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Design And Modeling of Grid Connected Hybrid Microgrid with Photovoltaics, Fuel Cells, And Energy Storage for Rural Communities in South-South Nigeria

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Abstract- The design and modeling of a grid-connected hybrid micro grid with photovoltaics, fuel cells, and energy storage for rural communities in South-South Nigeria is presented in this study, with the aim of providing continuous and uninterrupted power supply to residential and industrial users. The methodology involved the theoretical design of all subsystems, followed by modeling and simulation using MATLAB software. The hybrid micro grid system comprises eight subsystems: the grid, photovoltaic (PV) array, DC-DC boost converter, battery storage, fuel cell system, high voltage DC bus, AC-DC inverter, and load. The simulation results demonstrate the efficiency of the proposed system, with the grid providing 6kW, the PV system delivering a maximum of 5kW, the fuel cell offers a maximum of 4.8kW, and the backup storage producing a maximum power of 5.1kW. These results confirm the system's capability to meet the power requirements of the rural community, irrespective of the available energy sources. The study emphasizes the importance of hybrid micro grids in reducing energy poverty and improving sustainability in rural electrification, aligning with previous research that recognizes the potential of renewable energy systems. This comprehensive approach to rural electrification considers both technical and economic factors, offering a localized solution that accounts for resource availability and community demands.

Index Terms- Micro Grid, Photovoltaics, Fuel Cell, Boost Converter, Simulation, Renewable Energy

I. INTRODUCTION

The energy crisis in Nigeria has left many rural communities in Nigeria in partial darkness and slow economic growth. Electricity is one of the drivers of economic growth which promotes the growth of small micro enterprises (SMEs) in a society.

The literature on grid-connected hybrid microgrids, particularly in rural electrification, shows a growing recognition of renewable energy systems' potential to reduce energy poverty and improve sustainability.

Phrakonkham et al. [1] established the economic feasibility of micro grids over standard grid expansions and the need to address technical and economic considerations in their setup. This preliminary study shows the many problems and potential of incorporating renewable energy sources in hybrid systems. Mathema, [2] discusses renewable energy production's climate change susceptibility and microgrids' importance in rural development. The focus on appropriate size and operating methods utilizing modeling tools like HOMER shows the relevance of bespoke hybrid system solutions for rural electrification dependability and sustainability.

A case study in Ethiopia shows how grid expansion and off-grid hybrid solutions complement each other, highlighting the need for government incentives to boost economic viability [3]. This implies that hybrid systems may deliver steady electricity, but their economic viability generally depends on external assistance. Anh Nguyen [4] links micro grids' use of renewable resources to growing fuel costs and environmental concerns. Micro grid architecture is evolving as researchers concentrate on operational management to optimize performance and reduce costs. Leite et al. [5] demonstrate how modular systems may incorporate renewable sources and storage alternatives in micro grids.

This study emphasizes the necessity for effective coordination and management methods to maximize dispersed energy resources in rural areas. Johannes

Prinsloo et al., [6] emphasize smart energy systems and layered control mechanisms for energy delivery in remote rural settlements. They support the rising need for sustainable power solutions that adapt to local circumstances and resource availability. Anusha & Sheba Rani [7] concentrate on hybrid microgrid design methods, stressing energy management and operational tactics. This study is crucial for knowing how to combine technology for rural electrification. The research in ref. [8] [9] examine how policy promotes decentralized electrical networks. Their assessments of solar and battery-powered minigrids show that they can boost rural development and reduce greenhouse gas emissions. Later works, such as [10] [11, examine particular case studies and optimization methods, highlighting the challenges of constructing renewable-rich microgrids. These publications show how to analyze configurations for economic and environmental implications, aiding rural application design. Oulis Rousis et al., [12] and Ahmed Allam Sayed Alsanbawy, [13] examine hybrid AC/DC microgrid operations, demonstrating the benefits of integrating diverse energy sources and the need for robust control strategies to ensure stability and reliability. The study of hydrogen energy storage by Hassan Beshr et al. [14] shows a novel way to strengthen isolated microgrids. This unique energy management approach matches the growing interest in rural renewable energy integration. Chen et al. [15] offer a hybrid distribution generating system that uses wind and hydrogen, highlighting the necessity for rural energy supply and demand management. Their study shows how microgrid design evolves to satisfy community demands. Lotfi, [16] proposes a bi-level planning strategy for hybrid AC/DC systems to optimize investment and operating expenses.

This comprehensive model meets the demand for balanced microgrid renewable energy integration. Pasandi [17] emphasises the rising relevance of solar and fuel cell technology in microgrids, especially in islanding situations. This study highlights how renewable energy systems can reliably power varying demands. The work in ref. [18] explains hybrid microgrid sizing and dispatch algorithms, emphasizing the importance of renewable energy for future energy needs.

Okoduwa et al. proposed a methodology for Optimal sizing of a hybrid photovoltaic/fuel cell grid-connected power system including hydrogen storage.

The authors utilized HOMER and MATLAB software tools for capacity optimization, focusing on the hybrid energy system's configuration. Results from their study showed a significant reduction in the cost of energy (COE) demonstrating the economic viability of the proposed system. Researchers in ref [20], [21] discuss current advances in optimization approaches and techno-economic evaluations for hybrid micro grids in Nigeria, emphasizing the necessity for localized solutions that consider resource availability.

As the government continues to find ways to solve the energy crisis of Nigeria, many researchers and entrepreneurs now focus on designing and constructing a standalone renewable energy system in Nigeria which does not rely on the grid neither supply excess power to the grid, and although this has been the norm as seen from literature, The present study focus on connecting a hybrid microgrid to the national grid to ensure the continuous supply in electricity in rural communities in Nigeria. We focus on the renewable energy obtainable in the south south region of Nigeria and the overall efficiency of the system to supply different load including SMEs in the communities.

II. METHODOLOGY

A rural community in South South Nigeria is connected has each building supplied by a 240 V single phase line to neutral from the grid. The design comprises of grid connected hybrid microgrid consisting of photovoltaic, fuel cell and battery energy storage. The system consists of eight (8) subsystems, which is the grid, the Photovoltaic (PV) array, the DC-DC boost converter, battery storage, fuel cell system, high voltage DC bus, AC-DC inverter, and loads. The block diagram of Fig. 1 shows the microgrid system depicting the connections of the different subsystem.

A. Load Consumption

In Nigeria, electricity is distributed via a secondary distribution transformer near the consumer's home, which steps down the voltage to 200 V to 240 V, the domestic voltage. SMEs need 200 V to 240 V for daily operations. Thus, this system supplies 200 V to 240 V to each community facility using on-grid or renewable energy.

B.Grid Supply

The Nigeria's national grid is responsible for generating, transmitting and distributing electricity. The national grid operates on a three-phase line-to-line at 50 Hz frequency for generation and transmission, and for house hold consumption and SMEs, distribution is usually a single-phase line-to-neutral at 50 Hz frequency. This system uses a step-down transformer to step-down the voltage from the grid to 240 V, hence On-grid, each building should be supplied between 200 V to 240 V.

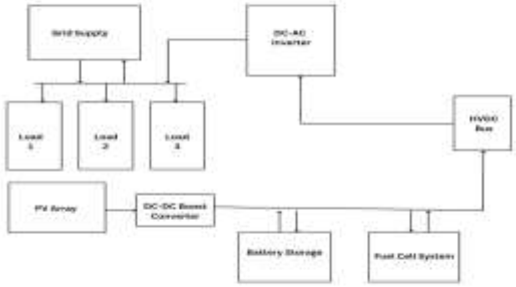

Fig 1: Block diagram of a grid connected hybrid micro grid system

C.PV Subsystem

1. Load Assessment

For a comprehensive load assessment, the power consumption in a particular building is calculated using all communal electrical equipment and projected daily energy usage. Table 1 illustrates a building's appliances and daily load (Wh/day). These are prevalent equipment in south-south Nigerian homes and businesses.

Table 1: Common Appliances in Residential and Commercial Buildings and their estimated Daily Load Consumption

S/N	Appliances	Power Rating (watt)	Qty	Active Hours/ Day (hours)	Total Wh/Day
1	LED light bulb	10	20	12	2400
2	Fan	60	5	10	3000
3	Television	100	2	4	800
4	Refrigerator/ Printer/Other Appliances	300	1	8	2400
5	Phone Charger	20	3	3	180
6	Laptop Charger	50	2	5	500
7	Electric Stove/Other Appliances	1000	1	7	7000
8	Electric Iron	2000	1	3	6000
9	Well Water Pump	800	1	4	3200
Total Energy Per Day					25 480

2. PV System Losses and Efficiency

PV systems lose 20–30% efficiency. Additional electrical components like battery storage, inverter, cable, and others will cause these losses. For losses, load consumption is modified as follows:

$$Adjusted\ load\ (Wh/day) = \frac{Total\ Load}{1 - System\ Losses} \quad (1)$$

Taking the system losses as 25% = 0.25, therefore:

$$Adjusted\ Load = \frac{25\,480}{1 - 0.25} = 33\,973\ Wh/day$$

3. Solar Irradiance and Temperature

Peak sun hours (PSH) refer to the number of daily hours with an average solar irradiation of 1000 W/m².

The south-south of Nigeria has 4–5 peak sun hours per day (Solarmarketing, 2024). In Abia state, Nigeria's south east, 4.7 PSH per day was observed (Idorenyin et al., 2019). From data, the PHS is projected to be:

$$PSH = 4.5\ hours/day\ (typical\ for\ south - south\ region\ of\ Nigeria)$$

4. Total PV Capacity Needed

The total PV capacity needed for a single building is given by the formula:

$$PV\ Capacity\ (W) = \frac{Adjusted\ Load\ (Wh/day)}{Peak\ Sun\ Hours\ (h)} \quad (2)$$

For an adjusted load of 33,973 Wh/day, the PV capacity is given by:

$$PV\ Capacity = \frac{33\ 973}{4.5} = 7\ 550\ W \quad (3)$$

5. PV Panels

Choosing a 300W rated panel with an output voltage of 48V monocrystalline type, the number of panels required for a single building is given by:

$$Number\ of\ Panels = \frac{Total\ PV\ Capacity}{Panel\ Power} \quad (4)$$

$$Number\ of\ Panels = \frac{7\ 550}{300} = 25.167 \cong 26\ panels$$

If each household requires 25 panels, then for a community of five hundred (500) buildings subdivided into hundred (100) commercial buildings and four hundred (400) residential building, the estimated number of panels is given by:

Total Number of Panels=26 ×500=13,000 panels

Hence the capacity of the PV system is given by:

Total PV Capacity=7550 × 500=3 775 000 W ≅4 MW

With each building requiring 5 200 watts of power from the PV system. for software optimization, only three (3) houses will be simulated, hence the solar panel required by 3 houses is:

Total Number of Panels for 3 buildings=26 ×3=78 panels

And the total PV capacity is given by:
Total PV Capacity=7550 ×3=22,500

C. Battery Supply

Except for grid breakdowns in Nigeria, where batteries operate as backups, grid-connected systems do not need battery storage. Only important loads require backup storage; therefore, only commercial houses need it for this design. Table 2 shows how key loads in commercial buildings generate energy.

Table 2: Critical Appliances in Commercial Buildings and their estimated Daily Load Consumption

S/N	Appliances	Power Rating (W)	Qty	Active h/Day	Total Wh/Day
1	LED light bulb	10	5	5	250
2	Fan	60	2	5	200
3	Phone charger	20	3	3	180
4	Laptop charger	50	2	5	500
5	Television	100	1	4	400
6	Refrigerator /Printer /Other Appliances	300	1	3	900
Total Energy Per Day					2812

The power consumption by each commercial building is given by:

$$Power_{building} = (10 \times 5) + (60 \times 2) + (20 \times 3) + (50 \times 2) + (100) + (300)$$

$$= 50 + 120 + 60 + 100 + 100 + 300 = 730\ watts$$

If the commercial buildings/load in the community is hundred (100), then the total energy consumption per day on battery power is given by:

total energy consumption by backup load= 2 812 ×100=281 200 Wh/day

The battery capacity (Ah) is given by:

$$Battery\ capacity\ (Ah) = \frac{Backup\ load\ (Wh/day) \times Backup\ Days}{Battery\ Volatge\ (V) \times Depth\ of\ Discharge\ (DOD)} \quad (5)$$

Taking the battery voltage as 48V, the depth of discharge (DOD) for lead acid battery is 50% to 80% and the DOD for Lithium-ion battery and the backup days as one (1) day. Given that:

Lithium-ion battery is = 95% (0.95)

The battery capacity is given by:

$$Battery\ capacity = \frac{281\,200\ \times 1}{48 \times 0.95}$$

$$= 9\,012.8\ Ah\ \cong 9013\ Ah\ \approx 9\,000\ Ah$$

If a Blue Power dry cell lithium battery with rated capacity of 300 Ah is used for this system, the number of batteries for the system is:

$$Number\ of\ batteries = \frac{Total\ battery\ capacity\ (Ah)}{Capacity\ per\ battery\ (Ah)} \quad (6)$$

$$= \frac{9\,000\ Ah}{300\ Ah} = 30\ batteries$$

D. DC-DC Buck-Boost Converter

This converter allows power flow in both direction, that is between a DC bus and a battery, hence it enables the battery charging and discharging. The DC-DC buck-boost converter performs the following functions:

- Battery charging and discharging
- Power sharing between two DC sources (PV and battery)
- Vehicle-to-grid (V2G) systems; that is, it allows the battery to be connected to the grid system.

The value of the inductor is given by:

$$L = \frac{V_{in} \times D \times (1-D)}{f_s \times \Delta I_L} \quad (7)$$

Where D is the duty circle such that for:

$$Boost\ converter: D = 1 - \frac{V_{in}}{V_{out}} \quad (8)$$

$$Buck\ Converter: D = \frac{V_{out}}{V_{in}} \quad (9)$$

The capacitor value is given by:

$$C = \frac{I_{out} \times D}{f_s \times \Delta V} \quad (10)$$

Where 〖ΔI〗 _L is the inductor ripple current which is typically between 20% to 40% of the output current, therefore;

$$\Delta I_L = 20\%\ (I_{out}) \quad (11)$$

And ΔV is the output voltage ripple, which is given by:

$$\Delta V = 5\%\ (V_{out}) \quad (12)$$

E. DC-DC Boost Converter

For maximum power extraction from the PV source, the DC boost converter must step up the PV panel voltage to match the system voltage. The boost converter has a switch, diode, inductor, and capacitor. The diode and MOSFET are selected based on the circuit's power needs, but the inductor is calculated using the formula:

$$L = \frac{V_{in} \times D}{f_s \times \Delta I_L} \quad (13)$$

The value of the capacitor is given by:

$$C = \frac{I_{out} \times D}{f_s \times \Delta V} \quad (14)$$

Allowing only 1% ripple voltage at the output of the boost converter:

ΔV=1% (V_out) (15)

F. The Inverter

The inverter converts panel-generated DC to AC for AC loads (Vince 2012). Inverters are 90% to 95% efficient due to power loss during conversion. The equation below calculates inverter efficiency (Marwa 2017);

$$Efficiency\ (\eta) = \frac{output\ power\ (to\ loads)}{input\ power\ (power\ from\ charge\ controller)} \quad (15)$$

Assuming worst case inverter efficiency to be 90%, so the input power to the inverter coming from the PV array is calculated using the equation below:

$$Input\ power\ (from\ PV) = \frac{output\ power\ (to\ load)}{Efficiency\ (\eta)} \quad (16)$$

To manage the system's Watts, the inverter must be powerful. Inverters should be 25-30% larger than load watts (Marwa 2017). Calculate the load's power to size the inverter. From earlier calculations, the load power was 32 792 Watts, hence PV array power is:

$$Input\ power\ (from\ PV) = \frac{131\,200}{0.90} = 145\,777\ Watt$$

A 150 000-Watt inverter is needed for design safety margin since the inverter should be 25-30% larger than the load's watt.

The DC/AC inverter's LC filter removes high-frequency harmonics from PWM output, delivering a pure sinusoidal voltage waveform. Required LC filter design parameters: Inverter output frequency (f_o) is the fundamental AC frequency, usually 50 Hz or 60 Hz, switching frequency (f_s) is the PWM signal frequency, usually 10 kHz or higher, and filter cutoff frequency (f_c) is typically set to a margin of 10% to 20% above the fundamental frequency. Expression of cutoff frequency:

$$f_c = f_o \times (1 + Margin)$$

Load current is given by:

$$I_{load} = \frac{Input\ power\ (from\ PV)}{V_{out}} = \frac{150\,000}{230} = 652.17\ A$$

Therefore, the allowable current ripple is given by:

$$\Delta I_L = 0.2(I_{load}) = 0.2(652.17) = 130.4\ A$$

The allowable voltage ripple is given by:

$$\Delta V_L = 0.05(V_{out}) = 0.05(230) = 11.5\ V$$

Inverter output frequency = 50 Hz
Switching frequency = 10 kHz

If the margin for cutoff frequency is set to be 20% above inverter output frequency, the cutoff frequency will be:

$$f_c = 50\ (1 + 0.2) = 60\ Hz$$

The inductor value is:

$$L = \frac{\Delta V_L}{4 \times f_s \times \Delta I_L} = \frac{11.5}{4 \times 10\,000 \times 130.4} = 2.2\ \mu H$$

The capacitor value is:

$$C = \frac{\Delta I_L}{2\pi \times f_c \times \Delta V_L} = \frac{130.4}{2\pi \times 60 \times 11.5} = 0.03\ F$$

The actual values used for inductor is 9.6 µH, and the capacitor value used is 0.0069 F.

G. Fuel Cell (FC) Subsystem

Fuel cells create electricity from hydrogen tanks. This system uses Proton Exchange Membrane (PEM) fuel cells because of its small size, ease of use, and low maintenance. Nexa fuel cell modules provide erratic DC electricity up to 1.2 kW. The nominal output voltage is 22–50 V DC. These fuel cells produce DC electricity, water, heat, and unused air using air as an oxidant. Nexa PEM fuel cell modules boast 1.2 kW output power, 99.99% hydrogen purity, ≤18.5 l/min consumption, 870 ml/h water emission, and 0.7-17 bar input pressure (Gencoglu 2009).

Fuel cell outputs are parallel-connected and fed into an inverter.

Fuel cell energy requirements are;

Total energy comsumption=total energy consumed per building ×number of buildings

$$= 25\,480\ \times 500 = 12\,740\,000\ Wh/day$$

which is the estimated energy consumed by the load. The electrolyser will receive power from the PV system for a complete day, which is 24 hours; hence the power required from the fuel cell is:

$$Power = \frac{Energy}{time} \quad (17)$$

$$Power = \frac{12\,740\,000}{24} = 530\,833w \cong 531\,kw$$

Given that the fuel cell used generates a DC power of 1.2kw, the number of fuel cell units required to generate 531 kw is:

$$number\ of\ units = \frac{531kw}{1.2kw} = 442.5\ units \cong 443\ units$$

The number of fuel cell units used will be 443, as a safety margin.

Therefore, the grid system will consist of an electrolyser that receive power from the PV system, which is connected to and deionized water and the hydrogen extracted is stored in the hydrogen tank which is then supplied to the 443 PEM fuel cell.

Hence for each building the required power from the fuel cell is 5200 watts.

For software optimization and as earlier stated, only three buildings are simulated which has a total capacity of 22 500 watts. Hence required energy from the fuel cell is given by:

Total energy comsumption=total energy consumed per building ×number of buildings

$$= 25\,480 \times 3 = 76\,440\ Wh/day$$

which is the estimated energy consumed by the load. The electrolyser will receive power from the PV system for a complete day, which is 24 hours; hence the power required from the fuel cell is:

$$Power = \frac{Energy}{time}$$

$$Power = \frac{76\,440}{24} = 3185w$$

Given that the fuel cell used generates a DC power of 1200W, the number of fuel cell units required to generate 3185W is:

$$number\ of\ units = \frac{3185W}{1200W} = 2.65\ units \cong 3\ units$$

The number of fuel cell units used will be 3, as a safety margin. The capacity of the fuel cell subsystem is expected to 22 500 watts, same as the PV subsystem.

III. RESULT AND DISCUSSION

The simulation was performed under three (3) different working conditions, which are; load supplied by grid, load supplied by PV, load supplied by fuel cell and load supplied by battery storage.

Grid Subsystem Simulation Result

All other sources were switched off and the grid provided the load for this scenario. Grid subsystem simulation results are in table 3. A grid-supplied H-type distribution transformer reduces grid voltage. Figure 3 shows the transformer linked to community buildings and supplying each load with 200 V. In this simulation, all loads are equal, hence table 3 and figure 4 show equal current flow across the three loads. Since load analysis was not done for the grid simulation, each building is presumed to utilize its own appliances and equipment.

PV Subsystem Simulation Result

For this scenario, all sources save the PV that powered the load were off. Apollo Solar Energy ASEC-300G6S solar panels generate 299.9916 Watts during simulation despite being rated at 300 Watts 45.07 V. TuTiempo.net data for Ekpoma indicates around 1000 W/m^2 sun radiation and 25°C weather sparks temperature. This is the greatest overall irradiation for the day (estimated 4.5 hours) and will be reduced throughout the complete system simulation to accommodate for real-life irradiation changes. Table 4 shows PV, DC-DC Boost, Inverter, and load outputs. In this simulation, all loads are equal, hence table 4 and figure 9 show equal current flow across the three loads. The load analysis shows that each load needs 5 200 watts, thus throughout the simulation, each load got 5 000 watts.

Battery Storage Unit

The system was simulated under severe situations when the battery powers the load without all sources. Figures 5, 10, and 14 demonstrate the battery and load waveforms with additional energy sources. From figures 5, 10, and 14, the battery state of charge starts at 50%, the current is negative, and the voltage rises as the battery charges. This continues while solar irradiation, grid supply, and fuel cell supply are available, regardless of value. To simulate sunshine, the energy sources were adjusted, and as the batteries charged, the load current, voltage, and power waveform varied with the supply. Battery discharge is seen in Figure 15. Assuming all energy sources are unavailable, the battery is 100% charged and has 198.8 V of full charge. According to the battery state of charge waveform, the load receives 5 100 Watts from the battery as it discharges, which is greater than the calculated value for a backup system if not all consumer appliances are plugged in but less than the required value if all are.

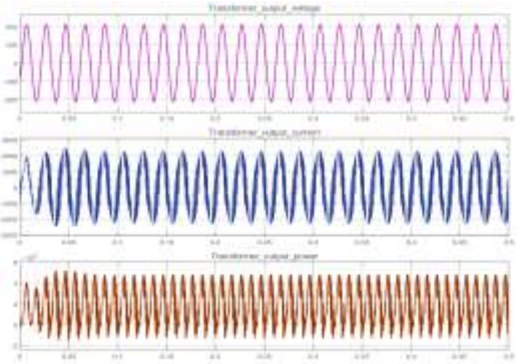

Fig.3: Output voltage, current and power waveform of H-type distribution transformer connected to the load

Table 3: Result obtained from grid subsystem simulation

S/N	Block	Output Voltage(V)	Output Current(A)	Output Power (kW)
1.	Distribution Transformer	200	2000	400
2.	Load One (1)	200	30	6
3.	Load Two (2)	200	30	6
4.	Load Three (3)	200	30	6

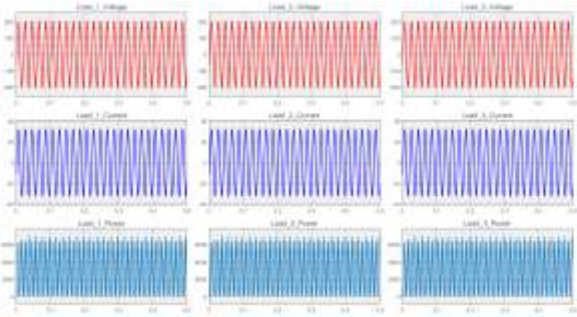

Fig 4: Voltage, Current and Power waveform of each load when connected to the distribution transformer

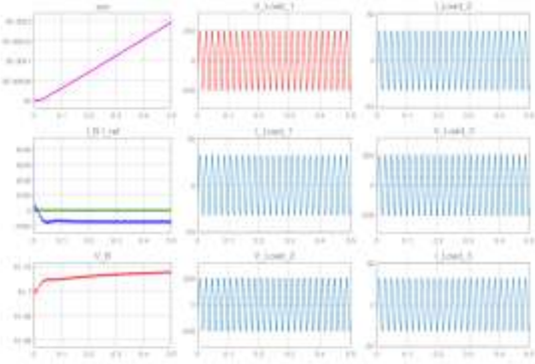

Fig. 5: Waveform showing the state of charge of the batteries, the battery current and the voltage and the various load supplied by the grid

Table 4: Result obtained from PV subsystem simulation

S/N	Block	Output Voltage	Output Current(A)	Output Power(W)
1.	PV Array	68.2 V	161.4	11 010
2.	PV DC-DC Boost	122.1 V	130.9	15 983
3.	Inverter	189.7 V	79.1	15 000
4.	Load One (1)	171.8 V	29.1	5 000
5.	Load Two (2)	171.8 V	29.1	5 000
6.	Load Three (3)	171.8 V	29.1	5 000

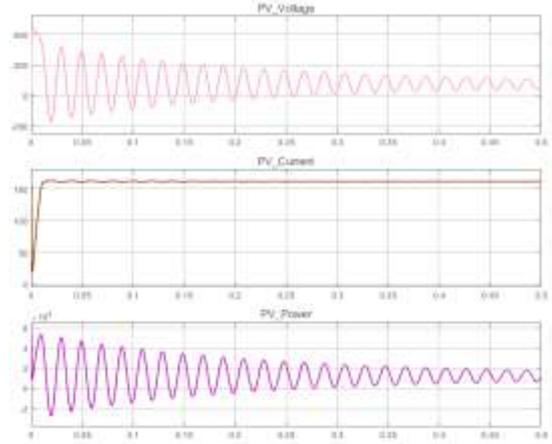

Fig. 6: Output voltage, current and power from photovoltaics array

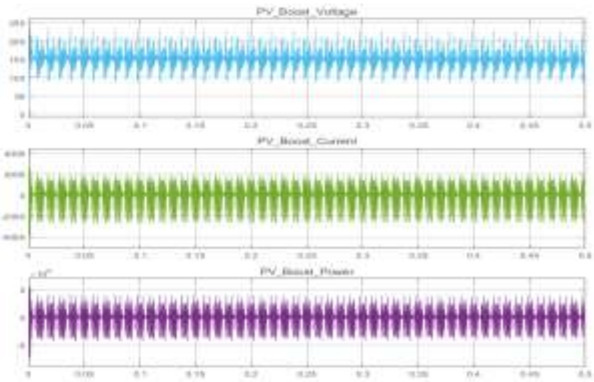

Fig 7: Output voltage, current and power from DC-DC boost converter

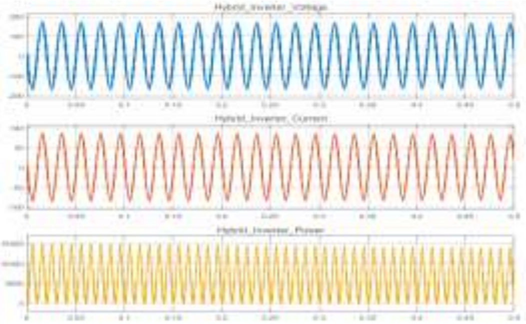

Fig. 8: Output voltage, current and power from Inverter on PV supply

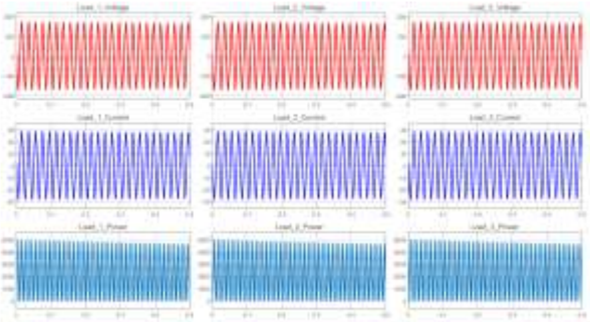

Fig 9: Voltage, Current and Power waveform of each load when connected to the Photovoltaics subsystem

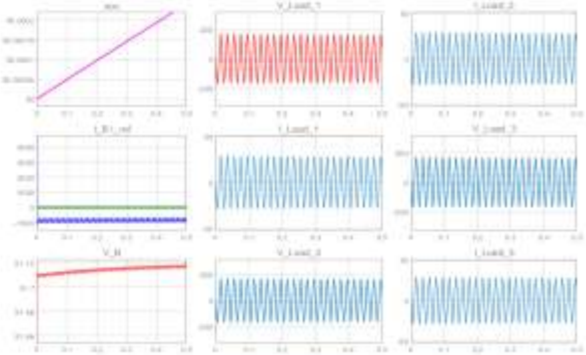

Fig. 10: Waveform showing the state of charge of the batteries, the battery current and the voltage and the various load supplied by the PV

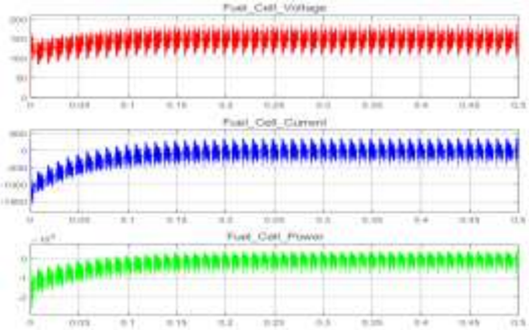

Fig. 11: Output voltage, current and power from the Fuel Cell Subsystem

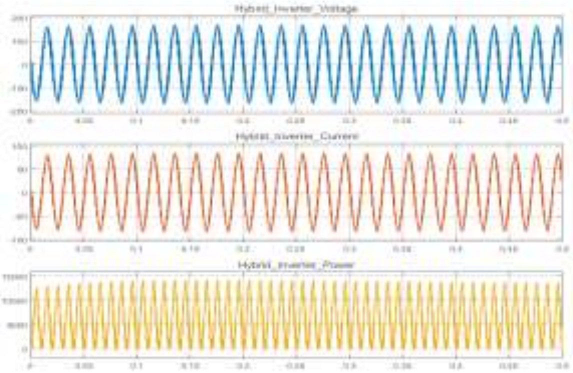

Fig. 12: Output voltage, current and power from the inverter on Fuel Cell supply

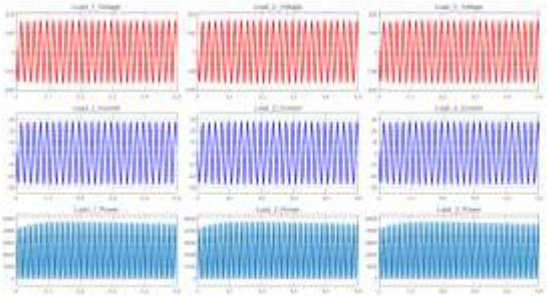

Fig 13: Voltage, Current and Power waveform of each load when connected to the Fuel Cell subsystem

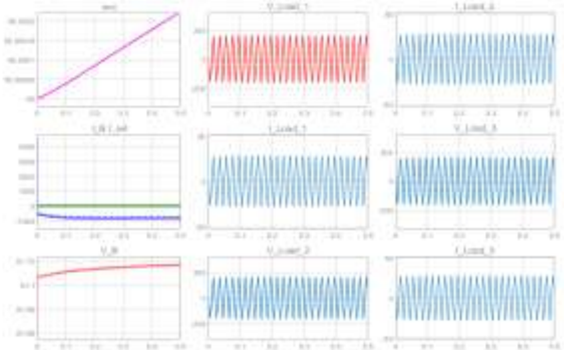

Fig. 14: Waveform showing the state of charge of the batteries, the battery current and the voltage and the various load supplied by the Fuel Cell

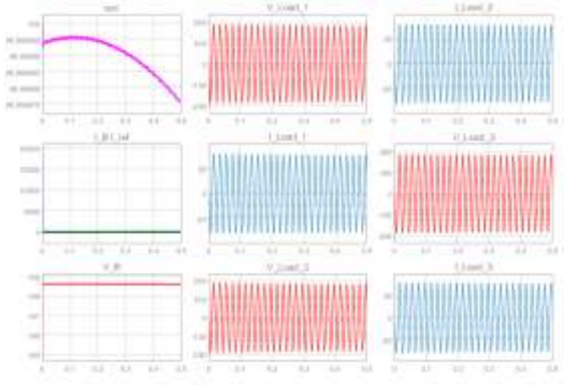

Fig 15: Waveform showing the state of charge of the batteries, the battery current and the voltage and the various load supplied by the discharging the battery

IV. CONCLUSION

The design and modeling of grid connected hybrid micro grid with photovoltaics, fuel cells, and energy storage for rural communities in south-south Nigeria was presented in this study. The objective was to model a system that delivers continuous uninterrupted power supply to residential and industrial Users. Theoretical methodology was adopted to design all the subsystems in the setup.

The MATLAB software was used to model all the subsystems and to carry out simulations based on the designs. Results obtained indicate that the Grid Connected Hybrid Micro grid, including Photovoltaics, Fuel Cells, and Energy Storage for Rural Communities, is highly efficient. The grid provided 6000 watts to the user, the PV system delivered a maximum of 5KW, the fuel cell offered a maximum of 4.8KW, and the backup storage produced a maximum power of 5.1KW. Thus, the system demonstrates its capability to meet the power requirements of the rural community, regardless of the available energy sources. The presence of such a system may foster community development, including the construction of financial institutions, small and medium-sized enterprises, and food storage facilities. Real-world factors such as grid stability, power quality issues, and the integration of smart grid technologies may also introduce additional complexities not fully addressed in this work. Therefore, further validation through real-world testing and implementation is recommended for further studies

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