

Design, Modeling, And Performance Analysis of A 10 Mw Hybrid Renewable Energy Microgrid Using MATLAB/SIMULINK

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Abstract

This paper presents the design, modeling, and simulation of a 10 MW hybrid microgrid system intended to improve electricity supply reliability in Onitsha, Nigeria. The proposed grid system integrates solar photovoltaic (PV) generation, wind energy conversion systems, battery energy storage systems (BESS), and a diesel generator backup, with the capability of operating in both grid-connected and islanded modes. MATLAB/Simulink was used to develop detailed system models and to evaluate the operational performance of the hybrid grid under varying renewable resource availability and load demand conditions. The results show that the 10 MW microgrid maintains stable voltage and frequency while ensuring efficient power management through coordinated control strategies and energy storage integration. The simulation also demonstrates improved power quality, reduced dependence on fossil fuel generation, and enhanced system resilience during disturbances. The study concludes that the deployment of a 10 MW renewable-dominated hybrid grid system offers a technically feasible and environmentally sustainable approach for improving electricity supply in rapidly growing Nigerian cities.

Keywords: *Microgrid, Renewable Energy, MATLAB/Simulink, Wind Turbine, Hybrid Power System, Grid*

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I. Introduction

Access to reliable electrical energy is a fundamental requirement for economic growth, industrial productivity, and social development. In many developing countries, particularly Nigeria, the national electricity grid has struggled to provide consistent and adequate power supply to urban and rural communities. Cities such as Onitsha, a major commercial hub in southeastern Nigeria, experience frequent power interruptions, voltage instability, and inadequate generation capacity. These challenges arise due to aging transmission infrastructure, insufficient power generation, transmission losses, and the limited integration of renewable energy technologies within the existing grid network (Okedu&Barghash, 2021).

In recent years, microgrid technology has emerged as a promising solution for improving energy access and enhancing the resilience of electricity systems. A microgrid is a localized energy system consisting of distributed generation units, energy storage devices, loads, and intelligent control mechanisms capable of operating either independently or in conjunction with the main power grid (Lasseter, 2019). Hybrid microgrids that combine renewable energy sources such as solar photovoltaic and wind turbines with conventional backup generators have demonstrated significant advantages including reduced greenhouse gas emissions, improved energy efficiency, and enhanced reliability of electricity supply (Hatziargyriou, 2020).

Nigeria possesses substantial renewable energy resources, particularly solar radiation and moderate wind potential across several regions. However, the adoption of renewable energy technologies remains relatively limited due to financial, technical, and policy constraints. Several studies have suggested that hybrid microgrids integrating renewable generation with energy storage systems could significantly reduce reliance on diesel generators while improving energy availability for residential, commercial, and industrial users (Ibrahim, Ilinca, &Perron, 2008).

The integration of battery energy storage systems (BESS) within hybrid microgrids further enhances system stability by mitigating the intermittent nature of renewable energy sources. Energy storage enables excess electricity generated during peak renewable production to be stored and utilized during periods of low generation or high demand. Advanced control strategies, such as maximum power point tracking (MPPT) for photovoltaic systems and pitch control for wind turbines, also contribute to maximizing energy extraction and improving operational efficiency (Guerrero et al., 2018).

This study therefore investigates the design and performance evaluation of a 10 MW hybrid grid system for Onitsha using MATLAB/Simulink simulation tools. The system integrates solar photovoltaic arrays, wind turbine generators, energy storage systems, and diesel generator backup units to ensure a stable and reliable electricity supply. The proposed system aims to address the growing electricity demand in Onitsha while promoting sustainable energy utilization.

II. Methodology

The development and analysis of the proposed grid system were carried out using a Model-Based Design (MBD) approach. MATLAB/Simulink served as the primary software platform for system modeling, simulation, and performance evaluation. The methodology involved modeling each subsystem of the hybrid grid and integrating them within a unified simulation framework.

A. Modeling of Microgrid Components

The proposed 10 MW grid system consists of the following subsystems:

- Renewable energy generation units
- Energy storage devices
- Power electronic converters
- Control and protection systems
- Electrical loads

Each subsystem was modeled in MATLAB/Simulink using SimPowerSystems blocks to replicate real operational characteristics of distributed energy systems.

B. Power Generation Subsystem

The primary generation sources of the hybrid grid include solar photovoltaic arrays and wind turbine generators. These renewable sources are complemented by a diesel generator that operates as a backup supply during periods of insufficient renewable generation.

C. Sizing of the 10 MW PV Array

To achieve a total generation capacity of 10 MW, photovoltaic modules rated at 300 W were considered. Multiple modules are connected in series and parallel configurations to obtain the required voltage and current levels.

The total number of modules required is calculated based on the rated power output of each module. The PV array configuration is therefore determined by selecting an appropriate DC bus voltage and arranging modules in strings to achieve the desired power capacity.

D. Maximum Power Point Tracking (MPPT)

To ensure maximum energy extraction from the PV system, a Perturb and Observe (P&O) maximum power point tracking algorithm is implemented. The MPPT controller continuously adjusts the operating voltage of the photovoltaic array in response to changes in solar irradiance and temperature.

By monitoring variations in power output and adjusting the voltage accordingly, the controller maintains operation near the maximum power point of the PV module.

E. Power Electronics Interface

Since photovoltaic modules produce direct current (DC), power electronic converters are required to interface the renewable sources with the alternating current (AC) grid.

The conversion system includes:

- A DC–DC boost converter that raises the PV output voltage to the required DC bus level.
- A three-phase DC–AC inverter that converts the DC power into AC power suitable for grid integration.

Pulse width modulation (PWM) techniques are used to regulate the switching operations of the inverter and ensure high-quality sinusoidal output voltage.

F. Wind Turbine Model

Wind turbines convert the kinetic energy of wind into electrical energy through a mechanical rotor and an electrical generator. The extracted power from wind depends on wind speed, air density, turbine swept area, and the power coefficient of the turbine.

In the proposed system, a double-fed induction generator (DFIG) is employed due to its high efficiency and ability to operate over a wide range of wind speeds. The DFIG is interfaced with the grid through back-to-back power converters that regulate rotor currents and maintain stable power output.

G. Mechanical Dynamics of the Turbine

The mechanical dynamics of the wind turbine are governed by the balance between aerodynamic torque and electromagnetic torque produced by the generator. These dynamics determine the rotational speed of the turbine rotor and directly influence the electrical power output of the wind generation system.

H. Control System Design

The microgrid control architecture manages the operation of the hybrid energy sources and ensures stable grid performance under varying load conditions. The control system includes:

- Grid synchronization using phase-locked loop (PLL) techniques
- Renewable power management
- Energy storage coordination
- Load balancing strategies

The control logic determines whether the system operates in grid-connected mode or islanded mode, depending on grid availability and local generation capacity.

I. Energy Storage System

Energy storage plays a crucial role in maintaining system stability by compensating for fluctuations in renewable energy generation. The storage system includes battery banks and supercapacitors, which provide both long-term energy storage and short-term power support.

Battery storage enables energy generated during periods of high solar irradiation or wind speed to be stored and utilized when generation decreases or load demand increases.

J. Diesel Generator Backup

A diesel generator is included in the hybrid system as a backup power source to guarantee continuous electricity supply. The generator operates automatically when renewable generation and stored energy are insufficient to meet the load demand.

The diesel generator model includes a governor control system that regulates fuel input and maintains constant engine speed to ensure stable electrical output.

K. Load Modeling

The electrical loads connected to the microgrid include residential, commercial, and industrial consumers. These loads are modeled in MATLAB/Simulink to represent real demand patterns and to analyze system performance under different operating conditions.

Demand response strategies are also incorporated to optimize energy utilization and reduce peak load requirements.

L. PV Cell Mathematica Model

A PV Cell is modeled using the single diode equation:

$$I = I_{ph} - I_0 \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) - \frac{V+IR_s}{R_{sh}} \quad (1)$$

Where

I_{ph} = Photo-generated current (A)

I_0 = Reverse saturation current (A)

q = Electron charge (1.6x10⁻¹⁹C)

V = Terminal Voltage of the PV cell (V)

R_s = Series Resistance (Ohm)

R_{sh} = Shunt Resistance (ohm)

n = Diode Identity Factor

k = Boltzmann constant (1.38 x 10⁻²³J/K)

T = Temperature (K)

II. Effect of Irradiance and Temperature

Photocurrent I_{ph} varies with solar irradiance G and temperature T given as;

$$I_{ph} = [I_{ph,ref} + \alpha_1(T - T_{ref})] \times \frac{G}{G_{ref}} \quad (2)$$

Where;

$I_{ph,ref}$ = Reference photocurrent at STC

α_1 = Temperature coefficient of current

G_{ref} = Standard irradiance (1000W/m²)

III. Reverse saturation current I_0 depends on temperature:

$$I_0 = I_{0,ref} \left(\frac{T}{T_{ref}}\right)^3 \exp \left[\frac{qE_g}{nk} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \quad (3)$$

Where E_g is the bandgap energy of silicon (1.12 eV).

C. Sizing the 5MW PV Array

The PV array consists of multiple modules connected in series and parallel.

Using a 300W PV module whose

$$V_{mpp} = 40V \text{ and } I_{mpp} = 7.5A$$

The required number of modules can be determined as;

Total power required is given as

$$P_{array} = 10MW = 10,000kW$$

The number of modules required is given

$$N_{total} = \frac{P_{array}}{P_{module}} = \frac{10000}{0.3} = 33,333 \quad (4)$$

String voltage selection is given as 1000 VDC

The number of modules per string is given as VDC

String voltage selection is assumed to be 1000 VDC

The number of modules per string can be determined using the equation below;

$$N_s = \frac{V_{DC}}{V_{mpp}} = \frac{1000}{40} = 25 \quad (5)$$

The number of parallel strings can be obtained

$$N_p = \frac{N_{Total}}{N_s} = \frac{33333}{25} = 1333 \quad (6)$$

Thus, the array configuration is 255 x 667P (25 modules in series, 667 parallel strings).

D. MPPT Algorithm

Table 1: Parameters for your 10 MW System

| S/N | Parameter | Value |
|-----|---------------------|----------------|
| 1 | Total PV capacity | 10 MW |
| 2 | PV module rating | 300 W |
| 3 | Total modules | 33,333 modules |
| 4 | Modules per string | 25 |
| 5 | Parallel strings | 1333 |
| 6 | Array configuration | 25S x 1333P |
| 7 | DC Bus Voltage | 1000 V |

The maximum power point tracking (MPPT) is used to extract maximum power. The P & O algorithm follows these steps:

First, to measure $V(k)$ and $P(k)$ at time k .

Second, compare power $P(k)$ with the previous power $P(k - 1)$.

Thirdly, if $P(k)$ is greater than $P(k - 1)$, increase the voltage, if slope $\frac{dP}{dV} > 0$,

and decrease the voltage if $\frac{dP}{dV} < 0$.

$$\text{If } P(k) < P(k - 1) \quad (7)$$

Reverse the voltage change direction to ensure the PV system operates at its maximum power point (MPP).

E. Power Electronics Conversion

To integrate the PV array with the grid system, the DC output will be converted to AC using power electronics.

DC – DC Boost Converter: The boost converter raises the PV voltage to the desired DC bus level, such as 1000V; that is;

$$V_0 = \frac{V_{in}}{1-D} \quad (8)$$

Where D is the duty cycle.

DC – AC Inverter: The three-phase inverter converts DC to AC using sinusoidal PWM (SPWM)

$$V_{ac} = M \times V_{dc} \quad (9)$$

Where M is the modulation index

I. PV Module

A generalized PV model is built using Matlab/Simulink to illustrate and verify the nonlinear I-V and P-V output characteristics of the PV module.

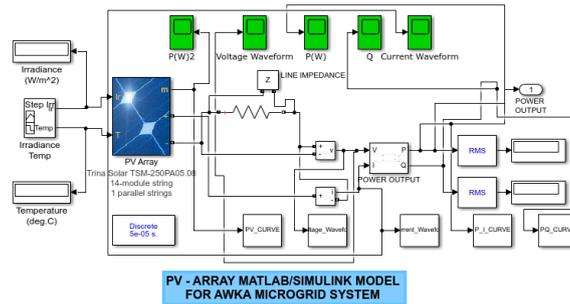


Figure 1: Matlab/Simulink Model of the PV Array

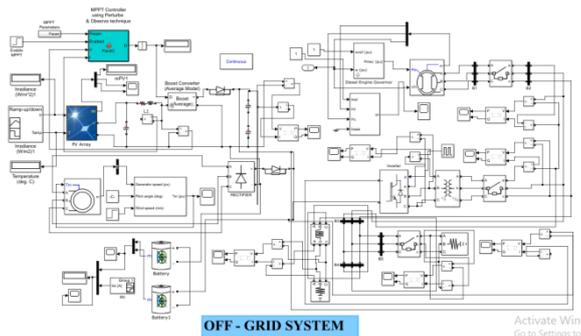


Figure 2: Modified Matlab/Simulink R2018a 10MW Enugu OFF-GRID Model Block (Matlab R2018a)

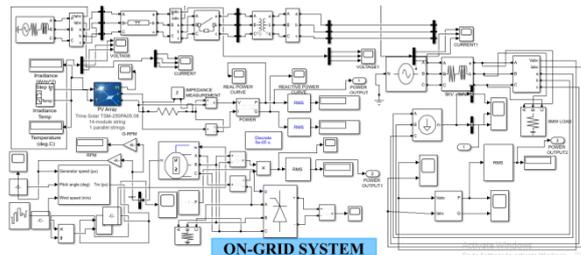


Figure 3: Modified Matlab/Simulink R2018a 3MW Enugu ON-GRID Model Block (Matlab R2018a)

The Simulink model of the PV module is shown in Figure 3.1 and 3.2. The behavior of photovoltaic (PV) cells can be modeled with an equivalent circuit that includes a photocurrent source, a single diode junction, a series resistance, and a shunt resistance.

II. Wind Turbine Model

The wind turbine is composed of a rotor, a generator, three blades, and a drive train. In case of high wind speed, the generator output power is controlled by adjusting the pitch angle.

Wind Turbine Model is such that;

$$P_w = \frac{1}{2} \rho A W_m^3 C_p(\lambda, \beta) \quad (10)$$

P_w = Power extracted from the wind (W)

ρ = Air density (kg/m³)

A = Swept Area of the turbine blade (m²)

W_m^3 = Wind Speed (m/s)

C_p = Power Coefficient

$$\lambda = \text{Tip - speed ratio} = \frac{\omega_r R}{W_m} \quad (11)$$

β = Blade pitch angle (in degrees)

III. Mechanical Dynamics of the Wind Turbine

$$J \frac{d\omega_r}{dt} = T_m - T_e - B\omega_r \quad (12)$$

J = Inertia of the turbine and generator (kg-m³)

T_m = Mechanical torque from the turbine (N-m)

T_e = Electrical Torque from generator (N-m)

B = Frictional Coefficient

ω_r = Rotor Speed (rad/s)

IV. Double-fed Induction Generator (DFIG) Model

The stator and rotor voltage equations in the synchronous reference frame (dq-frame) are given as follows:

$$V_{ds} = R_s I_{ds} + \frac{d\phi_{ds}}{dt} - \omega_s \phi_{qs} \quad (13)$$

$$V_{qs} = R_s I_{qs} + \frac{d\phi_{qs}}{dt} + \omega_s \phi_{ds} \quad (14)$$

$$V_{dr} = R_r I_{dr} + \frac{d\phi_{dr}}{dt} - (\omega_s - \omega_r) \phi_{qr} \quad (15)$$

$$V_{qr} = R_r I_{qr} + \frac{d\phi_{qr}}{dt} + (\omega_s - \omega_r) \phi_{dr} \quad (16)$$

Where, V , I , R_s , R_r and ϕ are voltage, current, stator resistance, rotor resistance and flux linkage respectively.

The electromagnetic torque equation for the turbine and generator model is given as;

$$T_e = \frac{3P}{2} (\phi_{ds} I_{qs} - \phi_{qs} I_{ds}) \quad (17)$$

Then,

The Power Converter Model is given as;

$$P_s = V_{ds} I_{ds} + V_{qs} I_{qs} \quad (18)$$

$$Q_s = V_{qs} I_{ds} - V_{ds} I_{qs} \quad (19)$$

Power is transmitted to the grid through a power electronic interface. A wind turbine extracts kinetic energy from the wind blowing through the blades. The Simulink model of a wind turbine equation is shown in figure 3.2.

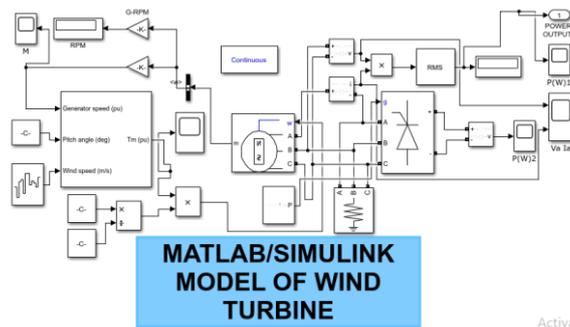


Figure 3.3: Matlab/Simulink Model of the Wind Turbine Block

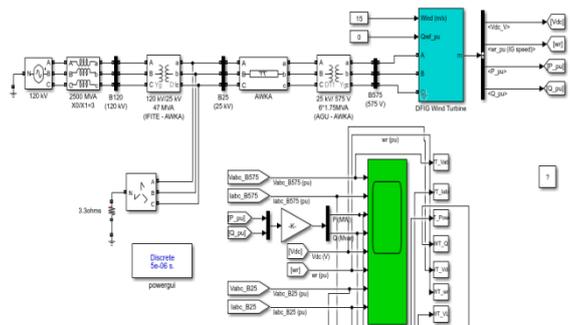


Figure 3.4: Modified Matlab/Simulink Model of the Wind Turbine Block (Matlab R2018a)

IV. Control System

Design an Inverter with Pulse Width Modulation (PWM) for DC-AC conversion. Implement Grid Synchronization (PLL-based control) for grid-tied operation. In order to operate the Micro-Grid in grid-connected mode or off-grid mode, a simple control logic circuit is designed in Matlab/Simulink in figure 10. In the on-grid system, when Power output from renewable greater than load power, excess power is exported to grid sell block and when renewable output less than load power, grid purchase block used. In the off-grid

system, when Power output from renewable greater than load power, batteries operate and excess energy stored in it's and when renewable output less than load power, diesel generator used to cover this shortage.

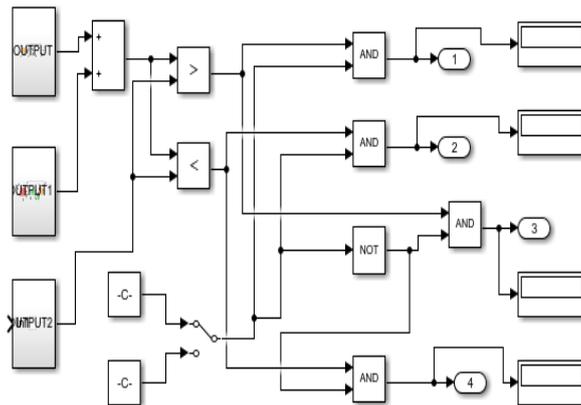


Figure 4: ENUGU 10MW MATLAB/Simulink Control Model

V. Inverter Controller Model

Inverter or power inverter is a device that converts the DC sources to AC sources. Power inverters produce one of three different types of wave output: Square Wave Modified Square Wave (Modified Sine Wave) and Pure Sine Wave (True Sine Wave)

The three different wave signals represent three different qualities of power output. Square wave inverters result in uneven power delivery that is not efficient for running most devices. Modified square wave (modified sine wave) inverters deliver power that is consistent and efficient enough to run most devices fine while sensitive equipment requires a sine wave. Figure 3.6 shows Model of Inverter block Matlab/ Simulink.

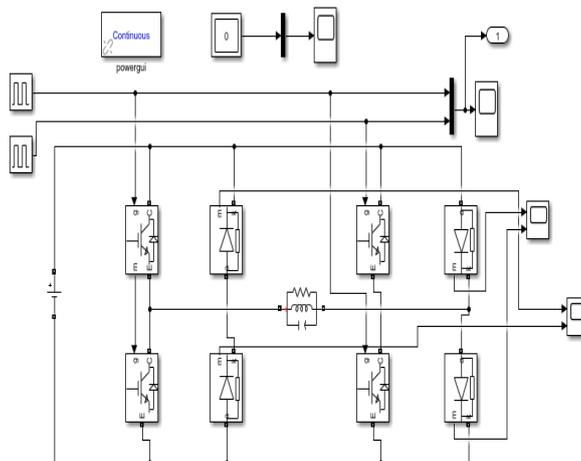


Figure 5: MATLAB/Simulink Inverter Block Model

VI. Energy Storage System (ESS)

The energy storage system involves the design a battery management system (BMS) for SoC control and Implementation of the Battery Model with a bidirectional DC-DC converter.

The electricity demand fluctuates depending on the time of the day and the time of a year. Since the traditional power grid is not able to store up electricity, the mismatch between supply and demand is more likely observed. As the concept of Micro-grid is becoming more pervasive, a mixed power system makes the best use of the different types of local generation. Some forms of generations have large response time and others have little flexibility in operation. In addition, some forms of generations can start up very quickly to provide more or less energy depending on the real-time load demand pattern. Provided these reasons clearly, the energy storage is beneficial in managing such a system. A desired form of energy storage is expected to provide the required power into the power system and store up sufficient energy at low electricity consumption. Two types of short-term storage are studied and modeled: Storage batteries, and Super-capacitor (Fouad M. A., et al 2017 and Jordi S. L. 2017).

VII. Battery Bank

There are several approaches to model a battery. A commonly used battery model is the Thevenin equivalent circuit. In this case Simulink implements set of predetermined charge behavior for four types of battery: Lead-Acid, Lithium-Ion, Nickel-Cadmium and Nickel-Metal- Hydride. Figure 3.7 illustrates a detailed modeling of charge & discharge battery in Matlab/Simulink.

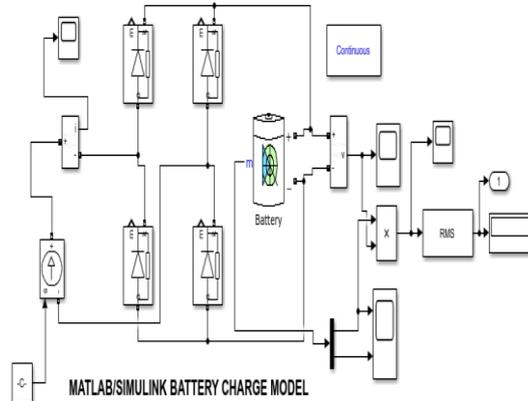


Figure 6: MATLAB/Simulink Charge Battery Model

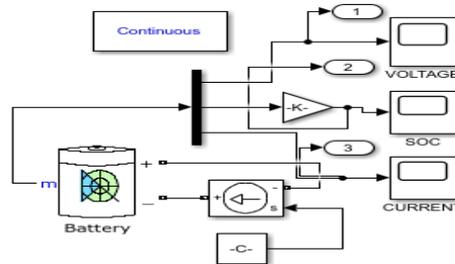


Figure 7: MATLAB/Simulink Discharge Battery Model

VIII. Super-Capacitor

The Super-capacitor, also known as ultra-capacitor, is the electrochemical capacitor that has higher energy density than common capacitors on the order of thousands of times. The equivalent circuit used for conventional capacitors can also be applied to super-capacitors.

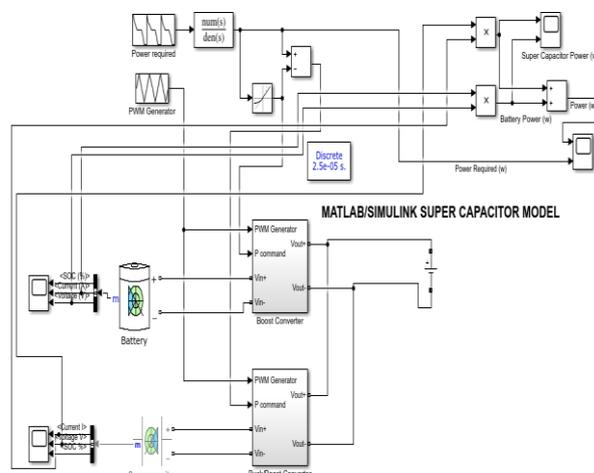


Figure 8: MATLAB/Simulink Super-Capacitor Block Model/Simulink

If the simulation time is much larger than the self-discharge time, the equivalent parallel resistance might be neglected as well. The actual capacity C varies with quantities as current, voltage and temperature. Equations of RL & RC circuits are shown in. Figure 3.9 illustrates modeling of super-capacitor block

IX. Diesel Generator Model

Diesel Engines; both spark ignition, (SI) and compression ignition (CI), were first among distribution generator technologies. The Diesel Engine model gives a description of the fuel consumption rate as a function of speed and mechanical power at the output of the engine, and is usually modeled by a simple first order model relating the fuel consumption to the engine mechanical power. The power output of the engine and the generator varies according to load in order to meet the demand.

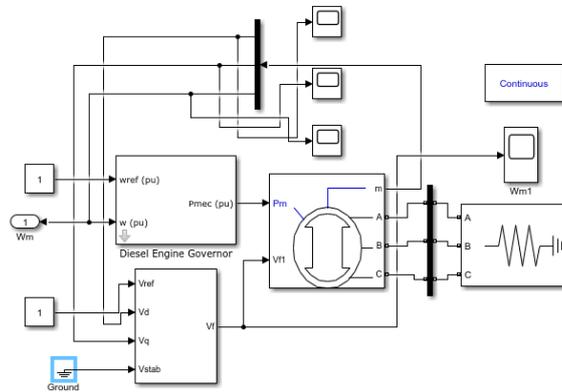


Figure 9: MATLAB/Simulink Diesel Engine Model for Enugu Grid System

The governor can be defined as a mechanical or electromechanical device for automatically controlling the speed of an engine by relating the intake of the fuel. The task of the governor is to adjust the fuel flow and then regulate the input of the engine and generator, hence provides the required power to meet the change in the load. Several types of governors exist such as mechanical, electronic, microprocessor based and others. Figure 3.10 illustrates the diesel engine model in Matlab/Simulink.

X. Loads

Load Modeling & Demand Response involves definition or identification of different loads (household, industrial) and Implementation of demand side management (DSM) using fuzzy logic or artificial intelligence (AI).

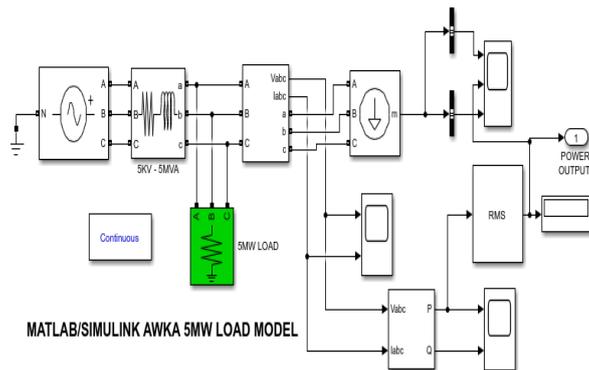


Figure 10: MATLAB/Simulink Diesel Engine Model for Awka Grid System

XI. Protection Devices

Fault Detection & Protection (AI-based predictive maintenance).

F. Performance Analysis & Results

In this section, the performance of power flow & voltage profile analysis using SimPowerSystems blocks of MATLAB/Simulink. Dynamic response responses to faults and transient stability were observed. Also, harmonic analysis & power quality performance was analyzed using FFT analysis in Simulink.

6. RESULTS AND ANALYSIS

7 Simulation Results and analysis of the PV Array Power Curve

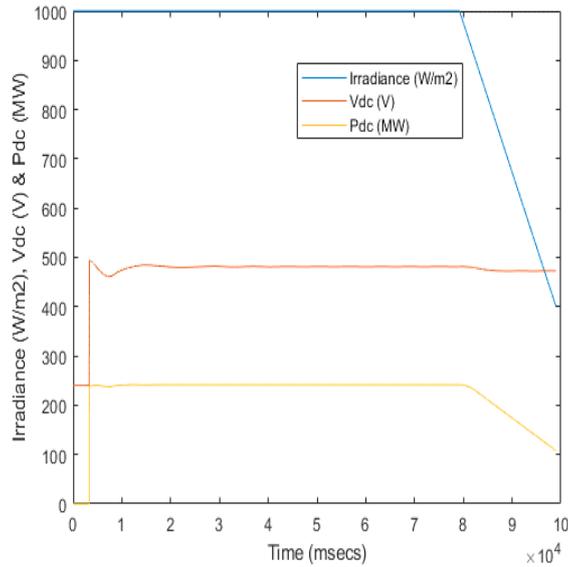


Figure 11: PV Power Waveform of PV Array

A. PV Power (250MW DC)

This is the total DC power output of a large scale photovoltaic (PV) power plant. Generated before conversion to AC through inverters for grid integration. The powerformulashow thatsuch a high-power system consists of multiple PV modules connected in series (to increase voltage) and parallel (to increase current). The AC output (after inverter conversion) is slightly lower due to efficiency losses (~95%-98%).

B. DC Voltage (500V DC)

This is the operating voltage of the solar array. It is achieved by connecting multiple solarpanels in series. Higher voltage reduces resistive losses in cables. Figure 4.1 – 4.3 were obtained when the figure 3.2 is simulated.

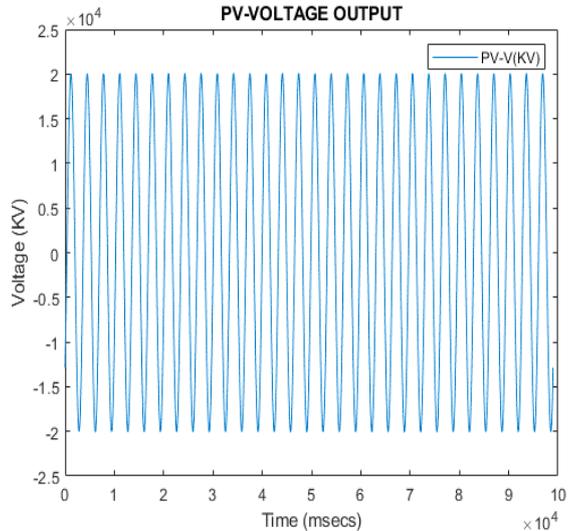


Figure 11: PV Voltage Waveform of PV Array

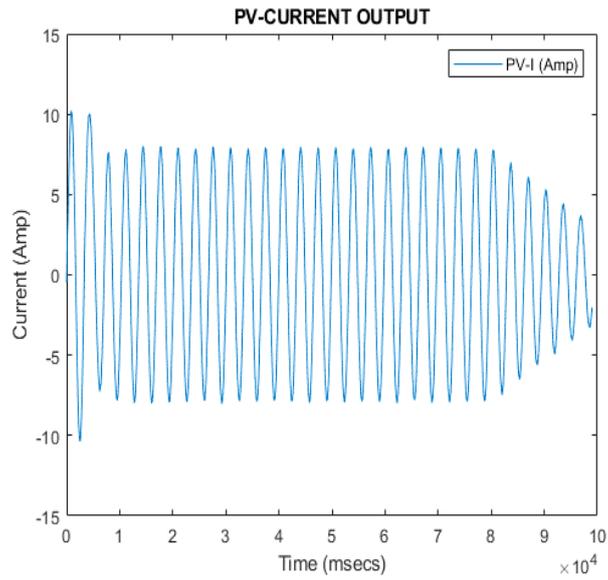


Figure 12: PV Current Waveform of PV Array

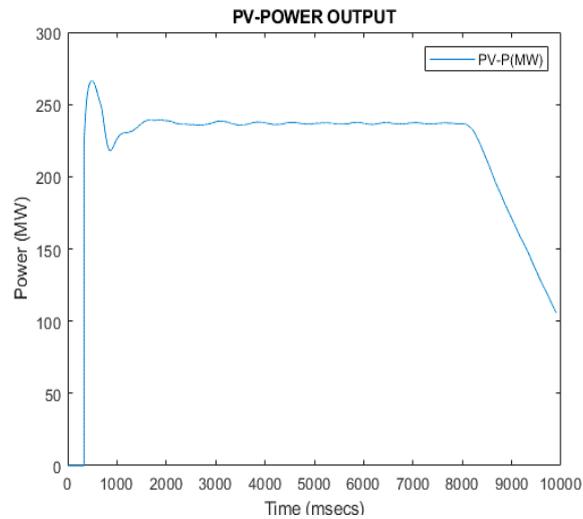


Figure 13: PV Power Output of PV Array

4.2 Simulation Results and Analysis of the Wind Power Curve

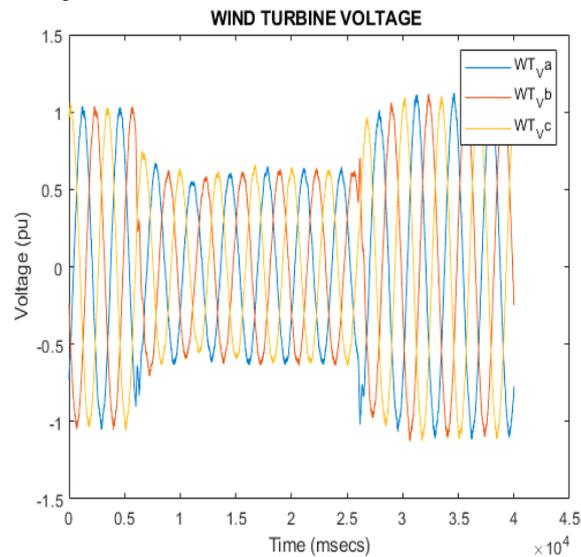


Figure 14: Wind Turbine Voltage Waveform

The wind turbine voltage is maintained at approximately 1.0 p.u., while the current is about 0.8 p.u. These values represent normalized quantities based on the rated capacity of the 10 MW hybrid grid system. A per-unit current value lower than 1.0 indicates that the turbine is operating slightly below its rated load condition, which is typical when wind speed varies or when the system demand is lower than the maximum generation capacity.

The active power output of the wind turbine reaches a peak value of approximately 3 MW within the hybrid generation system. This represents the electrical power delivered from the wind energy conversion system to the grid. The amount of active power generated depends primarily on the wind speed, the aerodynamic efficiency of the turbine blades, and the electrical characteristics of the generator. Since the total generation capacity of the system is 10 MW, the wind subsystem contributes a portion of the total power, while the remaining power is supplied by the photovoltaic array and other supporting sources.

The reactive power output reaches a peak value of approximately 1 MVAR. Reactive power does not contribute directly to useful work but plays an important role in maintaining voltage stability and improving the overall power factor of the system. Adequate reactive power support is necessary to ensure proper voltage regulation and stable operation of the hybrid grid.

The DC link voltage is approximately 1200 V. This voltage is produced by the back-to-back power electronic converter used in the wind energy conversion system. The converter first rectifies the variable-frequency AC output of the generator into DC and then inverts it back into grid-synchronized AC power suitable for integration into the electrical network.

The wind speed used in the simulation is approximately 12.2 m/s, which lies within the operational range of most modern wind turbines. Typical wind turbines begin generating power at wind speeds of about 3 m/s (cut-in speed) and reach their rated output at wind speeds between 10 m/s and 15 m/s. Therefore, the selected wind speed is appropriate for achieving significant power output while remaining within the safe operating limits of the turbine.

Reasons for Fluctuations in Voltage and Current Signals. Wind Speed Variability Changing wind speeds directly impact power generation. Grid Disturbances Voltage variations in the grid cause fluctuations. Power Converter Switching High-frequency switching in converters introduces small fluctuations. Mechanical Vibrations Imbalances in the rotor affect power stability. Load Changes Sudden changes in connected loads alter power flow. Control System Delays Turbine response to wind and grid changes is not instantaneous. Figures 4.4 – 4.9 were obtained when Figure 3.4 was simulated.

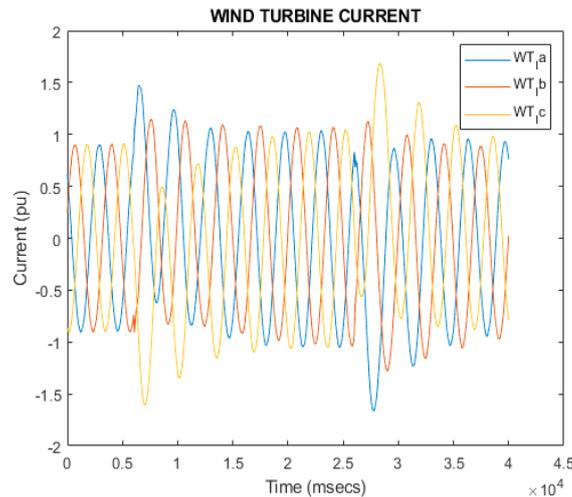


Figure 15: Wind Turbine Current Waveform

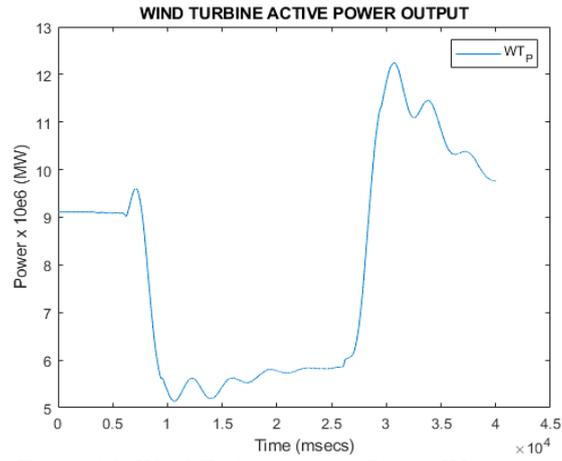


Figure 16: Wind Turbine Active Power Waveform

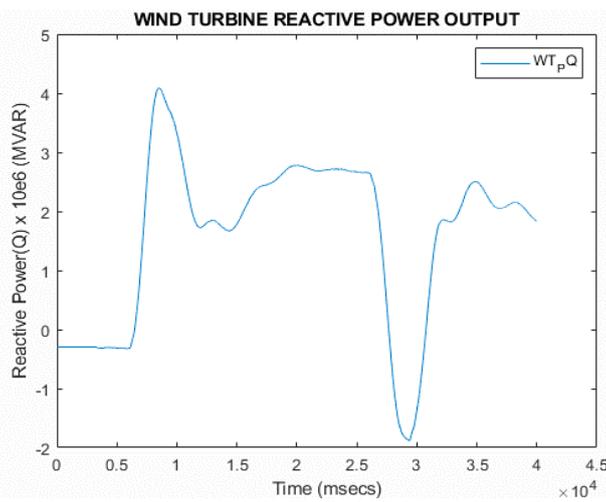


Figure 17: Wind Turbine Reactive Power Waveform

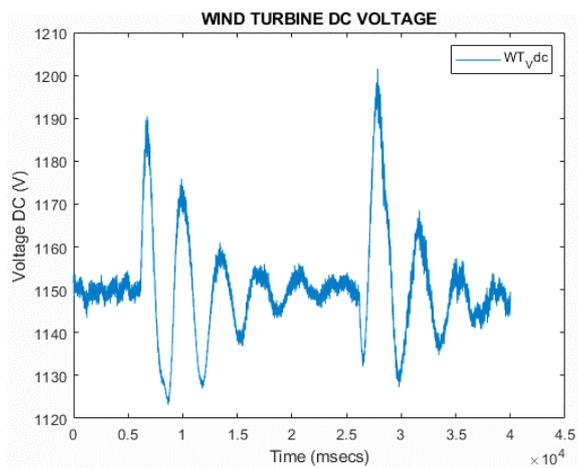


Figure 18: Wind Turbine DC Voltage Waveform

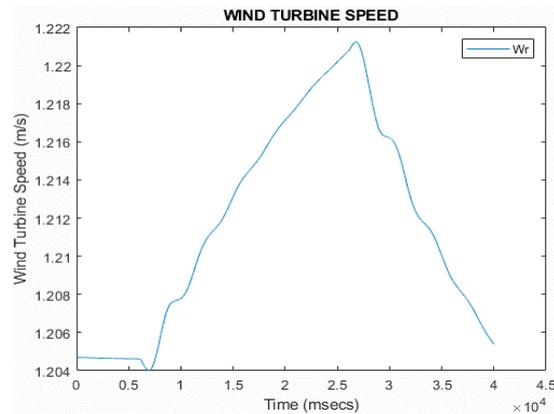


Figure 19: Wind Turbine Speed Waveform

Table 2: Simulation results, Parameters for Enugu Micro Grid System

| S/N | Parameters | PV | Wind Turbine (WT) |
|-----|--------------------------------|------|-------------------|
| 1 | Voltage (dc) kV | 20 | - |
| 2 | Irradiance (W/m ²) | 1000 | - |
| 3 | Voltage (V) | 500 | - |
| 4 | Power (MW) | 250 | - |
| 5 | V _{abc} (pu) | - | 1.0 each |
| 6 | I _{abc} (pu) | - | 0.8 each |
| 7 | Active Power (MW) | - | 12 |
| 8 | Reactive Power (MVAR) | - | 4.0 |
| 9 | Voltage DC (V) | - | 1200 |
| 10 | Speed (Wr) | - | 122 |

The simulation results obtained from the MATLAB/Simulink model demonstrate the operational performance of the 10 MW hybrid grid system under varying renewable generation and load demand conditions.

The photovoltaic array simulation shows that the system is capable of producing stable DC power output which is subsequently converted into AC power through the inverter system. The voltage and current waveforms indicate proper operation of the PV modules under standard operating conditions.

Similarly, the wind turbine simulation results illustrate that the turbine produces variable electrical power depending on wind speed variations. The integration of power electronic converters ensures that the generated power is compatible with the grid frequency and voltage requirements.

The energy storage system contributes to maintaining voltage stability by absorbing excess power during peak generation periods and supplying stored energy during power deficits.

Overall, the simulation confirms that the proposed 10 MW hybrid grid system can effectively maintain power balance, improve reliability of electricity supply, and enhance power quality in the distribution network.

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