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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 depends on the amount of electrical energy consumed in the country. 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 increase crime rates in the continents. Hence, there is urgent need to establish an alternative Renewable Hybrid Power Supply System which will provide continuous, reliable and effective power supply using advance control algorithm and Maximum Power Tracking Techniques. In order to satisfy the high energy demand in residential and industrial environments, electrical energy should be reliable, affordable, effective, and sustainable. Therefore, in this research work, feasibility assessment of the study area (Iseyin Community in Oyo State, Nigeria) for the establishment of Hybrid Power System (HPS) was carried out. The operating parameters and performances of the components of the Hybrid Power System were evaluated and the HPS Simulink models were developed using MATLAB/Simulink 8.1064 (2020a) version software. The Hybrid Power System Model (HPSM) developed comprises of Wind Turbine Generator (WTG) and Diesel Generator (DG) Models. Simulation of all the developed Simulink models were carried out. The optimization process was carried out using Optimum Power Point Tracking (OPPT) Techniques and Genetic Algorithms (G.A). Design processes and control algorithms were established for the production of reliable and efficient output power from the Hybrid Power System. The need for effective and reliable power supply under the events of faults and variation of loads necessitated the need for the establishment of MPPT Techniques and Control algorithms for the HPS. The MPPT techniques and control algorithms developed in this research work provided high stability and reliability even in the events of faults and variation of loads. The Simulink and validation results obtained made it possible to generate and supply continuous, reliable, effective and stable electrical power to the consumers. Finally, the developed HPS model in this research work was found to be very useful for the establishment of Hybrid Power Plants and generation of continuous, stable and reliable electric power for the consumers.

AIM AND OBJECTIVES OF THE RESEARCH

The aim of the research is to develop a Hybrid wind and diesel Power System Models for renewable energy system and establish design processes for the renewable energy micro grids using Optimum Power Point Tracking Techniques.

OBJECTIVES OF THE RESEARCH WORK

1. To evaluate the operating parameters and performances of the components of the Hybrid Power System Model (HPSM)
2. To develop Simulink models of the HPSM using MATLAB/Simulink 8.1.0604 (2020a) version software
3. To develop an effective Hybrid Power System model with Optimum Performance using Optimum Power Point Tracking (OPPT) Techniques.
4. To establish the design process and control algorithms for the development and effective operation of the HPSM using Wind Turbine Generator (WTG) and Diesel Generator (DG) Models.
5. To synchronize the HPSM with the existing grid, validate its operation and improve the stability and reliability of the system in order to ensure continuous power supply in the country

HYBRID ENERGY SYSTEMS

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. (Shumank Deep Srivastava, 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

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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.

MAXIMUM POWER POINT TECHNIQUES (MPPT) IN A WTG

i. Power generated in the wind turbine generator can be controlled by the Tip Speed Ratio (TSR) control techniques. This is done by keeping the Tip Speed Ratio in its optimal value in a variable speed generation. Hence, the aim of this method of Maximum Power Point Techniques (MPPT) process is to determine the optimum TSR by measuring the wind speed and rotor speed using the mathematical model equation below.

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

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 optimum TSR will ensure the operation of the wind turbine generator at maximum power point. Abdullah M.A et al (2011), Kumar. K, Ramesh Babu. N, Prabhu. K. (2017)

Tip Speed Ratio (TSR) for wind turbine generator is the ratio of the product of the radius of the turbine and the angular or rotational speed of the tip of a blade to the wind velocity. Binayak Bhandari,et.al (2014); Kumar. K, Ramesh Babu. N, Prabhu. K. (2017)

i. 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 2.28. For Wind Turbine generator, coefficient of performance C_p is less or equal to 0.593

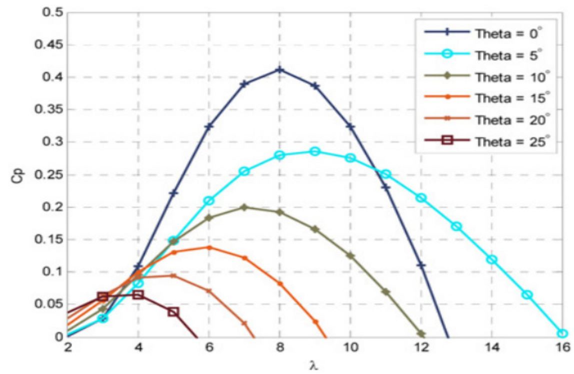

Figure 2.28 showing the coefficient of performance, C_p, and the Tip Speed Ratio λBinayak Bhandari, et. al (2014), Kumar. K, et. al . (2017)

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

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

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 2.29

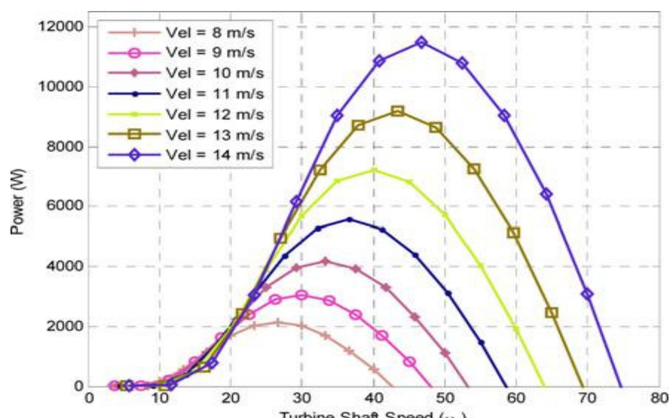

Figure 2.29: ***Wind Turbine Power Curve***

iii. 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. This is because maximum power

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point can be obtained in a varying wind speed by keeping the Tip Speed Ratio (λ) at its optimal value.

iv. 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.

v. The mechanical power of an induction machine like wind turbine generator is given as $P = \omega T$ …………………… (2.36)

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:

$$P_{wind} = \frac{1}{2}\ C_p\ \lambda\rho\ A\ V^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.37)$$

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, $\omega_{opt} = \frac{\lambda_{opt}\, V}{R}$ ……………………………………(2.41)

If the angular speed is higher than the turbine shaft speed at which maximum power can be obtained, then, the angular speed should be reduced in order to obtain the maximum output power. If the angular speed is lower than the turbine shaft speed at which maximum power can be obtained, then, the angular speed should be increased The process of changing the angular speed of the turbine in order to obtain maximum output power is called Maximum Power Point Tracking.

The output power of the wind turbine generator changes with the turbine shaft speed as shown in figures 2.30 and 2.31

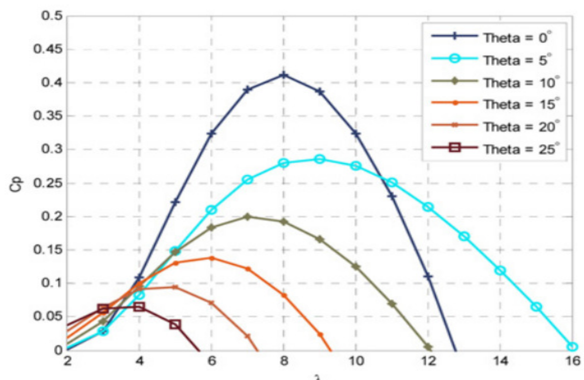

Figure 2.30: The Turbine power efficiency coefficient changes with the Tip Speed Ratio

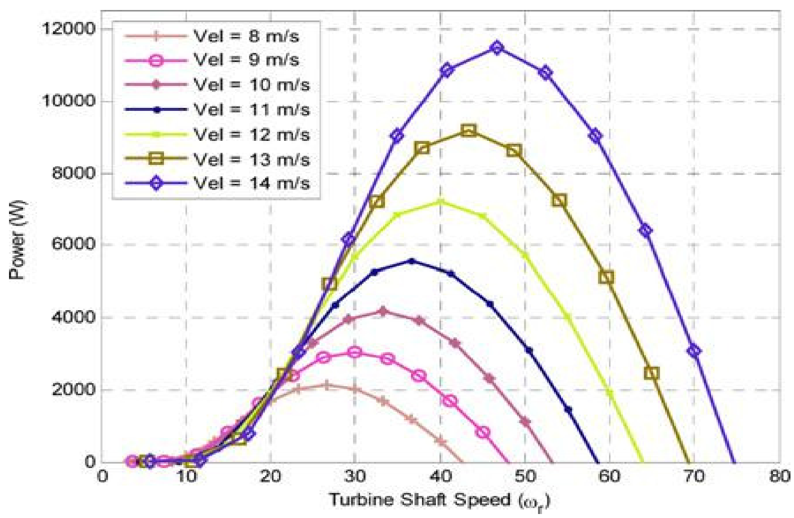

Figure 2.31: The output power of the wind turbine generator changes with the turbine shaft speed.

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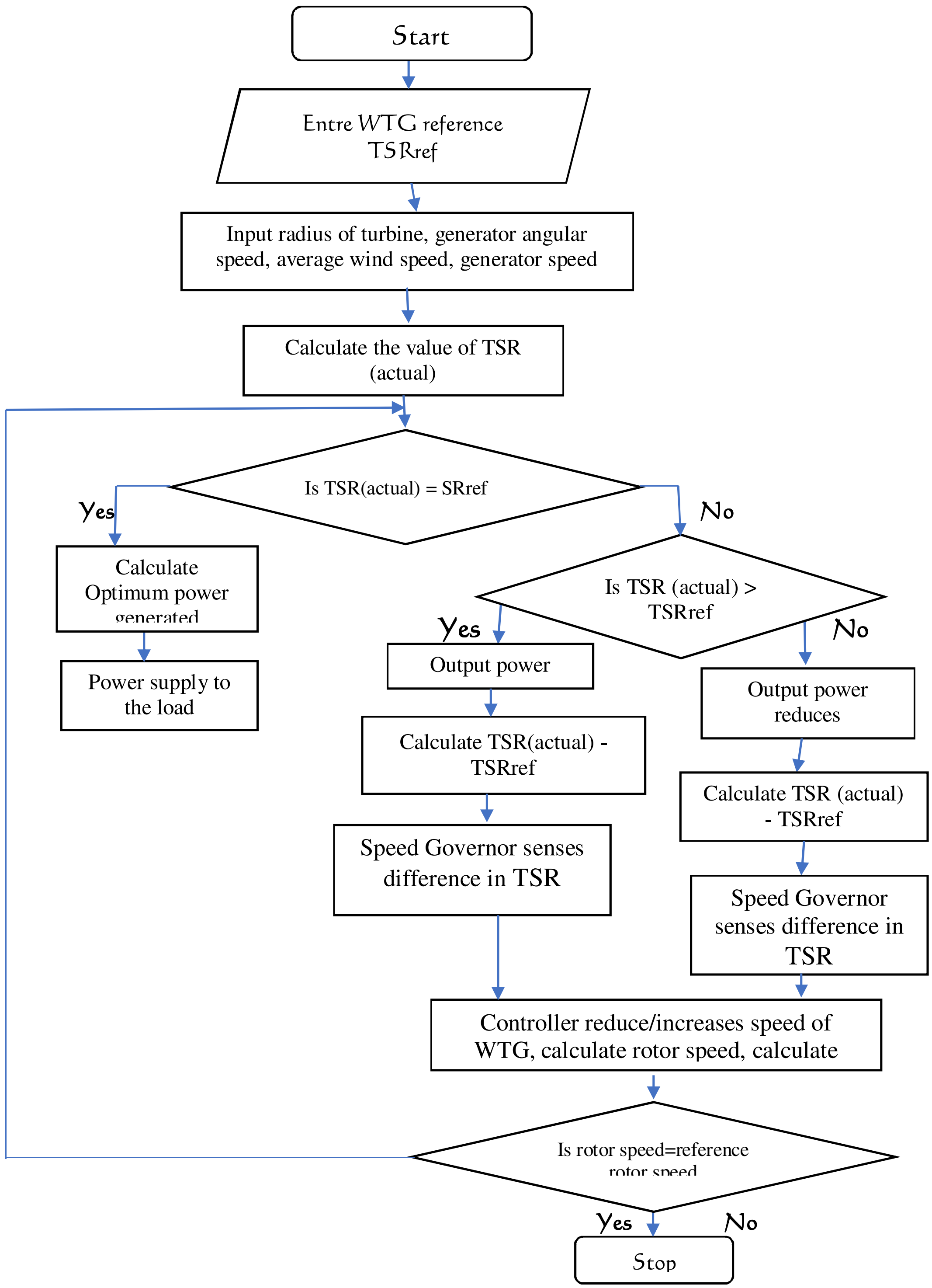
RESULTS

Figure 3.12: 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 3.29

$$\text{Optimum rotor speed} = \omega_{optimum} = \frac{\lambda_{optimum}}{R} V_{windspeed} \cdots\cdots\cdots 3.29$$

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 3.13

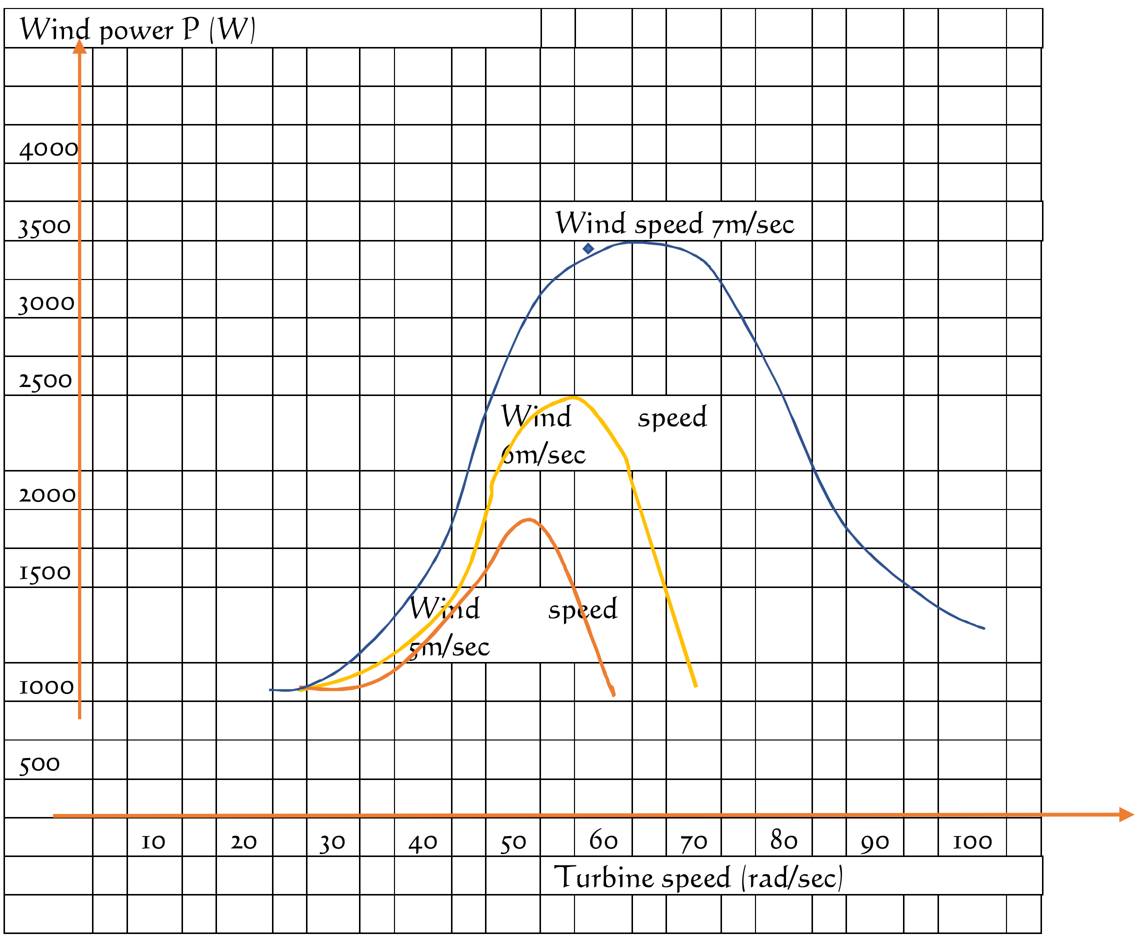


Figure 3.13: Wind Turbine Power- Rotor angular speed Characteristics

If the angular speed is higher than the reference or desired turbine shaft speed at which maximum power can be obtained, then, the angular speed should be reduced in order to obtain the maximum output power. If the angular speed is lower than the turbine shaft speed at which maximum

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power can be obtained, then, the angular speed should be increased This process of changing the angular speed of the turbine in order to obtain maximum output power is called Maximum Power Point Tracking.
Measurement of the speed of the blade is done by using tachometer. The wind speed is measured by using anemometer. The value of the TSR obtained is compared with the optimum value of the TSR which has been stated on the generator. This is done continuously and the difference is fed back into the controller which will adjust the speed of the WTG to operate at or close to the optimum value of the TSR. Maintaining optimum TSR leads to the generation of electric power in a Wind Turbine Generator at maximum point and efficiency as shown in figure 3.13.

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.

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

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

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

The tip speed ratio, angular rotor speed and output power generated is presented in table 3.6

Table 3.6: Tip speed ratio, angular rotor speed and output power of the wind turbine generator

S/N	Radius of blade(m)	ω	V	Rω	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 3.14

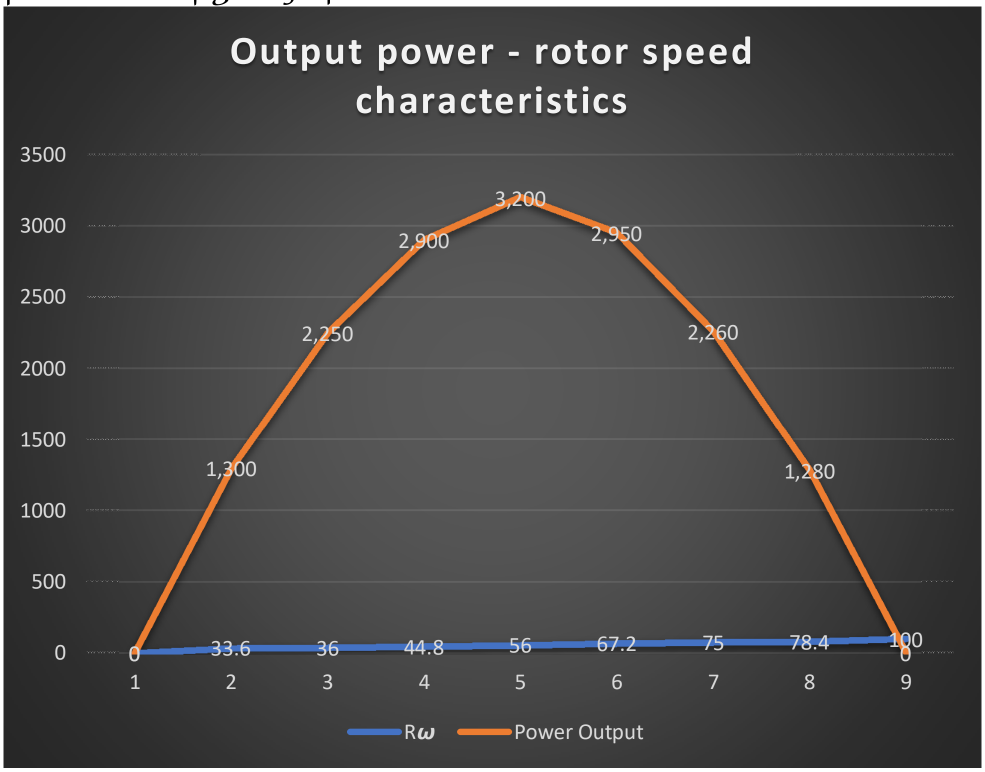

Figure 3.14: characteristics of the rotor speed and the output power generated in a wind turbine generator

a. Optimum Tip Speed Ratio Control method

Power generated in a wind turbine generator can be controlled by the Tip Speed Ratio (TSR) control technique. The aim of this method of optimization process is to determine the optimum TSR. From the optimum TSR, the optimum angular rotor speed can be obtained. Irrespective of the wind speed, optimum TSR for a given wind turbine generator is constant.

Therefore, maintaining optimum TSR will ensure optimum angular rotor speed and the operation of the wind turbine generator at maximum power point. In order to measure the measure the turbine speed and wind speed, anemometer and tachometer will be required. The TSR obtained will then be compared with the optimum value of TSR, which is already stored in the power system. The difference in the two values of TSR is fed to the controller which will adjust angular speed of the generator in order to ensure maximum power output as shown in the figure 3.16.

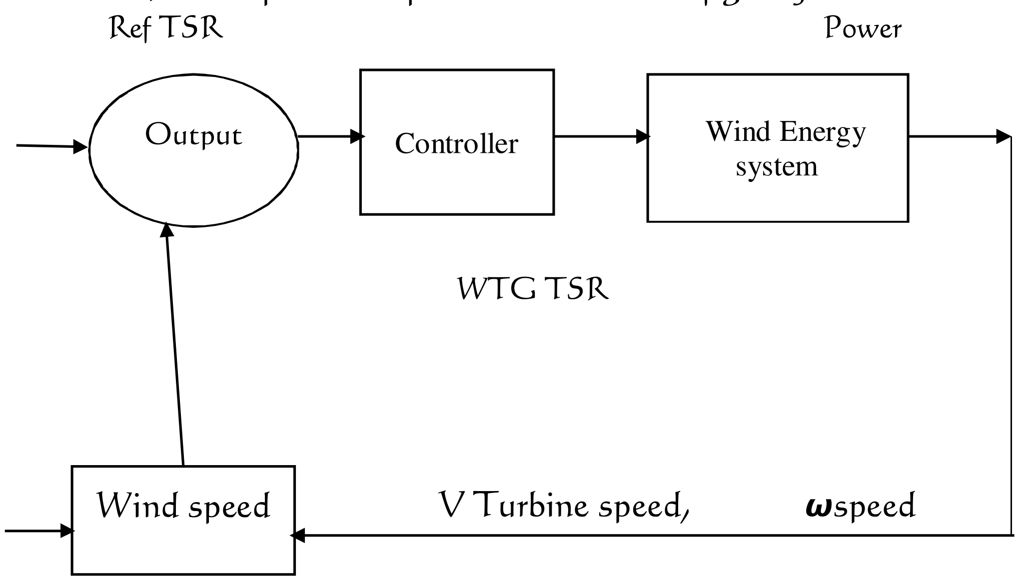

Figure 3.16: Working principle of TSR control techniques

3.26 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 3.20

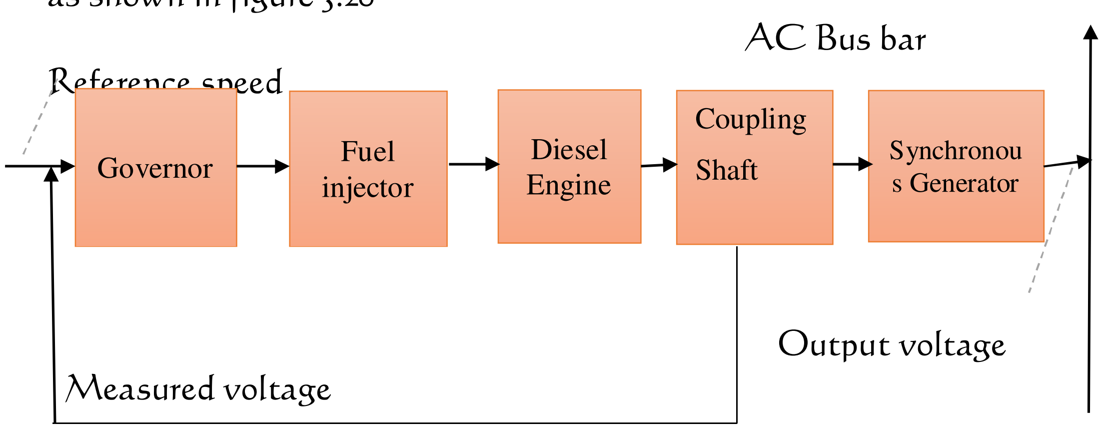

Figure 3.20: Components of Diesel Generator

3.27 Characteristics of the Fuel Supply System and the Rotor Speed

Figure 3.22 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

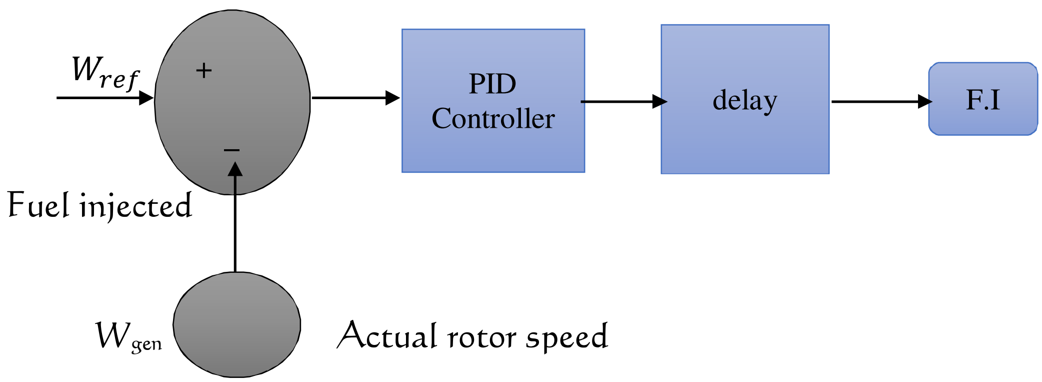

Fig. 3.22: Relationship between the reference speed of the generator (N_{ref}), actual generator speed (N_{gen}), and the fuel supply system of the generator.

In order to study the performance of the system, simulation process was carried out. The Simulink model takes excitation voltage, the rate of supply of fuel and rotor speed as input. It supplies stator output current and voltages as the output parameters. The load connected to the system was kept at 0.6 per unit, excitation voltage was kept at 0.9 per unit, the speed of the generator was kept at 0.8 per unit. The simulation process takes place in 2 seconds. Later, load connected to the generator was reduced to 0.5 per unit and speed of the rotor increases, for a few seconds. The speed governor senses this increase in speed and the difference in the reference speed and the rotor speed is fed back to the control system. Consequently, the speed governor reduces the opening of the throttle of the governor and the inflow of fuel into the combustion chamber is reduced. The reduction in the inflow of fuel reduces the speed of the generator. As a result, the output stator current reduced and the system output voltage regain stability after a very small fraction of second as shown in the simulation flow chart figure 3.23

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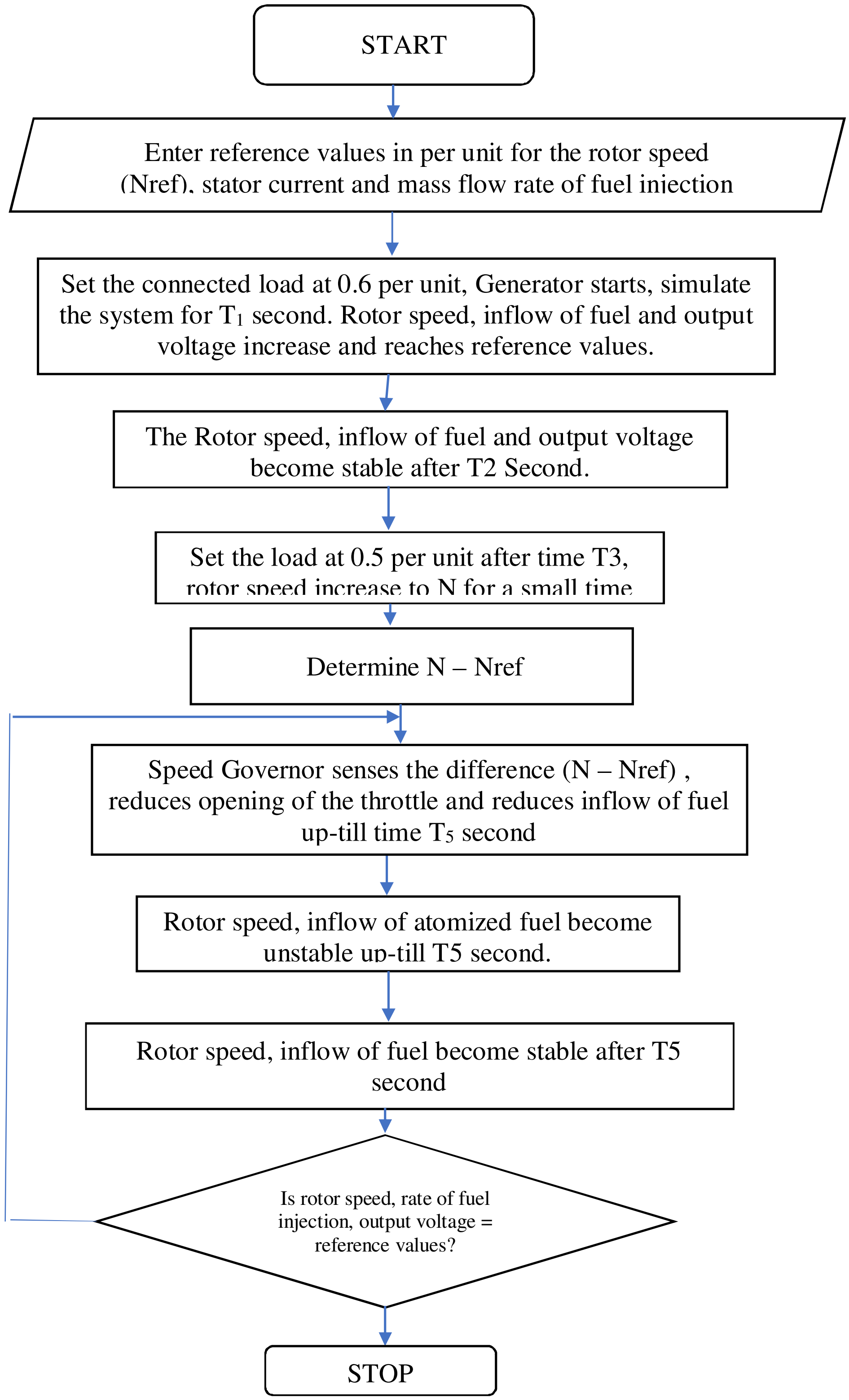
Figure 3.23: Flow Chart of the Diesel Generator Simulation Process



RESULTS

4.2.2 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 = $\omega_{opt} = \frac{\lambda_{opt}\ x\ V}{R}$

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

The tip speed ratio, angular rotor speed and output power generated is presented in table 4.2a and b

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 4.2a

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 tip speed ratio, angular rotor speed and output power generated is presented in table 4.2b

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The characteristics of the rotor speed and the output power generated is presented in figure 4.1

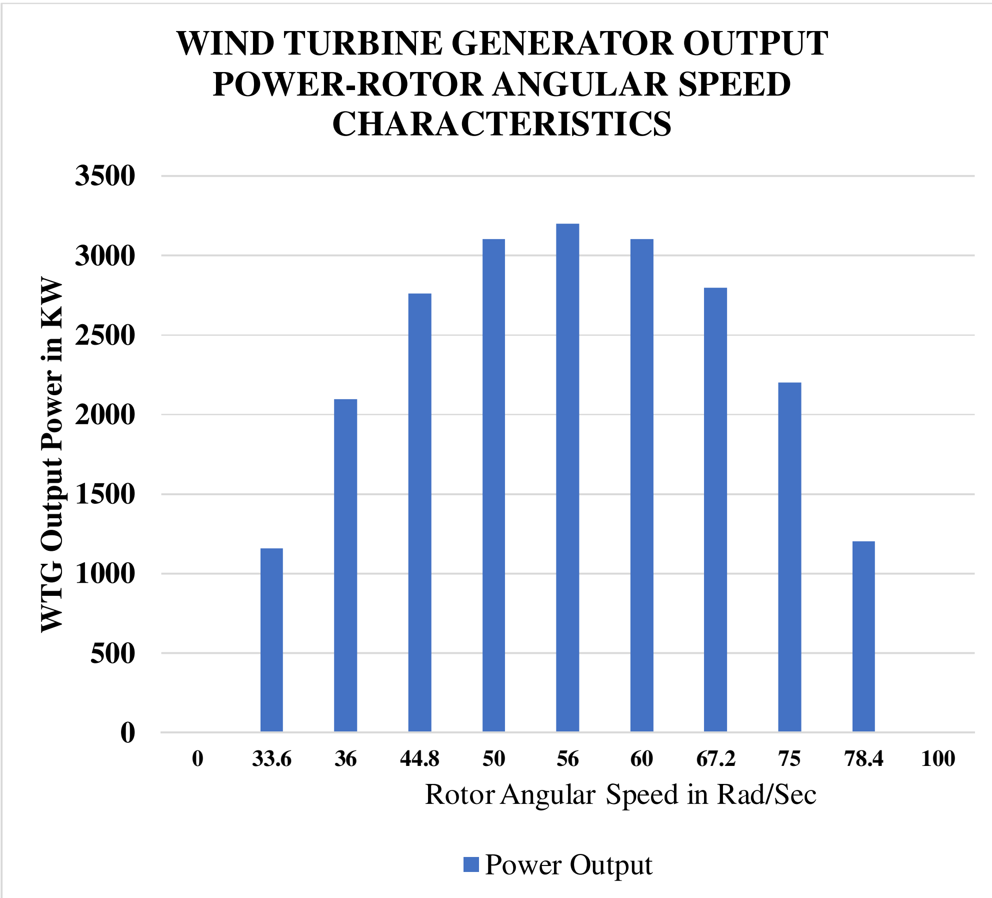

Figure 4.1: characteristics of the rotor speed and the output power generated from the wind turbine generator

Table 4.11: Parameters of the proposed 50 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	40 kVA	415 V	81.84	0.0025	2400

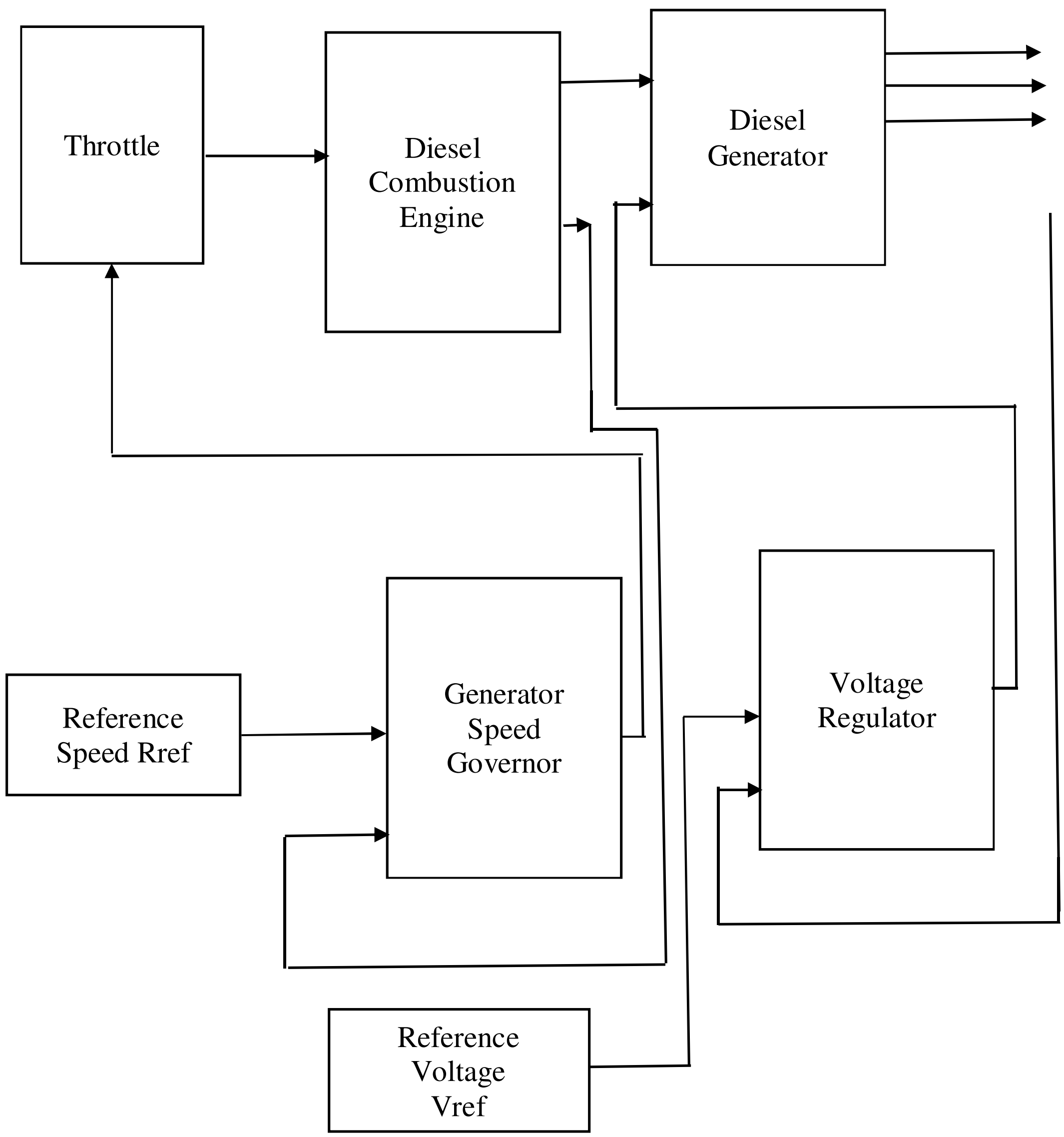

Figure 4.9: Components of Diesel Generator