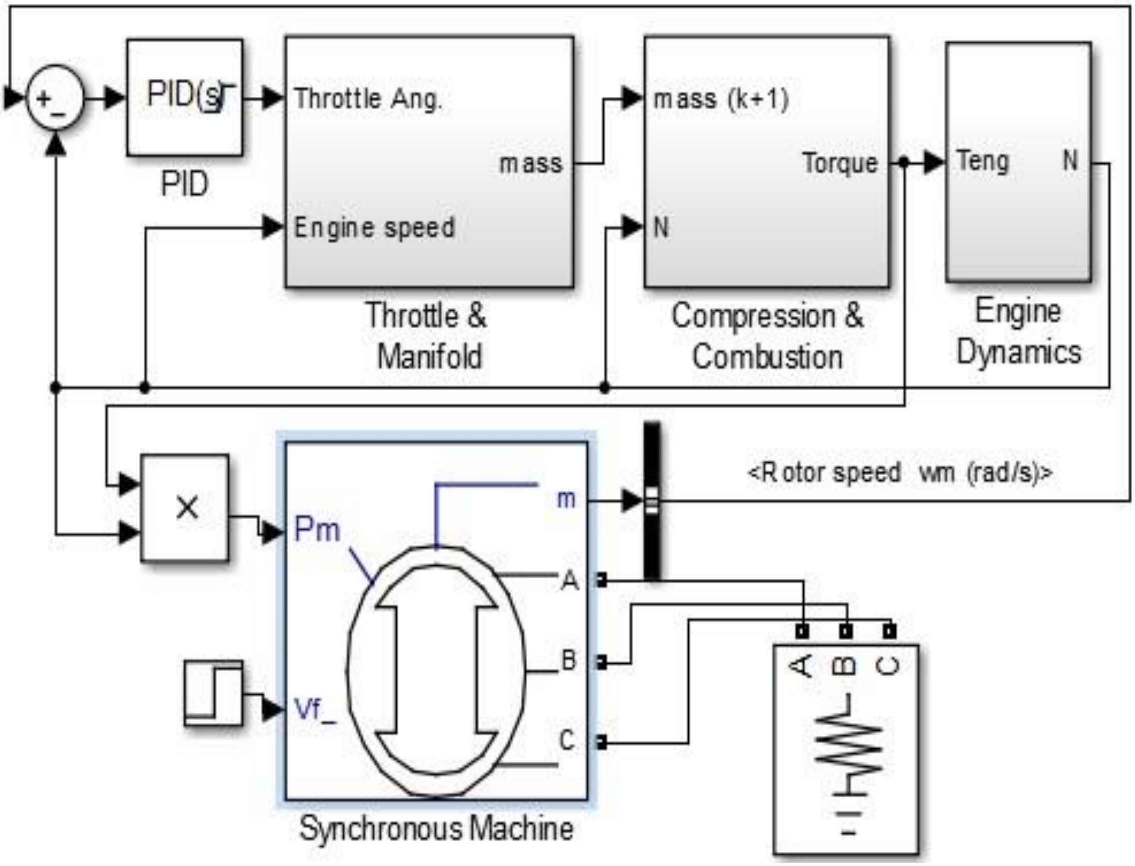

Figure 11. Developed Diesel Generator Simulink Model

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. This is demonstrated using the control Algorithm under Variation of loads as shown in the flow chart shown in figure 12.

Table 4. Shows the Output Power Generated from the Diesel Generator on Monthly Basis

S/N	**Months**	**Average Power Generated from the Diesel Generator (x 100 VA)**
1	January	416
2	February	448
3	March	450
4	April	452
5	May	282
6	June	456
7	July	452
8	August	446

9	September	245
10	October	242
11	November	240
12	December	208

Table 5 Shows the Output Power Generated/ Module at the reference Area on Monthly basis for the Solar Photo-Voltaic System and the Diesel Generator.

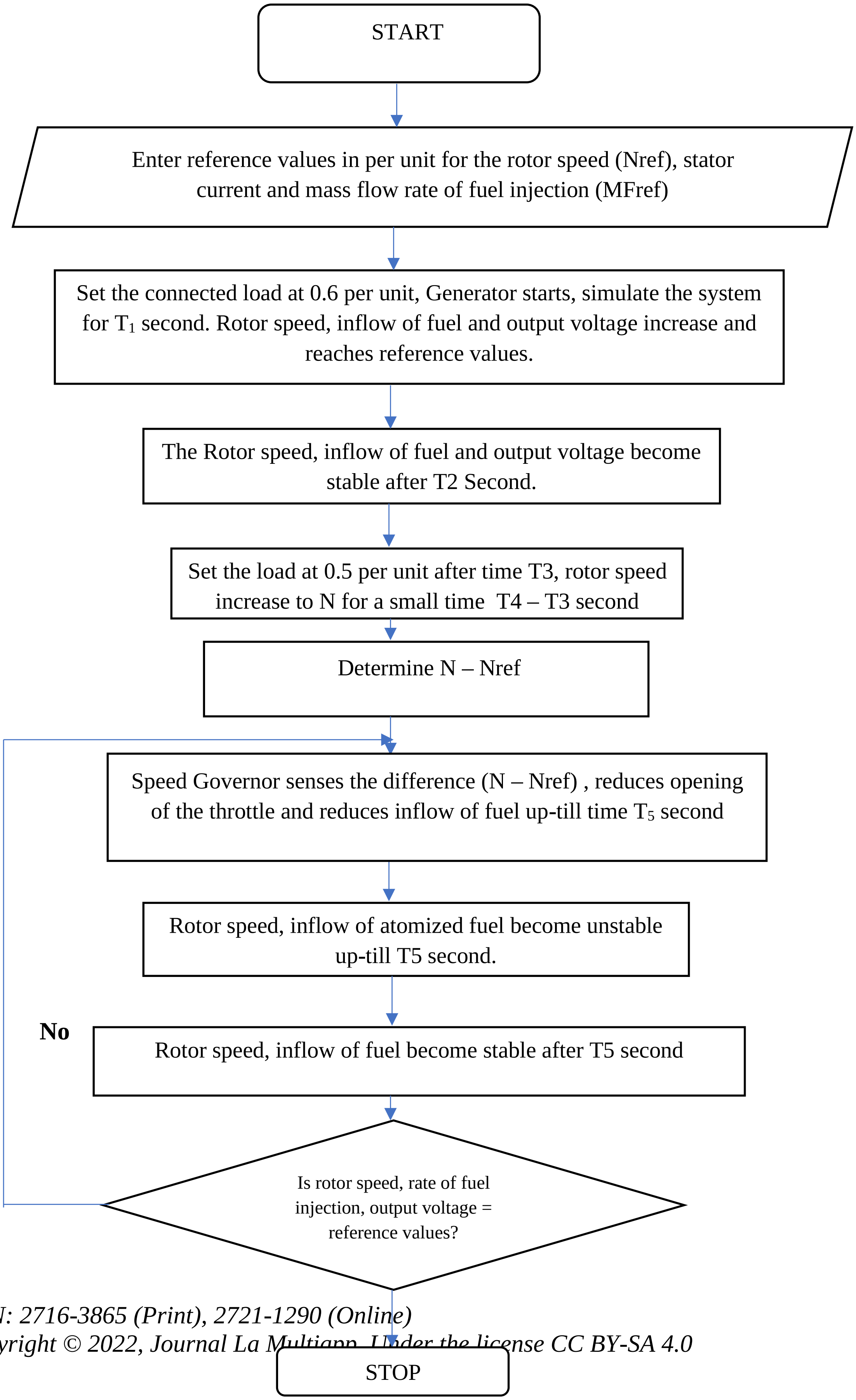

Figure 12. Generator Control Algorithm under Variation of loads

Table 5. Output Power Generated/ Module at the reference Area on Monthly basis for the Solar Photo-Voltaic System and the Diesel Generator

S/N	Months	Average Power Generated from the Solar Photovoltaic System (x 100 VA)	Average Power Generated from the Diesel Generator (x 100 VA)
1	January	315	416
2	February	308	448
3	March	311	450
4	April	268	452
5	May	180	282
6	June	162	456
7	July	154	452
8	August	272	446
9	September	170	245
10	October	272	242
11	November	291	240
12	December	300	208

The output power generated by each module at the reference area on a monthly basis is shown in Figure 12 for both the Solar Photovoltaic System and the Diesel Generator. Figure 14 shows the monthly output power generated by both the solar photovoltaic system and the diesel generator at the reference area. This data is shown in module form. The amount of power that was produced by both the diesel generator and the wind turbine generator is seen in Figure 15.

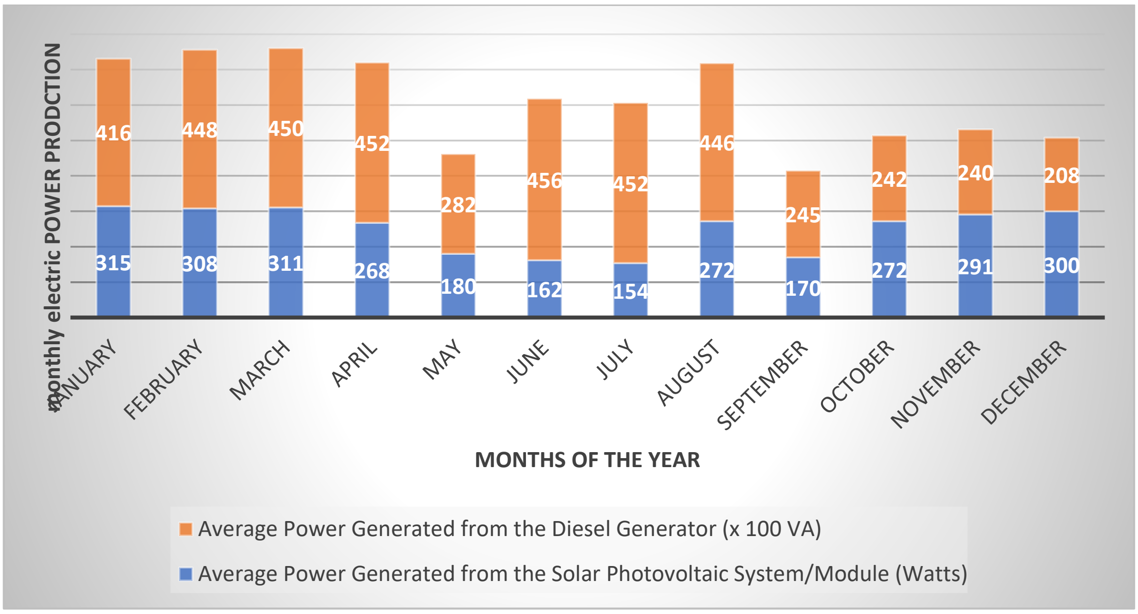

Figure 13. Output Power Generated/ Module at the reference Area on Monthly basis for the Solar Photo-Voltaic System and the Diesel Generator

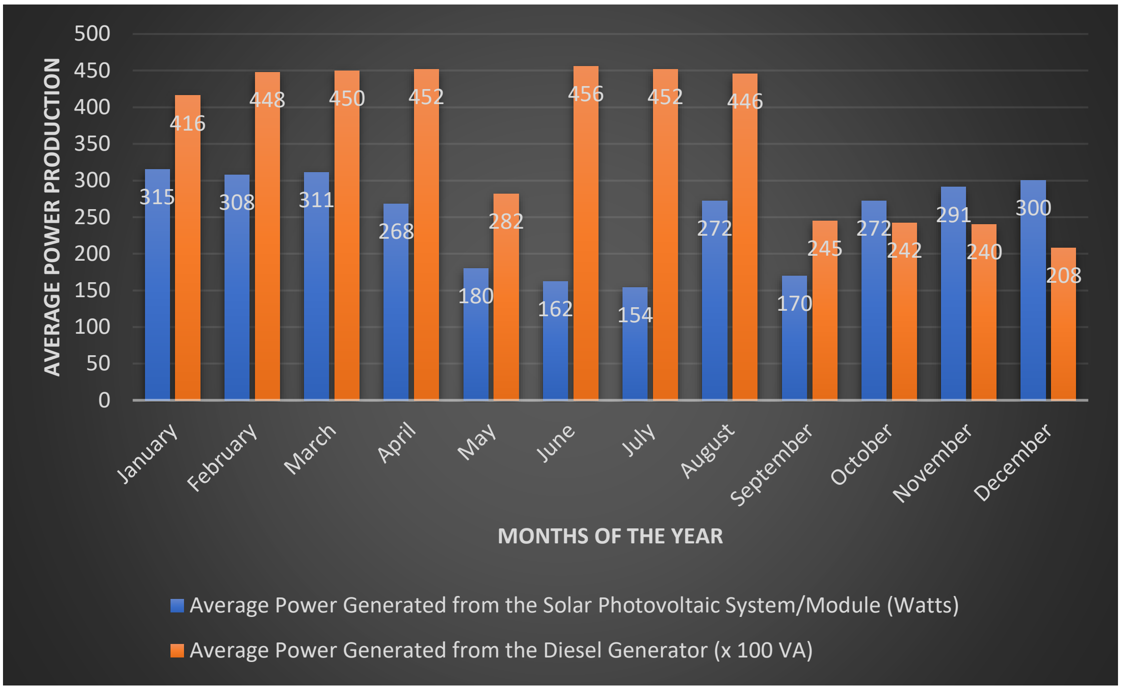

Figure 14. Output Power Generated/ Module at the reference Area on Monthly basis for the Solar Photo-Voltaic System and the Diesel Generator

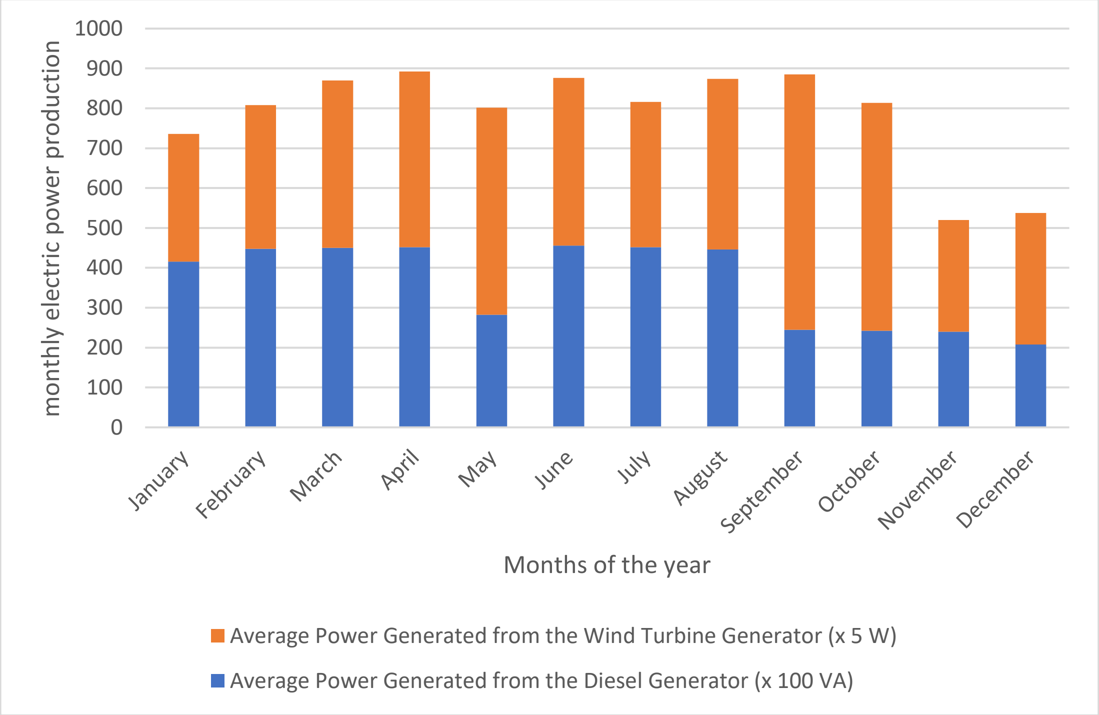

Figure 15. Output Power Generated from the Diesel Generator and the Proposed Wind Turbine Generator

The use of a simulated investigation made it possible to investigate the workings of the system from the inside. The quantity of excitation voltage, the rate at which fuel is supplied, and the rotor speed are some examples of legitimate inputs that may be presented to the Simulink model. Because it is responsible for supplying both current and voltage at the stator's terminal, both of these values are included in the output characteristics of this component. The output characteristics of this component may be found in the table below. This is due to the fact that it is responsible for providing both quantities. It should go without saying that I am talking to the current as well as the voltage. In the experiment, the numbers 0.6 per unit were used as constants for the system load, 0.9 per unit was used as a constant for the excitation voltage, and 0.6 per unit was used for the generator speed (0.8 per unit). These characteristics are presented here in their whole and unaltered original form. After two seconds have elapsed, the procedure for the simulation will generally be considered complete.

After a certain amount of time has passed, the load on the generator is decreased to 0.5 per unit, and the speed of the rotor within the generator starts to quickly rise. When the speed of the rotor deviates from the reference speed, the speed governor is able to detect the difference and will signal an alert to the control system when this occurs. Because of this, the speed governor will tighten its grip on the throttle, which will result in a decreased amount of fuel being injected into the combustion chamber of the engine. This will be a direct consequence of the situation. The data points to the fact that this conclusion is the one that makes the most sense. The amount of gasoline that is still left in the tank has an influence on the rate at which the generator's blades slow down. As a direct consequence of this, the output stator current dropped, and within a few microseconds, the output voltage of the system became stable. Everything that took place was a direct result of running the simulation. This was made possible as a direct consequence of the stator output voltage being more consistent all throughout the system. Because of the system's capacity to keep the input voltage at a consistent level, all of this was made possible. A reduction in the amount of current that was moving through the output stator was the only thing that could have caused this event.

Conclusion

Hybrid Energy Systems comprise a wide range of energy sources for the generation of electricity in a modern community or for the generation of electricity in a rural electrification where grid extension is not possible or uneconomical. Hybrid renewable energy system has a wide range of advantages. The design and development of various Hybrid Energy System components has more flexibility for future extension and growth because the number of generation units can be increased with increase in demand so as to ensure continuous operation with existing system (Srivastava & Banerjee, 2015). Excess power generation can also be fed into the grid and this will lead to revenue generation. The hybrid energy system studied in this research work is a hybrid WTG–DG hybrid system (Wind Turbine Generator and Diesel Generating System). This is because of its optimal performance and sustainable energy solutions provided at minimum cost. The hybrid power system model developed provides continuous and reliable power supply to the end users. The output power provided by the hybrid energy system is maximized using Optimum Power Point (OPP) Tracking Techniques in order to ensure continuous power supply at maximum efficiency and optimum output power.at minimum cost. Advance control of the renewable energy micro grids using Optimum Power Point Tracking Techniques and algorithms was also established. In addition, the stability, reliability and efficiency of Hybrid Power System Models developed I this research work is higher and the running cost is lower than that of conventional power generation resources.

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