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Design and Analysis of A 5MW Grid System: A Case Study of Enugu Metropolis

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Abstract- This study presents the design, simulation, and performance evaluation of a 5MW microgrid for Enugu, Nigeria, aimed at delivering a sustainable, reliable, and cost-effective power solution. The proposed microgrid integrates solar photovoltaic (PV) panels, wind turbines, battery energy storage systems (BESS), and diesel generators, with grid interconnection to ensure an uninterrupted energy supply and reduced reliance on fossil fuels. Detailed MATLAB/Simulink simulations were conducted to assess system performance under varying load demands and renewable energy availability. The results demonstrate the microgrid's capability to maintain voltage and frequency stability, optimize power generation, and effectively manage dynamic load requirements. Variability in renewable generation, grid disturbances, and system losses were mitigated through advanced control strategies, energy storage optimization, and load-balancing techniques. The study also provides recommendations for optimal renewable resource allocation, enhanced energy storage deployment, smart inverter integration, and economic feasibility, including pilot implementation and funding strategies. The findings underscore the 5MW Enugu Microgrid as a resilient, environmentally sustainable, and economically viable solution to meet the region's increasing electricity demand while promoting renewable energy adoption.

Keyword: Microgrid, Wind Power, Stability, MATLAB/Simulink, Power, Generation

I. INTRODUCTION

Reliable, affordable electricity is vital for socio-economic progress in both developed and Reliable and affordable electricity is essential for socio-economic development in both developed and developing countries. In Nigeria, cities such as Enugu, the capital of Enugu State, experience frequent power outages, voltage fluctuations, and insufficient supply despite growing population and urbanization. These challenges are largely due to aging grid infrastructure, limited generation capacity, weak transmission and distribution networks, and inadequate reactive power support, all of which compromise the grid's ability to meet demand (Agupugo & Tochukwu, 2022).

Globally, microgrids are emerging as decentralized, resilient energy systems capable of alleviating grid stress and expanding energy access. Typically, a microgrid integrates distributed generation sources (e.g., solar PV, wind turbines), energy storage, advanced control systems, and the capability to operate autonomously or in conjunction with the main grid. Hybrid microgrid configurations, particularly in remote or underserved areas, have demonstrated reduced costs, improved reliability, and lower environmental impacts (Jarso, Jin, & Ahn, 2025; Mishra et al., 2025).

In Nigeria, remote and peri-urban communities face high diesel generation costs, unreliable grid supply, and limited solutions that align with local renewable energy potential and community demand profiles. Economic analyses of renewable microgrids, such as studies in Imufu, Nigeria, indicate potential cost savings and environmental benefits but also highlight high initial capital investment alongside regulatory and technical challenges (Agupugo & Tochukwu, 2022). Enugu, benefiting from favorable insolation and solar energy potential, has seen limited deployment of solar-dominated or hybrid microgrid systems. Reliable electricity is especially critical for essential services, including hospitals, schools, and small industries, where current reliance on diesel generators or prolonged outages is high. Incorporating renewable energy storage technologies, such as battery energy storage systems (BESS), alongside smart energy management strategies can mitigate generation variability and reduce dependence on fossil fuel-based backups (Khamharnphol et al., 2023).

II. METHODOLOGY

The method used in designing and simulating the microgrid system is the Model-Based Design (MBD). This involves using MATLAB/Simulink for the modeling and simulation.

A. Modeling of the Microgrid Components using MATLAB/Simulink

As mentioned in chapter two, the components of the Microgrid system includes Distributed energy sources (the PV Modules, Generator Supply and Battery Source), Control systems, Energy Storage devices, Loads, and Protection Devices (manual and/or motor-actuated).

B. Power Generation Subsystem

Photovoltaic (PV) Model with MPPT controller.

Add Wind Turbine Model (DFIG/PMSG) and connect to a converter.

I. PV Cell Mathematica Model

A PV Cell is modeled using the single–diode equation:

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

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;

$$I_{ph} = \left[I_{ph,ref} + \alpha_I(T - T_{ref})\right] \text{ x } \frac{G}{G_{ref}} \quad (2)$$

Where;

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

α_I = Temperature coefficient of current

G_{ref} = Standard irradiance (1000W/m^2)

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 and I_{mpp} = 7.5A

The required number of modules can be determined as;

Total power required is given as

$$P_{array} = 5MW = 5000kW$$

The number of modules required is given

$$N_{total} = \frac{Parray}{Pmodule} = \frac{5000}{0.3} = 16667 \quad (4)$$

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

$$N_P = \frac{N_{Total}}{N_S} = \frac{16667}{25} = 667 \qquad (6)$$

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

D. MPPT Algorithm

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 $\frac{dP}{dV} < 0$.

If P(K) < P(k - 1) (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;

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

Where D is the duty cycle.

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

$$V_{ac} = M \, x \, V_{dc} \qquad (9)$$

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.

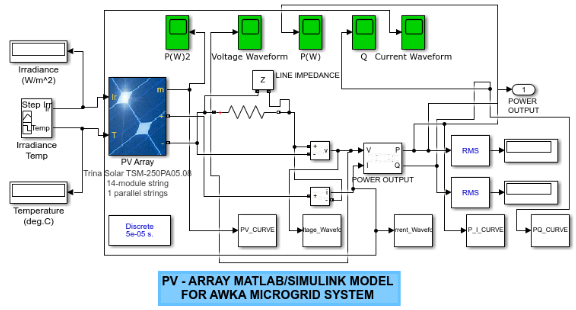

Figure 1: Matlab/Simulink Model of the PV Array

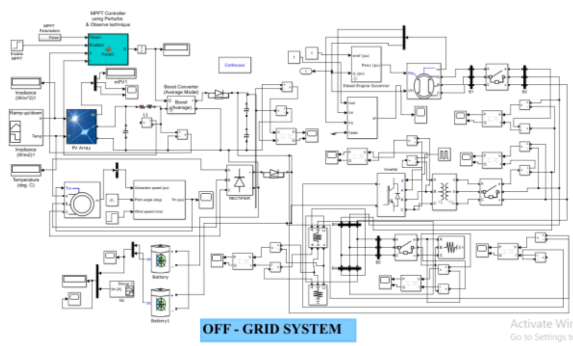

Figure 2: Modified Matlab/Simulink R2018a 5MW Enugu OFF-GRID Model Block (Matlab R2018a)

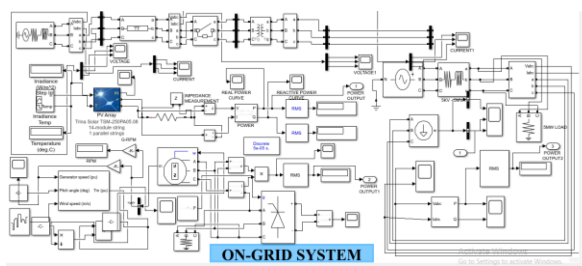

Figure 3: Modified Matlab/Simulink R2018a 5MW Enugu ON-GRID Model Block (Matlab R2018a)

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/m^3)

A = Swept Area of the turbine blade (m^2)

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-m^3)

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:

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

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

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

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

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;

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

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.

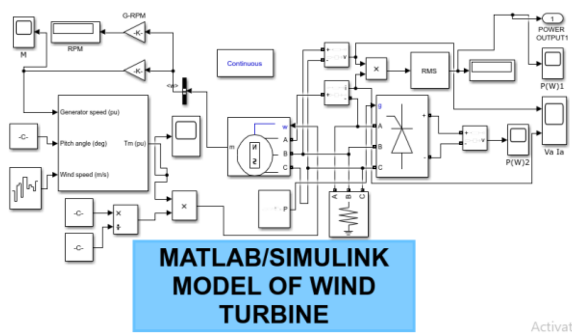

Figure 3.3: Matlab/Simulink Model of the Wind Turbine Block

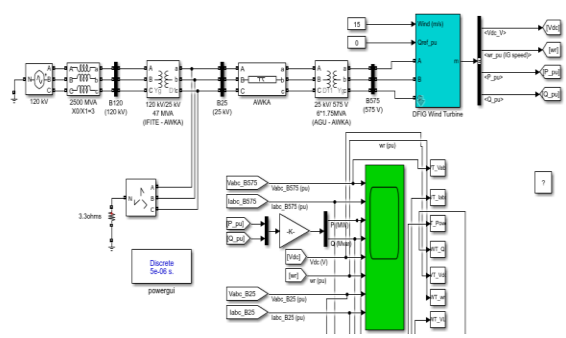

Figure 3.4: Modified Matlab/Simulink Model of the Wind Turbine Block (Matlab R2018a)

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.

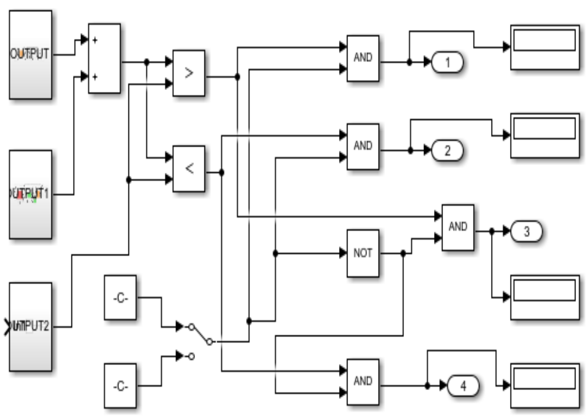

Figure 4: ENUGU 5MW MATLAB/Simulink Control Model

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.

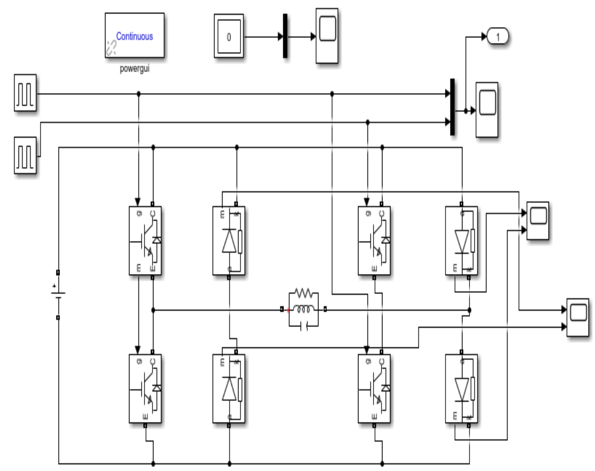

Figure 5: MATLAB/Simulink Inverter Block Model

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.

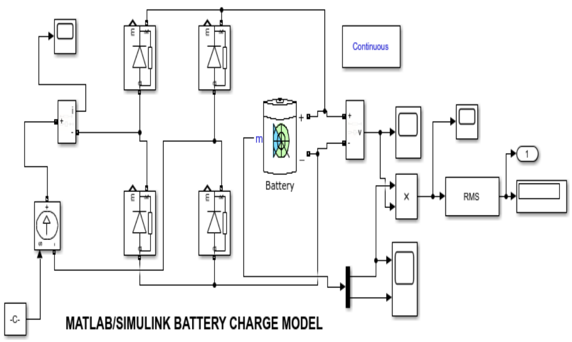

Figure 6: MATLAB/Simulink Charge Battery Model

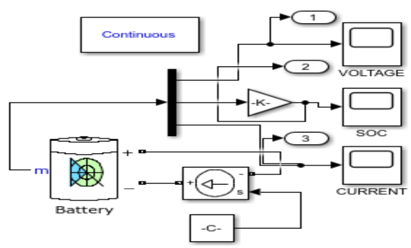

Figure 7: MATLAB/Simulink Disharge Battery Model

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.

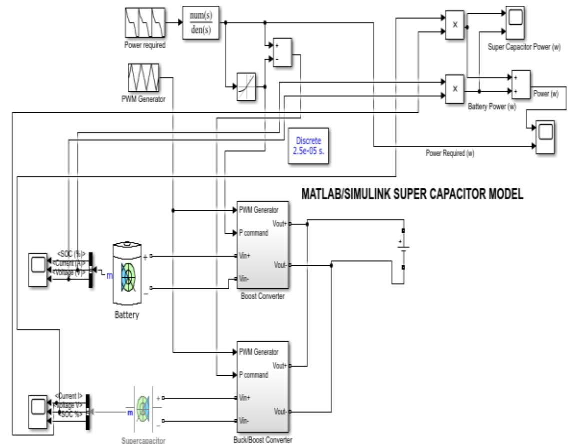

Figure 8: MATLAB/Simulink Super-Capacitor Block Model/Simulink

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.

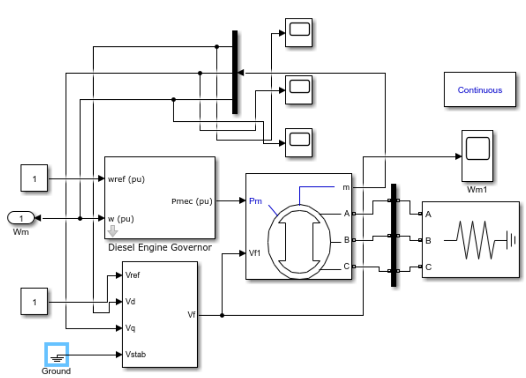

Figure 9: MATLAB/Simulink Diesel Engine Model for Enugu Grid System

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).

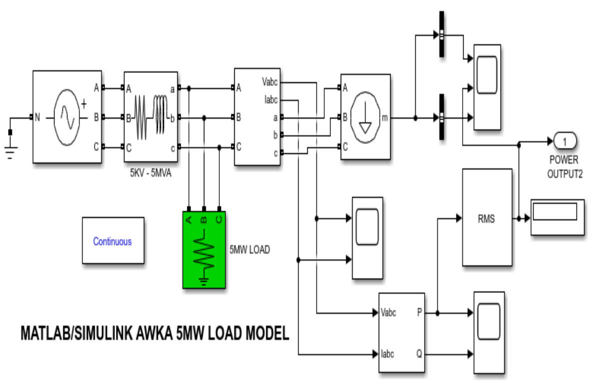

Figure 10: MATLAB/Simulink Diesel Engine Model for Awka Grid System

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 were analyzed using FFT analysis in Simulink.

VI. RESULTS AND ANALYSIS

7 Simulation Results and analysis of the PV Array Power Curve

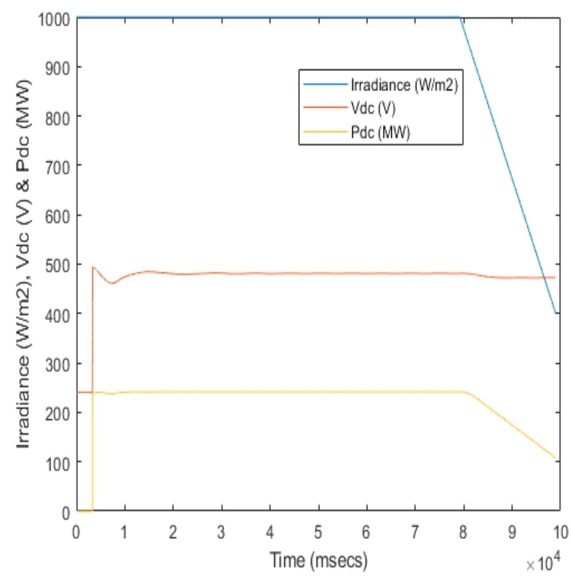

Figure 11: PV Power Waveform of PV Array

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 power formula show that such 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 solar panels in series. Higher voltage reduces resistive losses in cables. Figure 4.1 – 4.3 were obtained when the figure 3.2 is simulated.

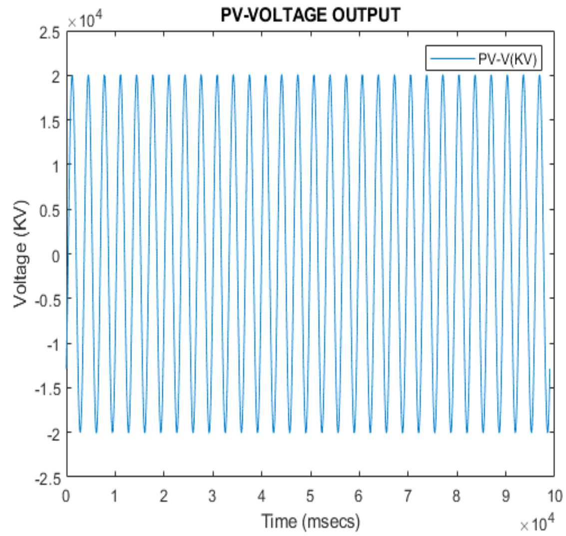

Figure 11: PV Voltage Waveform of PV Array

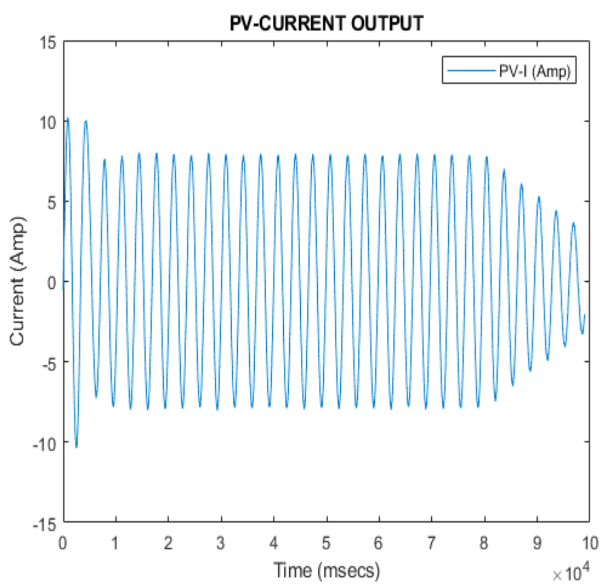

Figure 12: PV Current Waveform of PV Array

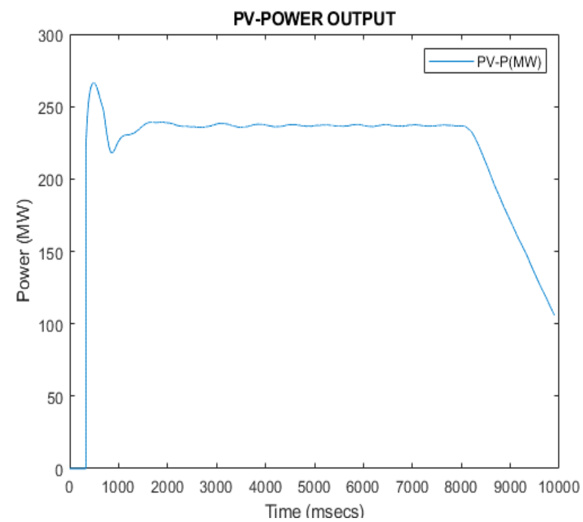

Figure 13: PV Power Output of PV Array

4.2 Simulation Results and Analysis of the Wind Power Curve

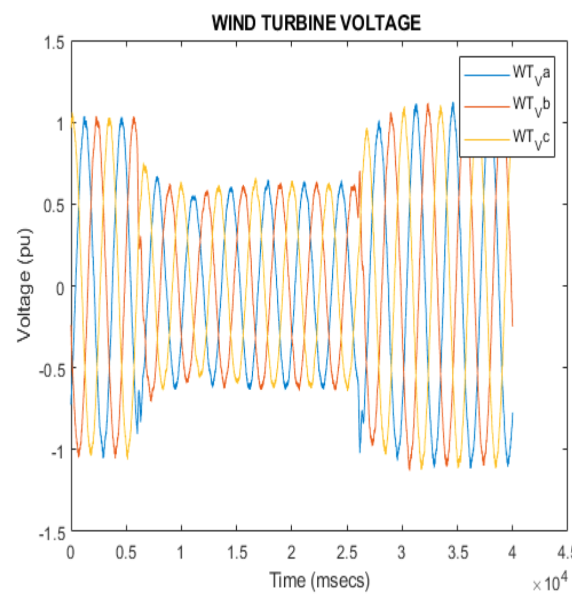

Figure 14: Wind Turbine Voltage Waveform

The Wind Turbine voltage is 1.0 p.u and the current is 0.8 p.u. They represent the normalized current based on the system rating. Less than 1.0 p.u. suggests the system is operating below full load.

Active Power is 12 MW Peak. This is the active power delivered by the wind turbine to the grid. It depends on wind speed, turbine efficiency, and generator capacity.

Reactive Power is 4 MVAR Peak. This is non-working power used for voltage regulation. It is essential for maintaining power factor and grid stability.

DC Voltage is 1200V Peak. It is generated in wind turbines with power electronic converters such as back-to-back converters. It converts variable AC to DC before being inverted back to AC for grid compatibility.

Wind Turbine is a Speed 12.2 m/s. it is unusually high; typical wind speeds for turbines range from 3 m/s to 25 m/s. The wind speed is acceptable since it is within the normal standard range.

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.

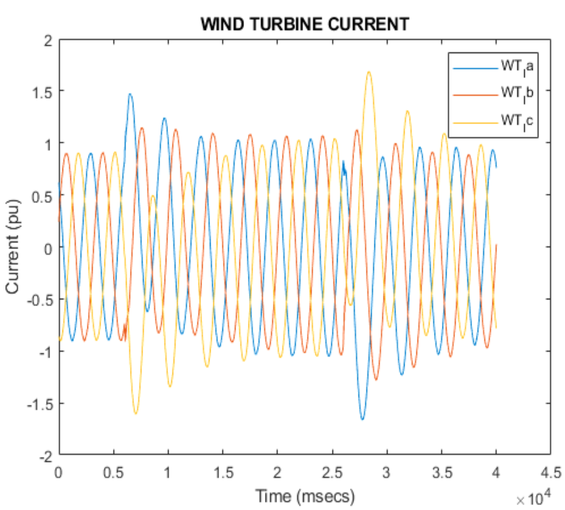

Figure 15: Wind Turbine Current Waveform

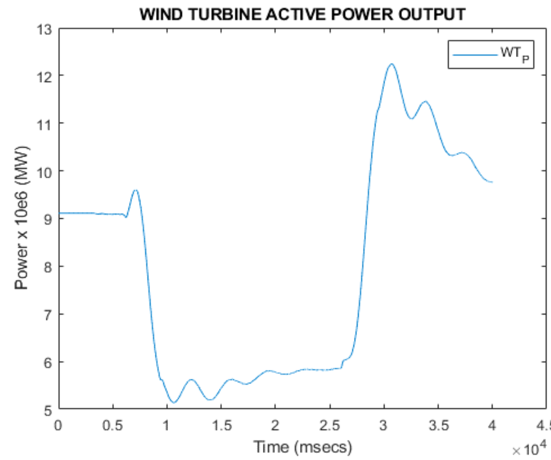

Figure 16: Wind Turbine Active Power Waveform

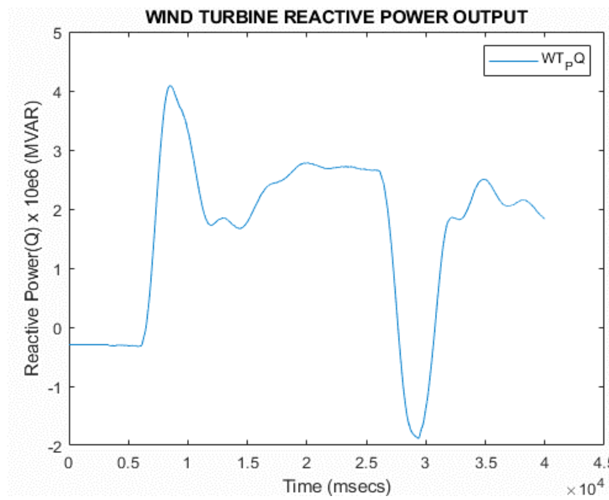

Figure 17: Wind Turbine Reactive Power Waveform

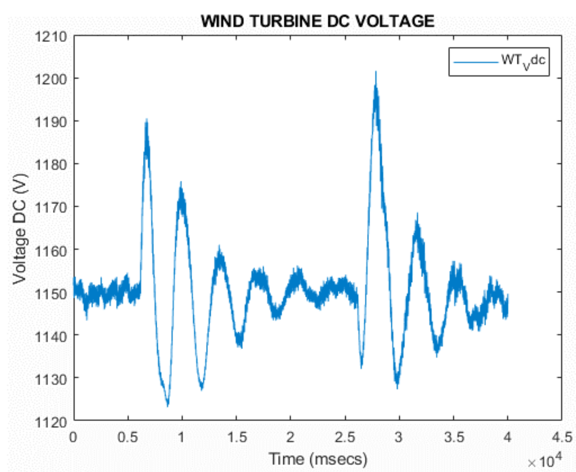

Figure 18: Wind Turbine DC Voltage Waveform

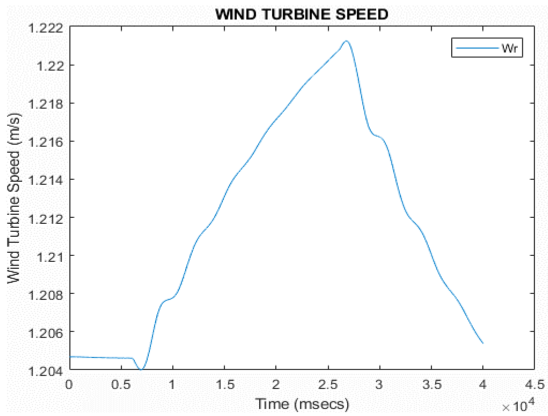

Figure 19: Wind Turbine Speed Waveform

Table 1: Simulation results, Parameters for Enugu Micro Grid System

S/N	Parameters	PV	Wind Turbine (WT)
1	Voltage (dc) kV	20	-
2	Irradiance (W/m2)	1000	-
3	Voltage (V)	500	-
4	Power (MW)	250	-
5	Vabc (pu)	-	1.0 each
6	Iabc (pu)	-	0.8 each
7	Active Power (MW)	-	12
8	Reactive Power (MVAR)	-	4.0
9	Voltage DC (V)	-	1200
10	Speed (Wr)	-	122

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