Design And Simulation Of A DC Microgrid System For A Remote Community In Nigeria

by

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Abstract

The thesis presents the design and modelling of an off-grid Stand-alone Photovoltaic (PV) system for a house and DC microgrid system for a remote community. Using a 48V DC bus, the system was sized using Homer Pro and dynamic simulation was done in Simulink. Optimization results presented various designs out of which the most preferred cost effective and efficient system for the house and remote community was selected. The selected remote community is isolated and located far away from the city with no access to the electricity grid. The community is made up of 9 residences which are not more than 100m apart. House 1 was selected as the standard house with a load of 1kWh/day, while the other 8 houses have a load difference of ±10% with reference to house 1. Using a 48V DC bus, the PV systems were designed for each house in the community. The systems were sized using Homer Pro. Optimization results presented various cost effective design for each community house. Sensitivity analysis was carried out to show the robustness for both the single residence and the community microgrid design. Simulation results showing the stability of the system and power sharing in the community using a 48V DC bus. Microgrid dynamic simulation is done in Simulink. Complete details of system design and dynamic simulation results are presented and explained in this thesis.

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List of Abbreviation and Symbols

PV	Photovoltaic
DC	Direct Current
AC	Alternating Current
HOMER	Hybrid Optimization of Multiple Energy Resources
MPPT	Maximum Power Point Tracking
NPC	Net Present Cost
COE	Cost of Energy
O&M	Operation and Maintenance
SOC	State of Charge
IRR	Internal Rate of Return
kW	Kilo Watt
Ahr	Ampere hour

Chapter 1

Introduction and Literature Review

1.1. Introduction

A large percentage of the world population living in rural areas have inadequate supply of electricity or in most cases no access to the utility grid. The sub-sahara Africa region contributes highest to this percentage [1]. Renewable energy is energy derived from resources which are regenerative or cannot be depleted. For example, solar, wind, hydro, wave, tidal, geothermal, ocean thermal. These renewable resources are crucial in the design of an environmentally friendly and sustainable power system [2],[3]. Nigeria producing about 2.5 million barrels of crude oil daily, 2.175 billion tons of coal and lignite, with natural gas reserve of about 187 trillion ft^3 [4], and in addition to this conventional energy resources, there is a huge potential for renewable energy resources because studies have shown[5] that there are about 277 potential sites for small-scale hydropower which could yield about 734MW of power, whereas, with an average of 6.5h of sunshine daily, the value of solar energy by year in terms of energy measurement is about 27 times that of conventional energy sources [6]. Solar energy happens to be one of the most reliable alternative sources of energy; it has many advantages which includes easy installation of Photovoltaic (PV) system, reduced maintenance cost, no noise due to absence of moving parts [7] [8].

The inaccessibility to electricity has been a major challenge in Nigeria for most remote area and even some urban areas. This power insufficiency is a major hindrance to development both technologically and economically in the country. Non access to electricity in most rural areas has resulted to increase in poverty and has posed as a major obstacle to a better standard of living. In Nigeria it have been estimated that only about 22.6% of rural communities have access to electricity [9]. Hybrid system which is the combining of renewable and conventional resources would be the most efficient and cost effective system to adopt in comparison to a diesel only system which is the current alternative means of power supply in Nigeria. The implementation of a stand-alone hybrid system in remote areas with no access to electricity can improve the standard of living in these areas. This system would be most preferable and would play a major part in generation of electricity, reduction in environmental pollution and also result in a cost-effective system since extension of the grid to these remote areas is not economically feasible.

1.2. Types Of Solar PV Generation And Distribution System

There are two types of solar PV hybrid system

- Grid-Tied Solar PV system
- Off- Grid Solar PV System

1.2.1. Grid-Tied Solar PV System

These are large photovoltaic system and there are various PV grid connection methods. Such as: the centralized string technology where one inverter is used for many strings of

PV; the string technology where one inverter is used for each string; the multi-string technology is where each string having a DC-DC converter are all connected to a central DC-AC inverter. The current trend is towards one inverter per module AC coupling. But issues are circulating currents, harmonics and high decommissioning cost. by grid-tied PV system, the inverter are usually replaced with transformers as seen in the figure below.

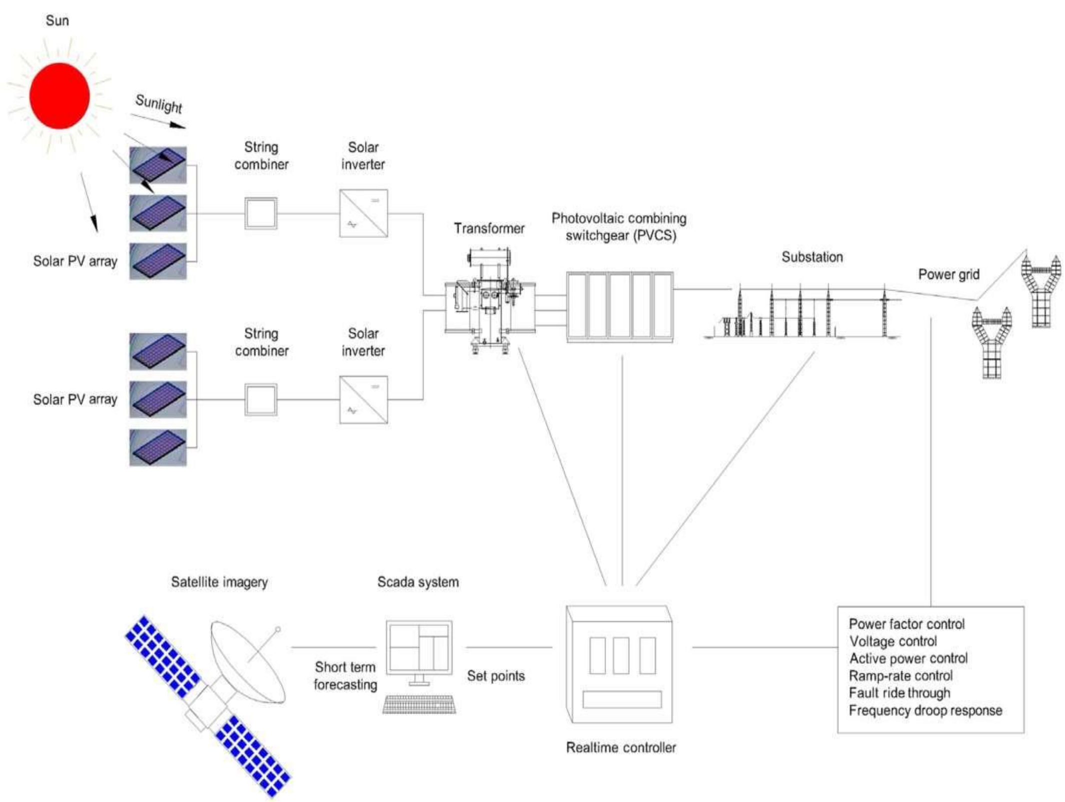

Fig.1.1 Schematic of a grid-connected solar PV system.

The figure 1.1 above shows the schematic of a grid-connected solar PV system Usually, they also have a SCADA (Supervisory Control and Data Acquisition) system that log data (i.e voltage, currents) coming from various points in the system. They log and control power factor, voltage control, active power control, ramp-rate control, fault ride through, frequency droop response. There is also a real time controller, for instance, in a case where there is a power failure in the grid, the switch gear will disconnect the system from the grid. For the data logging, if it is a remote system, then the data from the data logging system may be transmitted through satellite. If it is near town, or if there is a communication line running near the power line, then it may be connected through fibre or through simple telephone lines.

1.2.2. Off Grid Solar PV System

Nigeria, by utilization of its abundant renewable energy potential, has the capability to improve electrification rate by implementation of off-grid energy infrastructure to rural households, communities and business. Rural communities are usually areas of the country with population less than 20,000 inhabitants, and at a distance of over 10km from the urban area. Studies from Rural Electrification Strategy and Implementation Plan (RESIP) in 2015 and from World Bank show that for remote communities, mini/micro grid is the most cost-effective and optimal solution in comparison to grid extension to these remote areas, [10], [11]. For local communities, which have inadequate supply of electricity or in most cases no access to electricity, different off-grid system such as mini-grid, micro-grids or isolated stand-alone system would be the best option both economically and technically in terms of providing electricity.

Nigeria is rich in renewable resources; it has abundance in coal, natural gas, wind, solar, hydro, biomass. If small scale off-grid system is accepted and implemented, the energy need of inhabitants living in rural communities would be met in a short period of time rather than the extension of the national grid network to such areas [12].

The average solar irradiation in Nigeria ranges from 4.0 – 6.5kWh/m^2/day, with an average of 4 – 7.5 hours of sunshine [13]. The average daily direct radiation reaches about 4.65kWh/m^2/day in Southern region of the country. With this high potential of solar that can be utilized as alternative source to supply part of the energy needs in Nigeria. This is shown in the figure 1.2 below.

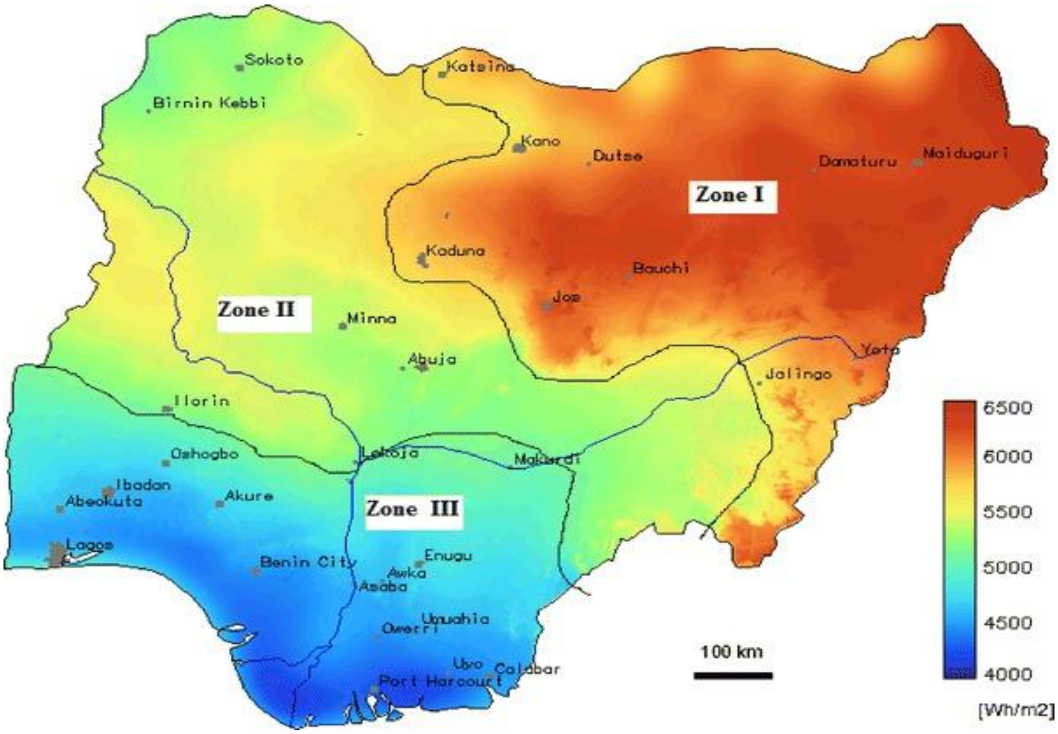

Fig.1.2 Solar irradiance distribution in Nigeria.

1.3. Stand-Alone PV System For Remote Residence

Hybrid systems are systems which comprises of conventional generation and one or more renewable energy sources. Most hybrid systems are stand-alone systems, which operate “off-grid”(i.e not connected to the electricity/utility distribution system). For the times when neither wind nor solar system are producing, most hybrid systems provide power through batteries and/or and engine generator powered by conventional fuels, such as diesel. If the batteries run low, the generator can power and recharge the batteries.

Most Nigeria households in remote residences lack access to electricity or suffer inadequate supply of power. In order to match up to the energy demand, majority of low-income houses resort to diesel generator system despite the high maintenance cost and environmental pollution caused by emitted gases from the generator, they consider this a more affordable option to renewable energy system. The reason behind this is due to limited information on the advantage of the off grid system, no knowledge of the actual life cycle cost and best way of raising the capital cost.

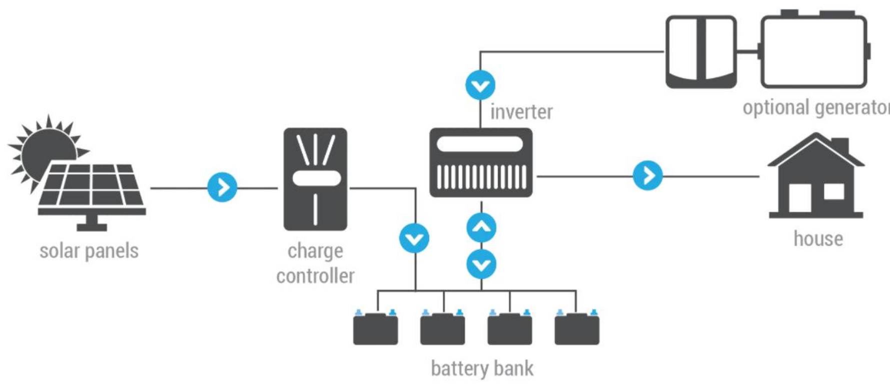

Fig.1.3 Stand-alone solar PV system.

The figure above shows the stand-alone PV system. Stand-alone/isolated PV system is sometimes comprised of some component which is battery, DC-DC converter, DC-AC inverter, voltage generator, battery, emergency backup generators. The Photovoltaic cell is the primary source of power and they are made from semiconductors which converts sunlight to electricity, series of cells come together to form a module, and modules are connected in series and parallel to form an array. A battery is a storage medium that stores electrical energy produced by the PV and is mostly utilized during sun down when the PV is no longer producing power to supply the load. In order to prevent battery overcharging/over discharging and reversal of current, a voltage regulator is mostly incorporated. For a house with AC load, an inverter is used to convert the DC coming from the PV into alternating AC. DC-DC converters are used mostly to either increase or decrease the voltage. There are three types of DC-DC converters which are; boost converter, buck converter and buck-boost converter.

1.4. Microgrid PV System For Remote Community

A PV based microgrid is a locally confined and independently controlled electric power system whereby distribution architecture integrates both distributed loads and distributed energy sources. The most common mode of design architecture for remote community microgrid is the islanded mode; this is due to the fact that they are located far from existing utility transmission network. Communal microgrids can be connected to the utility grid for system economic improvements, operations improvement, to improve stability, and in return the utility grid also enjoys improvement in availability of power, improved stability and reduced conductor size[14].

Communal microgrid can be classified into AC-coupled or DC-coupled depending on the common bus voltage. Majority of most household loads require AC power and AC is the main form of power transmission and distribution globally, hence the importance of AC-coupled common bus voltage. Conventionally, AC enables the efficient transmission of voltage and high-voltage power transmission over long distances. However, there are issues prevalent with AC-coupled microgrid system which includes:

- The need for regulation of voltage and frequency values through active and reactive power control

- In cases where decentralized power source is a synchronous generator having an AC output is connected directly to the utility grid without proper power electronic interface, stability is controlled through machine shaft's torque and speed control.

In this study, we focus on DC coupled microgrid. This is due to the fact that a communal microgrid using DC bus avoids many of the power conversion steps required when making use of AC bus. This leads to higher energy efficiency and saves cost. In terms of stability, since the DC coupled systems have no reactive power interactions, there are few stability issues in comparison to AC coupled bus system. There are various types of DC-coupled Microgrid grid configurations.

1.4.1. DC-Coupled Microgrid with Decentralised storage system: In this system the voltage generated by the PV is distributed in DC form throughout the community. Each house also has a storage system (battery) for backup power during the night period or rainy days with no adequate sunlight. Because in this type of community, most house load is DC, there is no need for inverter for conversion to AC. For maximum power tracking the DC-DC converters is connected to each PV system for keeping power at a maximum and also for controlling charge of the storage system (battery). In this system, future connection to the microgrid is easy as no modifications to the interfacing inverter are necessary.

1.4.2. DC Microgrid with Centralized Storage system: this system is similar to the DC microgrid with decentralized storage system, just that in this case, storage system is centralized. There is still the necessity for DC-DC converter for maximum power tracking for each PV system, however, charge control is performed by an appropriately sized central converter which is connected to the central battery. The disadvantage with this system is that future connection to the microgrid would be complex because with the increase in demand would be a proportionate increase in storage capacity which would result in purchase of a new appropriately sized DC-DC central converter to meet the system requirement. This system will require higher cost of maintenance and upgrade.

1.5. Tools Used For The Design

1.5.1. Sizing Tool:

There are several sizing tools such as Homer Pro, REOpt, iHOGA, Hybrid 2, RETScreen, Insel, etc. But for this research we made use of the Homer pro.

Homer Pro models micropower systems with single or multiple sources. For example, Photovoltaics (PV), wind turbines, Run-of-river hydro, Diesel generator, Cogeneration Micro-turbines, Batteries, Grid, Fuel cells, Electrolyzers, etc.

Homer, the micro power optimization model, performs both off-grid and grid-connected systems designs. You can use Homer Pro to perform analysis to explore a wide range of design questions such as:

- Which technologies are most cost-effective?
- What size should components be?
- What happens to the project's economics if costs or load change?
- Are the renewable resources adequate?

Using the sensitivity and optimization tool of Homer all of these difficult questions can be answered. Homer has a way of finding the least cost system component combination to the required load. It can also simulate variety of system configuration and performs optimization for lifecycle costs, and also generates sensitivity analysis results for most inputs [15].

1.5.2. Simulation Tool

There are various simulation tools such as openDss, PVSol-Premium, MatLab Simulink, etc. for this project we made use of the Matlab Simulink tool. Continuous system simulation is crucial in determining the performance of the system in real world scenario.

The Matlab/Simulink was used to show the dynamic simulation of the hybrid power systems design and to determine the power quality of the system.

1.6. Motivation And Research Objectives

The selected sites for this project are located in remote areas of Edo State Nigeria. These areas are completely cut off from the utility grid and have no access to electricity. The research aim is to design an efficient and low cost system for these areas by designing a suitable independent electricity generation system. The research objectives include:

- Sizing and designing of a Hybrid PV System to fulfil the load requirement for a house(s) in remote Edo State Nigeria.
- Dynamic simulation of a house hybrid power system.
- Design of a DC microgrid system for a remote community
- Optimization of the system for economic feasibility using Homer Pro software to determine:
    I. Net present Cost of each system configuration
    II. Comparison between base system(diesel only) and Current system (Hybrid PV system)
    III. The robustness of the system through sensitivity analysis
- Dynamic simulation of the proposed PV system and DC microgrid system to determine stability and power quality of the system.

The thesis is structured as follows: Chapter 2 gives detailed sizing and analysis of a standalone PV system for a remote house in Edo State, Nigeria. Chapter 3 presents the dynamic simulation result for the off grid PV system of the remote house. Chapter 4 illustrates the design of a DC microgrid system for a remote community in Edo State, Nigeria. Chapter 5 includes the dynamic simulation of the DC microgrid system of the remote community. The conclusion and recommendation is presented in chapter 6.

1.7. Conclusion

This chapter gives an overview of the present state of electricity generation and distribution in Nigeria and insufficient/lack of supply of electricity in remote area. Also, it emphasises on renewable energy and importance in implementation of solar energy system in remote areas of the country. It shows that this type of energy combats the present state of environmental pollution caused by the release of carbon monoxide as a result of excess use of fossil fuels from the use of diesel generators. A 48V DC common bus system was selected after several reviews from previous studies as regards voltage for residential load. For sizing and economic analysis Homer Pro was selected, and Matlab Simulink was selected for dynamic simulation of the systems.

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Co-authorship Statement

I am the principal author and my thesis supervisor, Dr. M.Tariq Iqbal, is the Co-author in all the research papers used in the preparation of this thesis. I carried out most of the research work which includes, literature reviews, sizing, designs and simulation of systems. I also carried out the preparation of original manuscripts and revision of each of them based on my Co-authors feedback and the peer reviewers throughout the peer-review process. The Co-author, Dr. M. Tariq Iqbal, was responsible for supervision of the entire research work, he also reviewed and made corrections for each manuscripts. He also contributed research ideas throughout the research process and in the preparation of each manuscript.

Chapter 2

Sizing and Analysis of an Off-Grid Photovoltaic System for a House in Remote Nigeria

Preface

A version of this manuscript has been published in the ***Jordan Journal of Electrical Engineeering Vol 8, No 1 (2022)*** *. I am the primary author and carried out most of the research works, including the literature reviews, system sizing , design and result analysis. I prepared the original manuscript and also revised the final manuscript based on feedbacks from the co-author and the peer-review process. The Co-author, Dr. M. Tariq Iqbal, supervised the entire research work, reviewed, made corrections and contributed research ideas for the actualization of the manuscript.*

This chapter is a version of "Sizing and Analysis of an Off-Grid Photovoltaic System for a House in Remote Nigeria", J. C. Ozogbuda and M. T. Iqbal, *Jordan Journal of Electrical Engineering* Vol.8 No.1, Pages 17- 26, 2022.

Abstract

This paper presents the design and modelling of an off-grid Stand-alone Photovoltaic (PV) system for a house located in remote Benin City, Edo State in Nigeria, with no access to the electricity grid for fulfilment of load requirement in order to meet the basic electrical needs. Using a 48V DC bus, the system was sized using Homer Pro. Optimization results presented various design system for which the most preferred cost effective and efficient system consists of a 1.23kW solar with 325W each (4 modules), 4 batteries of 12V, 1.60kW inverter, and a 4.80kW generator. The hybrid system was a preferred result in comparison to the base system (diesel generator only). Sensitivity analysis was also carried out to test the adaptability of the system with a load variation of 20%, and Solar PV input variation of 10%. Result showed that the lowest cost investment may not give the best returns. Therefore a hybrid configuration selected.

2.1. Introduction

Renewable energy is a term used to refer to forms of energy that is naturally obtained from the environment and from sources that can be replenished naturally. They include solar energy, hydro power, geothermal energy, wind energy, biomass. They are abundantly available in our world, running and maintenance cost are very low [1], it makes a smart and sustainable city, they emit little or no waste into the environment, it do not deplete. A large majority of population; mostly those living in rural or remote areas are geographically isolated from the grid [2]. Greater population of Nigerians do not have access to electricity, as the installed power capacity is 12.5MW for a population of over

200 million, as compared to other nations of the world (for example, Brazil with a population of 210 million with installed power capacity of 150GW). Hence, the need to salvage for this inadequate supply of which solar technology (Renewable energy) is the solution.

Nigeria located on the Gulf of Guinea, is a developing country with the largest producer of oil in Africa and 11th largest in the world. Brazil has a similar population but produces twenty-four times the amount of energy. The energy in Nigeria is also very unstable. Half of the population do not have access to energy while the other half experience long black outs for up to 7 hours a day. Because of this, many choose to benefit from oil-based generators. These generators are dangerous and very unstable. Poor maintenance has resulted in oil spills and flaming of natural gases.

The government has launched a program called renewable energy program. Its objective is to decrease greenhouse gas emissions by 50% within 2030 to provide reliable energy for the entire population and to provide alternative to cooking with coal and firewood in rural parts of the country. They are also working to ensure that houses are also energy efficient. The ideal tools to revive keen renewable energy for the country are solar panels, windmills and hydroelectric power plants.

Various households in developing countries such as Nigeria have remote communities that are cut out from the utility grid and integrating these areas to the grid could be capital intensive. Hence, in remote areas in Nigeria, the best alternative is the use of solar energy from the sun which is converted to electrical energy for powering domestic appliances in those communities. Due to the geographical location of Nigeria, solar energy is readily available which makes it the best option for remote locations. Egbon designed a standalone solar PV which was carried out in the northern part of Nigeria, results showed that with a 4kW array made of 24(12V, 500Ah) batteries, 5 kVA, a 48 volts inverter built in with charge controller, is sufficient to meet the load demand of a typical household in the remote areas of Kano State, Nigeria. The system was found to be reliable and cost effective with the capability of producing power for a period of 3 days in a rainy day using the backup batteries [3].

Numerous researches in renewable energy resources in Nigeria have been carried out with the objective of determining the feasibility in the country**.** Onyebuchi carried out an estimate on solar energy potential in the country with a device conversion efficiency of 5% resulting in 15.0×10^{14} kJ of useful energy in a year, which equates to 258.62 million barrels of oil, amounting to 4.2×10^{5} GW/h of production in electricity yearly [4]. Chineke and Igwiro revealed the abundance of solar energy resources that can be harnessed in Nigeria. The country has an average solar irradiance of 5.25kWh/m^2/day at the northern area. It has been estimated that the average sunshine hours in Nigeria is 6.5 hours. This produces an average solar intensity of about 1,934.5kWh/m^2/year. In the span of one year an average of 1770TWh/year of solar energy hits the surface of the land area in Nigeria. This amounts to 120,000 times the yearly electricity energy generated by National Electricity Company in the country known as Power Holding Company of Nigeria (PHCN) [5].

One of the cleanest sources of energy which produces DC power is the PV. Use of the PV system can reduce losses resulting from the conversion of AC to DC by a factor of 30% [6]. Kumar proposed a control algorithm for proper operation of the PV system in household application due to the unpredictable changes in solar irradiation and load [7].

Shimomachi carried out analysis using Electrical Transient Analyser Program (ETAP) to determine AC and DC distribution of power in a residential capacity, considering factors such as architecture of residence and distribution of load. From the analysis, comparison was made for an AC voltage of 220V with several DC voltages using a typical size 4 wire gauge, and the result revealed that the 48V DC has an efficiency of about 4% and 9% more than a 380V DDC and AC 220V respectively. Hence, a 48V DC is the best option for an isolated residence [8].

Studies carried out for sizing of PV hybrid system in remote areas, showed the reduction of Life Cycle Cost (LCC), CO_2 emission and dumped energy when compared to kerosene use or diesel generator only scenario [9, 10].Al-Rashed carried out economic analysis for a PV hybrid system for a house in remote Jordan with a load demand of 37.5kWh/day and peak load of 6.98kW. The system was optimized using HOMER, and the optimal solution was found to be using 12.1kW PV, 7.7kW diesel generator, 36kWh nominal battery and 4.82kW converter. The system showed a minimum Net Present Cost(NPC) of $66,012, Cost of Energy(COE) of $0.338/kWh and lower gas emission in comparison to other solutions[11].

This paper aims to present an efficient stand-alone PV hybrid system for remote residence to meet the challenges of inaccessibility to the electrical grid in Edo State, Nigeria. A 48V DC bus was along with a 1.6kW inverter with output 220V AC, for supply and also to increase the efficiency of the standalone system. The case study is for a typical house in remote Edo State, Nigeria. The objective of this research is the sizing and designing of the system. This paper is divided into the following: section 2 shows the structure of the design and sizing. Section 3 gives detailed economic analysis. Section 4 provides the sensitivity analysis and result. Lastly, section 5 presents the conclusion.

2.2. System Sizing

2.1.1. Site Selection and Electrical Loads

The selected site is located at Benin-Asaba highway in Edo State, Nigeria. It is an off-grid two-bedroom bungalow residence with no access to the utility grid. Primary source of power is the generator. On Google maps it has the following co-ordinates: Latitude: 6°17'22.2"N, Longitude: 5°59'31.8"E (6.28949409312645, 5.992154342254569).

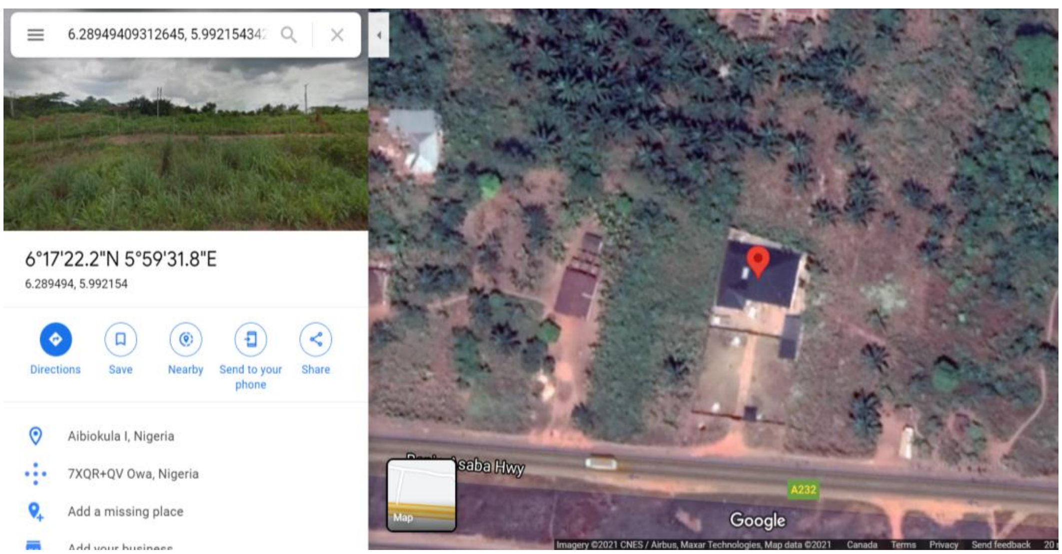

Fig. 2.1. Location of site on Google maps.

Fig. 2.2. Site photo 1.

Fig. 2.3. Site photo 2.

In determining the load, the table consisting of the daily energy consumption for a house in remote Edo state, Nigeria (Table 2.1) below shows a list of the appliances in the residence, the power rating, energy consumption and duration of usage per day for each of the appliances using generator.

Table 2.1. Daily energy consumption for a house in remote Edo State, Nigeria.

Appliance	Quantity	Power Rating (W)	Total Wattage (W)	Duration (Hours)	Total Energy (kWh)
Ceiling fans	2	60	120	7	0.84
Television	1	50	50	5	0.25
Deep Chest freezer	1	140	140	10	1.4
Water Pump	1	750	750	0.2	0.15
LED bulb	7	8	56	6	0.34
Double arm streetlight	2	70	140	3	0.42
Total load:			1.26kW		3.4kWh

2.1.2. Design Calculation:

Efficiency of PV, η_{pv} = 12%

Solar irradiance = 5.75KWh/m^2/day

Available energy $= \dfrac{5.75kwh}{m^2 - day} \times 0.12 \times 5m^2 = 3.45kwh/day$

In a year, $3.45 \times 365 = 1,259.25kwh/year$

Typical house load $= 3.4 kwh / day$

5 days backup $= 5 \times 3.4 = 17 kwh$

Using a 48V bus:

Battery bank Ahr $= \frac{17,000}{48} = 354.1667 Ahr$ (100% depth of discharge)

Say each battery = 35Ahr, 12V

Strings of Battery = $17,000 / 48V / 35 = 10.1 \approx 10$ strings (Too many batteries)

For a 48V bus, four 12V battery will be connected in series to make 48V, therefore strings of battery = 4 × 10 = 40 strings (100% depth of discharge). Since 100% depth of discharge will reduce battery life, it is therefore not allowed. Therefore, we use 50% depth of discharge = 80 batteries will be required.

2.1.3. Generator Specification and Maintenance/Operating Cost:

If the solar resources are not available, some of the load demand will be mitigated, some from the battery and some from the generator, so therefore a small generator is added to the configuration. Generator specifications for household are listed in Table 2.2 below showing the cost specification, capital cost, maintenance and operating cost.

Table 2.2 Generator specifications for the household.

Specification	Details
Model	Elemax SH2900DX(Gen50)
Maximum output	5.5HP(horsepower)
Maximum output (kW)	4.8kW
DC output (V)	12V/8.3A
Fuel Tank	15L
Double arm streetlight	2
Cost of Generator	$350
Maintenance cost/Month	$20
Fuel cost/month	$102 - $117
Total Average cost of Maintenance/Month	$130

The generator is fuelled with 7 to 8 liters of fuel daily, which is approximately 210 to 240 liters per month. The home is completely off the grid and runs on generator mostly from 8pm at night to 6am the next day morning. 1 liter of fuel in Nigeria costs = $1.51.

2.3. Solar Irradiance of Location

The output of light energy from the entire disk of the sun, measured at the earth is called solar irradiance. Solar irradiance is a crucial factor of consideration in the design of a PV system. The Homer Pro is a very useful tool that gathers data from around the world. Data such as; wind resources, temperature, solar resources, and hydro resources. The figure below shows the solar irradiance of a location in the remote part of Benin City, Edo state, Nigeria. From the data gotten from Homer Pro, it showed that the annual average solar irradiation of the location is 4.66kWh/m^2/day. (See fig.2.4 below). Designed system block diagram is provided in fig 2.5.

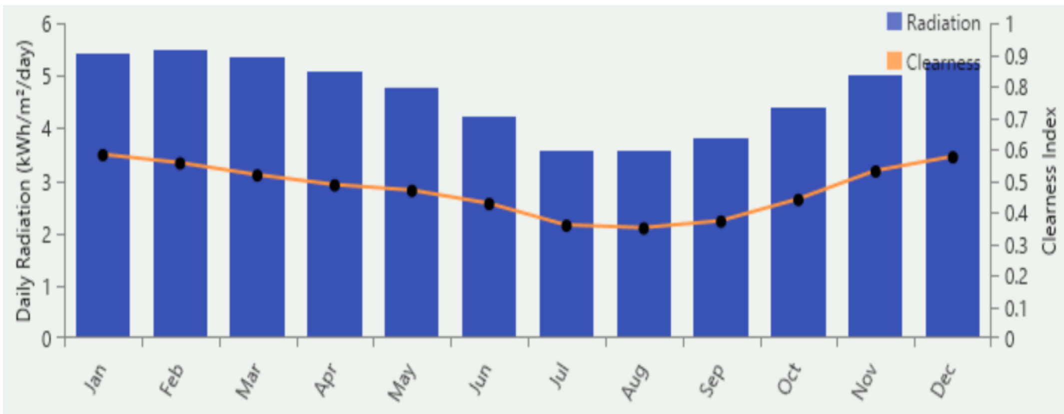

Fig. 2.4. Average monthly solar irradiance of selected location.

Figure 2.4 above shows the average solar irradiance of the remote location in Nigeria, the chart shows the monthly distribution of solar radiation for a span of one year. With an average solar irradiation of 4.66kWh/m^2/day, the chart shows peak radiation during the beginning months of the year and towards the ending of the year. These periods normally known as “dry season” are characterized with lots of sunshine and little to no rain fall.

2.4. System Component

Design was carried out using optimization software called Homer Pro. The system components selected for the design includes a generator, solar PV, and a battery. The figure 2.5 below shows the design configuration and system components in the Homer Pro software.

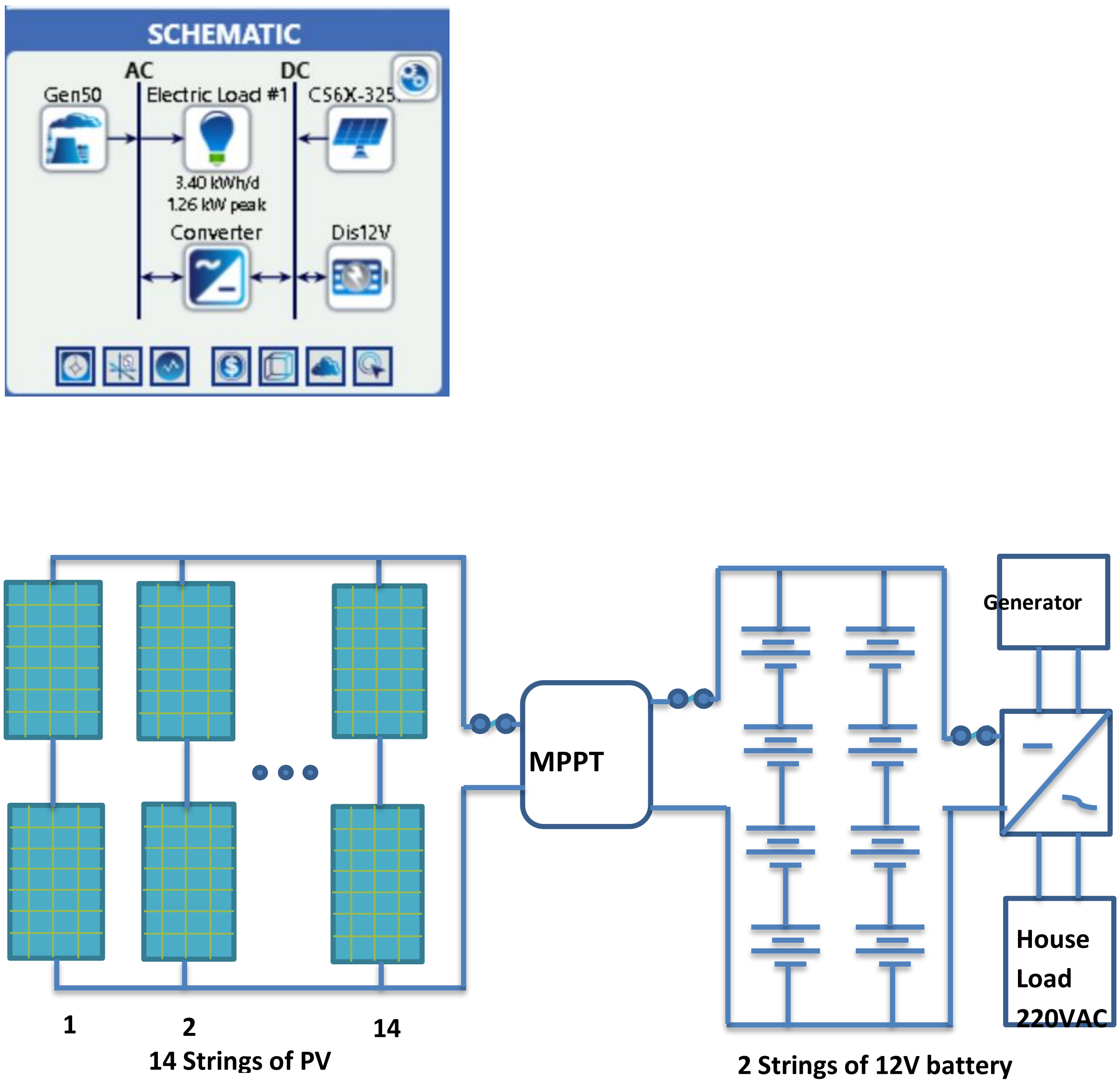

Fig. 2.5. PV-hybrid system.

Homer Pro software was used to perform sizing of the system. The system consists of a 48V DC bus with DC load, CS6X-325P solar PV, 12V battery, 5.5HP (Horsepower) generator and a 1.6KW converter connected to it as seen in figure 2.5 above. After simulation of the system, the optimization result obtained showed the Net Present Cost (NPC), operating cost, initial capital, power rating of components, Renewable fraction , and other important parameters with possible configurations that would yield a cost effective and efficient system as seen in fig. 2.6 below.

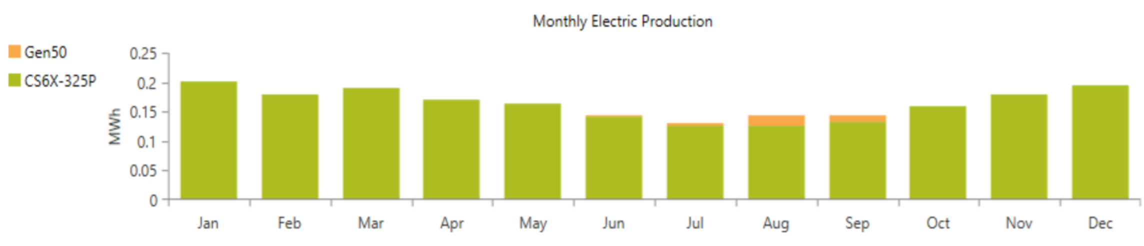

Fig. 2.6. Electrical output for the PV-battery hybrid system.

Figure 2.6 above shows the monthly electricity production of the PV relative to the generator. From the chart it can be seen that the PV produces a greater amount of electricity in the span of one year in comparison to the generator which generate very little amount in the span of one year.

2.5. Economic Analysis

The software (Homer Pro) also incorporates a tool called “compare economics” tool. This tool aids in the comparison between the possible configuration s obtained from the optimized results to determine the most cost-efficient and reliable system to adopt for a specific load system. From the compare economics analysis, looking at the Net Present Cost (NPC) of the base system (A generator) and the current system (A configuration of PV, Generator, Battery, and Converter), it shows that the current system is most cost efficient and the better option as compared to the base system. Fig.2.7 below shows the economic comparison between the two systems. NPC of generator is $780076, while for the hybrid power system the NPC is $12084 that is much lower than existing arrangement.

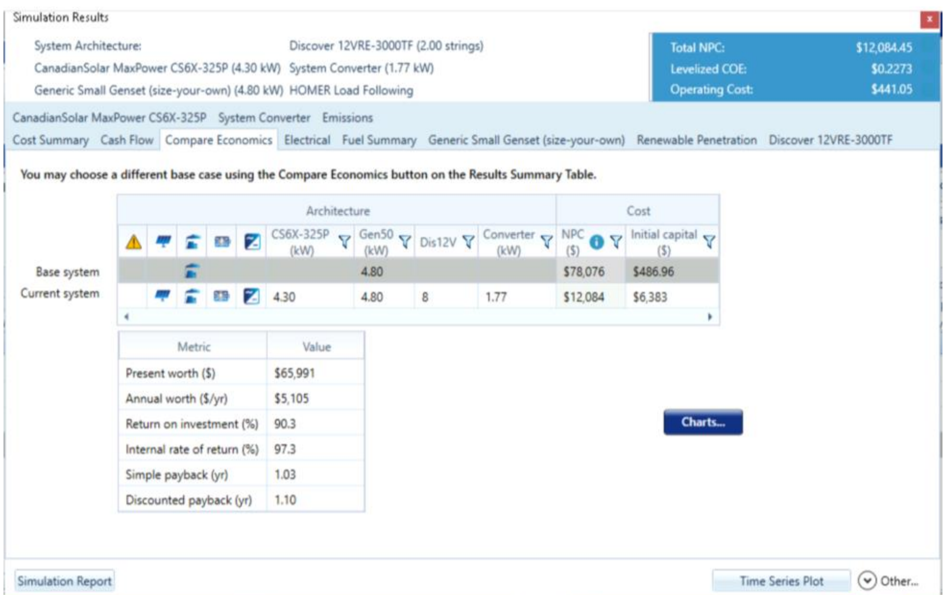

Fig. 2.7. Comparison between base and current system.

Homer Pro is a great tool not just for finding the low-cost systems but with doing investment analysis. Building upon the deeper understanding of Homer Net Present Cost, What it means, and how it handles project and component lifetimes, Homer can determine payback and internal rate of return by comparing a particular simulation to another base simulation. In this project, the base case/business as usual case (The system you might design if you were not doing an incremental investment in renewables or storage) would be just generators, since it is the traditional way of supplying power in remote areas. By selecting a base case, Homer will calculate the payback for all the systems within each optimization result. In the wining system architecture, Homer has calculated the simple payback as one year and showed a 97% internal rate of return. And you can see the value calculated for other system as well as shown in the fig.8 below. With a 92.6% renewable fraction, the system would cost $6,383 to install, $441.05 for annual operating cost and a Net Present Cost (NPC) of $12,084, which is more economical in comparison to the diesel only case that has an NPC of $78,076.

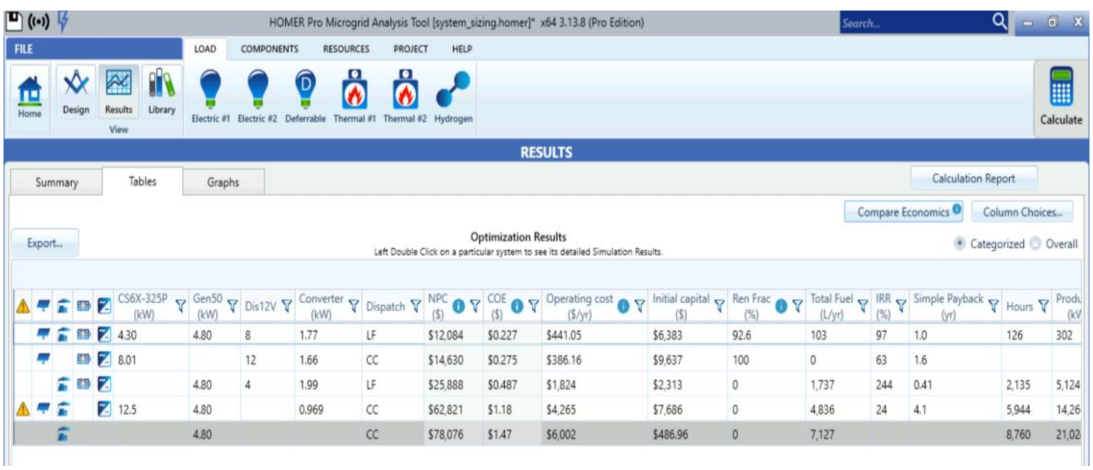

Fig. 2.8. Payback rate and Internal Rate of Return (IRR).

The details of how the internal rate of returns (IRR) and simple payback values was realized is also shown in the fig.2.8 above.

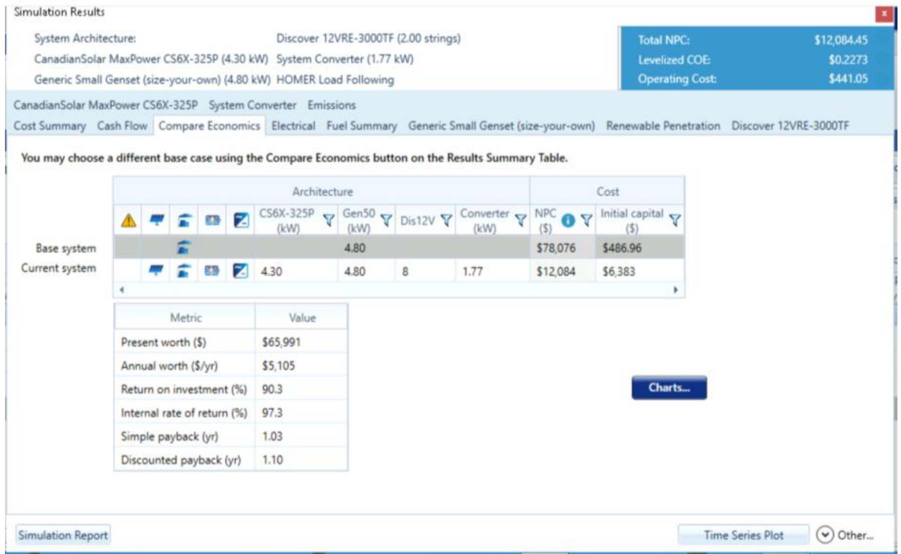

Fig.2.9. Detailed analysis of compare economics.

In the fig.2.9 above, shows additional calculations such as present worth of investment $65,991, annual worth of investment relative to diesel case $5,105, as well as the return of investment 90.3%, and some different ways of calculating simple paybacks and internal rate of return.

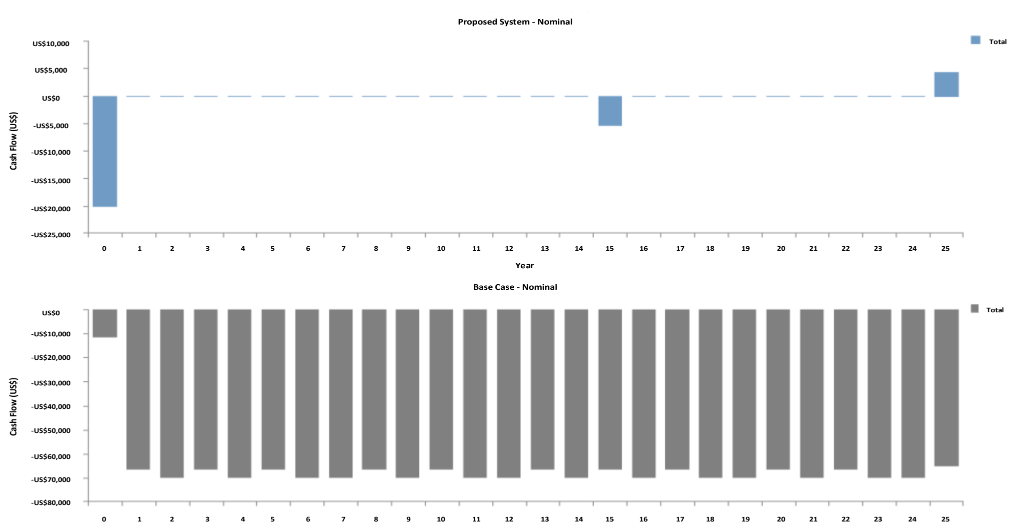

Fig. 2.10. Chart presentation for Current System and Base System.

In the chart presentation for current and base system as shown in fig.2.10 above, the selected hybrid design reveals a large capital outlay and relatively modest operational cost as compared to the diesel system where you have a relatively smaller capital outlay but significantly higher operational cost.

2.6. Sensitivity Analysis

At the most fundamental level, the simulation layer in Homer tells us what it cost to operate a system, the fuel it will use, the energy that will cycle through the batteries that determine how long it will last before needing to be replaced. The real heart of Homer is the optimization algorithm that tells us what system is best. If you only do one optimization, you only know what system is best for one scenario. So, sensitivity analysis tells us what happens if for example, prices changes, the load grows or the technology improves, how that system design could be adapted for different markets.

In this model, we are performing a sensitivity analysis on the load and solar PV. We have a range of load variation from 11.3KW up to 13.5KW (20%) and a range of solar PV input variation from 77% up to 99% (10%). (Indicating that sometimes PV modules are clean or dusty).

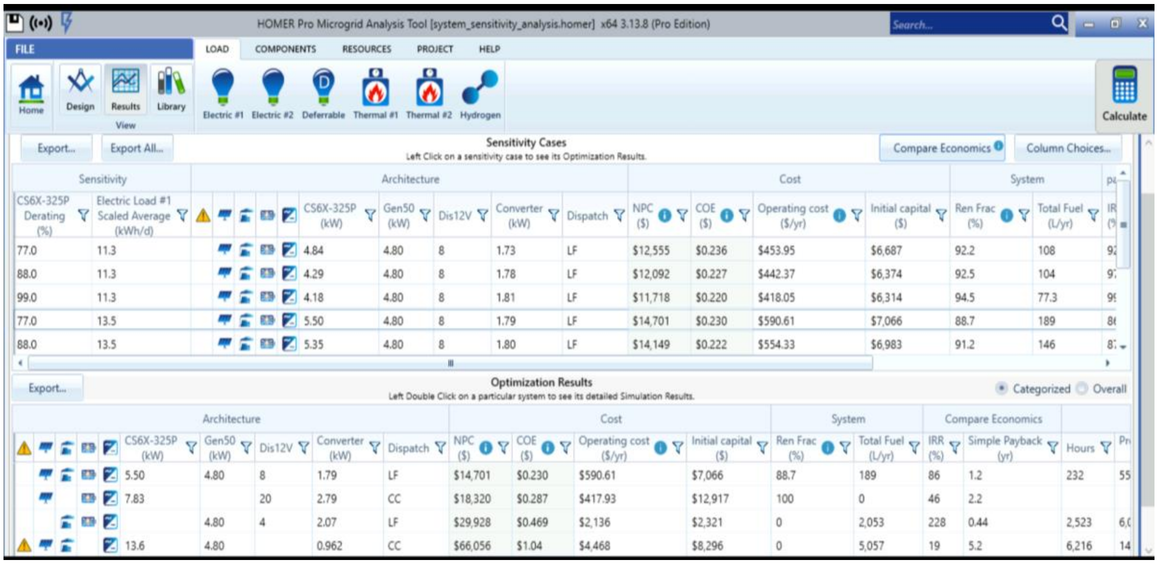

Fig. 2.11. Simulated result of sensitivity analysis

After simulation,, the result shown in fig. 2.11 above reveals two set of tables: the sensitivity case table and the optimization results. In the sensitivity case table, there are several entries. For each sensitivity cases in this table, Homer displayed the lowest cost design, which means that each of the systems have the lowest net present cost after comparing all the various design options. For example, for the case of 77% CS6X-325P solar PV and 13.5KW of average electric load per day, the lowest cost design found has 5.50KW of PV, 8 of the 12V lead acid battery, a 1.79KW converter, and a 4.80KW generator. By selecting this system, it changes the optimization result table. The optimization result updates to show how all the different system simulated, all the different design options performed at the selected sensitivity case (i.e., the 77% CS6X-325P Solar PV Derating factor and 13.5KW of average electric load per day). In the optimization table, it is noticed that the lowest net present cost/lowest cost system is always at the top of the table. It is all ranked according to the net present cost. The top system in the sensitivity table is the same system as selected in the sensitivity case table above it. It is also seen that the overall winner at this sensitivity case costs $7,066 to install, and on average it costs about $590.61 to operate each year. The operating cost may vary from year to year but $590.61 is the average operating cost. And together, the initial capital cost and the annualized operating cost can be used to calculate the net present cost (NPC) that is used to compare systems.

2.7. Conclusions

The study involved the sizing of a residence in remote Edo State in Nigeria having an average load of 1.26KW and energy consumption of 3.4KWh. Using a 48V DC bus, Homer Pro was used to determine the most optimal system for the off-grid residence both in terms of system design and economic feasibility for solar PV installation. From the optimization result, looking at the Net Present Cost (NPC) of all the possible system design, the PV, converter, and battery configuration is a better option as compared to the diesel only based system. Sensitivity analysis was also carried out for a solar PV input variation of 10% and load input variation of 20%, to determine the adaptation of the system. From the sensitivity case analysis, it is interesting to note that the lowest cost investment may not be one of the best returns. For example, for the sensitivity case with 77% (Dirty PV array) solar PV input variation and 13.5KW electrical load, the third entry of its optimization result shows that less money was spent and there was no investment in PV, but it gets a faster rate of return on the initial capital of about 228%. In essence, a little bit less money was invested with a little different operational savings, but recouping investment relative to the diesel only case would be faster as compared to the fully optimal low cost design.

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Chapter 3

Dynamic Simulation of a Stand-alone Photovoltaic Hybrid System of a Remote house in Nigeria.

Preface

*A version of this manuscript has been published in the **2021 IEEE 12th annual, Information Technology, Electronics and Mobile Communication Conference (IEMCON).** I am the primary author and carried out most of the research works, including the literature reviews, system design, dynamic simulation and result analysis. I prepared the original manuscript and also revised the final manuscript based on feedbacks from the co-author and the peer-review process. The Co-author, Dr. M. Tariq Iqbal, supervised the entire research work, reviewed, made corrections and contributed research ideas for the actualization of the manuscript.*

This chapter is a version of "Dynamic Simulation of a Stand-alone Photovoltaic Hybrid System of a Remote House in Nigeria", J. C. Ozogbuda and M. T. Iqbal, *2021 IEEE 12th annual, Information Technology, Electronics and Mobile Communication Conference (IEMCON).* DOI: 10.1109/IEMCON53756.2021.9623160.

Abstract

In the remote part of Nigeria, most households suffer from lack of electricity due to inaccessibility to the utility grid. This paper presents the simulation of a Photovoltaic (PV) hybrid system with battery and generator backup of an off-grid Stand-alone PV system for a house located in remote Benin City, Edo State in Nigeria. House peak load is 1.26kW and daily energy consumption is 3.4kWh, with no access to the electricity grid for fulfillment of load requirement to meet the basic electrical needs. The system is designed in Homer Pro and simulated using the Matlab Simulink software, it comprises of a 1.23kW PV made up of 4 modules (325W each with 2 in series and 2 in parallel), A MPPT (maximum power point tracking), a DC –DC buck converter, 4 backup battery of 12V, 350Ahr connected in series and a 4.8kW emergency generator system with a 1.6kW inverter which converts the output DC voltage of 48V from the converter to an alternating AC. The inverter is connected directly to a step-up transformer which boosts the voltage from to 220V AC for supply to the load. Result shows different scenarios and configuration. With a 50% State of Charge (SOC) of the battery and full electrical load, the PV charges the battery and supply power to the load. However, when the volatage of the battery is below 49V the emergency generator turns ON to charge up the battery. Whereas, in the scenario of 98% SOC of the battery, regardless of the load, the generator is not operational because the control of the generator automatically turns off when the battery is above 49V. The system dynamic simulation results and response to changing inputs are presented in this paper.

3.1. Introduction

The supply of electricity in non-electrified remote areas can be produced by distributed renewable energy [4]. Ankit proposed a Matlab based model of a standalone photovoltaic system for a small rural community of 15 households located in Subardan areas, with each household taking an average electricity demand of 1.7kWh/day, the total yearly load demand for the rural community was estimated to be 9800.632kWh. Using yearly metrological data to develop the model, simulated result shows that the system is exceedingly robust and can handle the dynamics associated with irradiance, temperature, and load demand [1].

Kartika performed simulation and development of Solar PV system for the fulfilment of load demand in isolated areas. The system comprised of PV solar panel, a DC-DC boost converter and a two-level inverter connected to the load. PI controller was used in controlling and maintaining the DC link constant regardless of variation in the input and output parameters which resulted to constant inverter output [2]. Wahyu proposed a PV hybrid with battery backup system for powering a Base Transceiver Station (BTS) telecommunication system to supply telecommunications system in rural communities with inaccessibility to electricity. To supply the BTS load by 43177.78Wh/day with 48V voltage system can be generated with 50 solar panels. From the simulated results it was found that PV modules which is the major generator to supply the base station is not sufficient due to inconsistency in supply, hence, to ensure continuity of electricity supply batteries and generator backup were integrated to the system [5]. Chaudry proposed an off grid PV system for a house in Pakistan having a load of 7.81kWh/day, the system comprised of 8 batteries and 36 PV. From the design, simulated result showed that the configuration is sufficient enough to power the house efficiently independently from the national grid [6]. Arif carried out a design for an off grid solar system for a house with average energy consumption of 40kWh per month located in a remote community in Pakistan, the system comprised of 4 solar panels of 140W, giving a total of 560W PV, 4 batteries each having 125Ahr and a 1kW inverter. Result showed the system provided better electrification solution with an energy production of 726kwh per annum [7].

This paper aims to present the Matlab dynamic simulation of stand-alone PV hybrid system representing a remote residence in Edo State, Nigeria having a peak load of 1.26kW and daily energy consumption of 3.4kWh/day. The system comprises of a 1.23kW PV (325W each), MPPT for maximum power tracking, DC –DC buck converter, a backup battery and generator system with a 1.6kW inverter which converts the output DC voltage of 48V from the converter to an alternating AC. The case study is for a typical house in remote Edo State, Nigeria. The objective of this research is the dynamic simulation of the system. This paper is divided into the following: section 2 shows the site location. Section 3 gives full the system components and specifications. Section 4 provides the dynamic simulation and result. Lastly, section 5 presents the conclusion.

3.2. Site Location

The selected site is situated in Edo State, Nigeria. The residence is a two-bedroom bungalow with no access to the utility grid. On Google maps the selected site has the following co-ordinates: Latitude: 6°17'22.2"N, Longitude: 5°59'31.8"E

(6.28949409312645, 5.992154342254569). All system components were selected using Homer Pro. Figure 3.2. shows all components in a block diagram. Table 1 provides a list of all selected components.

Fig.3.1. Location of remote site in Edo State Nigeria.

3.3. System Components

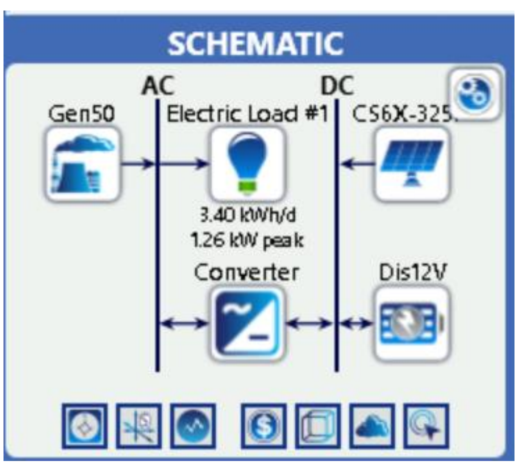

Fig. 3.2. Homer Block diagram of all selected components.

Table 3.1. List of system components and specifications.

Appliance	Quantity	Specification
PV	4, 325W modules	1.23kW
Battery	4, 12V, 350Ahr	48V
Generator	1	4.8kW
Inverter	1	1.6kW

3.4. Dynamic Simulation

The figure 3.3 below shows the dynamic system design carried out in the Matlab Simulink environment, the configuration of the system is made up of a PV system of 1.23kW comprised of 4 modules each of 325W, with 2 connected in series and 2 in parallel. MPPT is applied to the PV to ensure that the PV gives power at its maximum. The DC – DC buck converter is used to step down the voltage of the PV to the bus voltage of 48V, the PV charges both the battery and supplies power to the load. The system also incorporates a permanent magnet synchronous generator which serves as an emergency backup power system for charging the battery when the voltage of the battery goes below 49V due to inconsistency in solar resources. The output 48V DC from the buck converter is fed directly to the inverter which converts the DC to alternating AC. The 48V AC is stepped up by a transformer to 220Vrms AC which is used to power the load. A MPPT is used to control a DC-DC buck converter. Generator is a permanent magnet type, and its 3-phase output is connected to DC using a full bridge rectifier. Inverter produces 50Hz output that is stepped up to 220V using a transformer. Load is divided into two sets to represent a changing load. System simulation results are discussed in the following sections

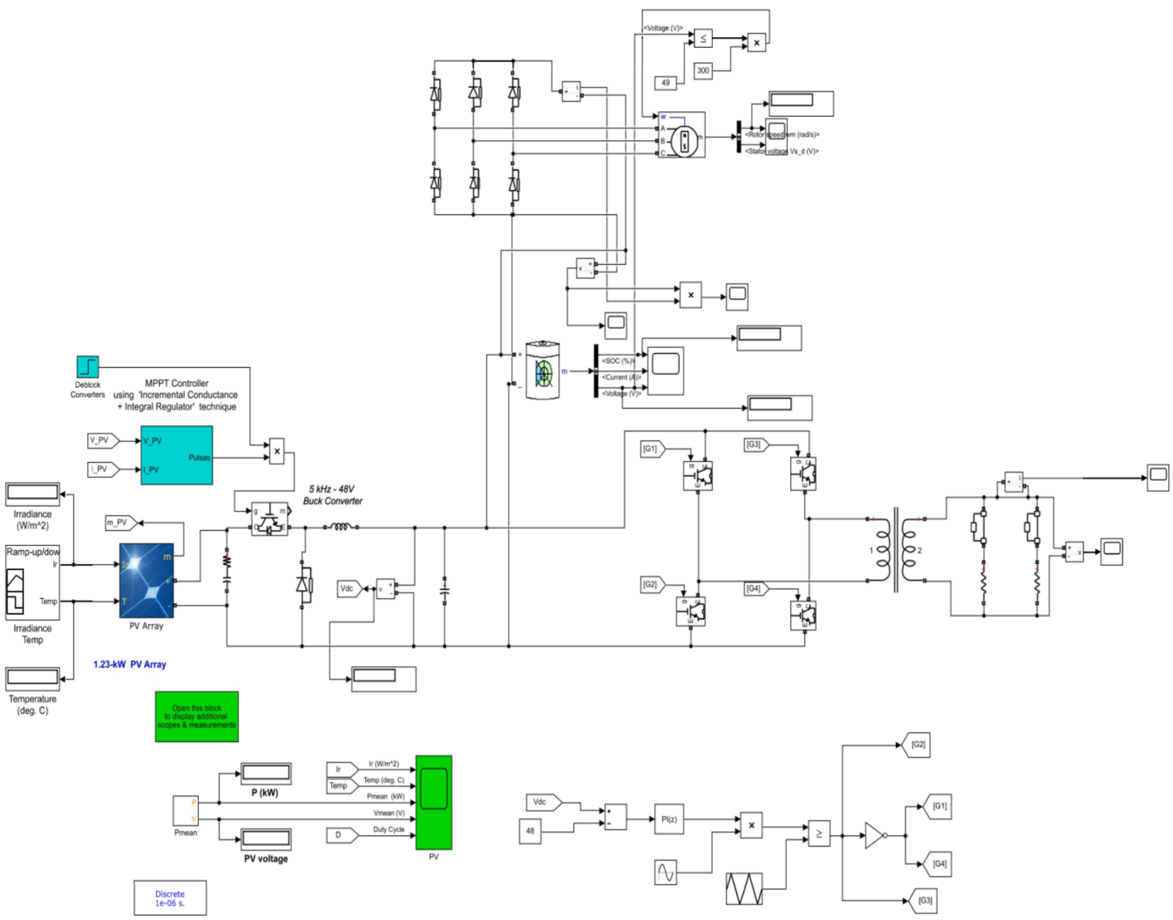

Fig. 3.3. PV-battery-generator hybrid system simulation in Simulink.

3.4.1. Half load, 50% State of Charge (SOC), and Generator

The figure below shows the Irradiation, Temperature, Power, Voltage, and duty cycle of the PV. The duty cycle varies according to the solar resources. The flow of the duty cycle follows the Irradiance and power of the PV when the battery is not connected. This result shows that the designed MPPT is able to track the input solar variation.

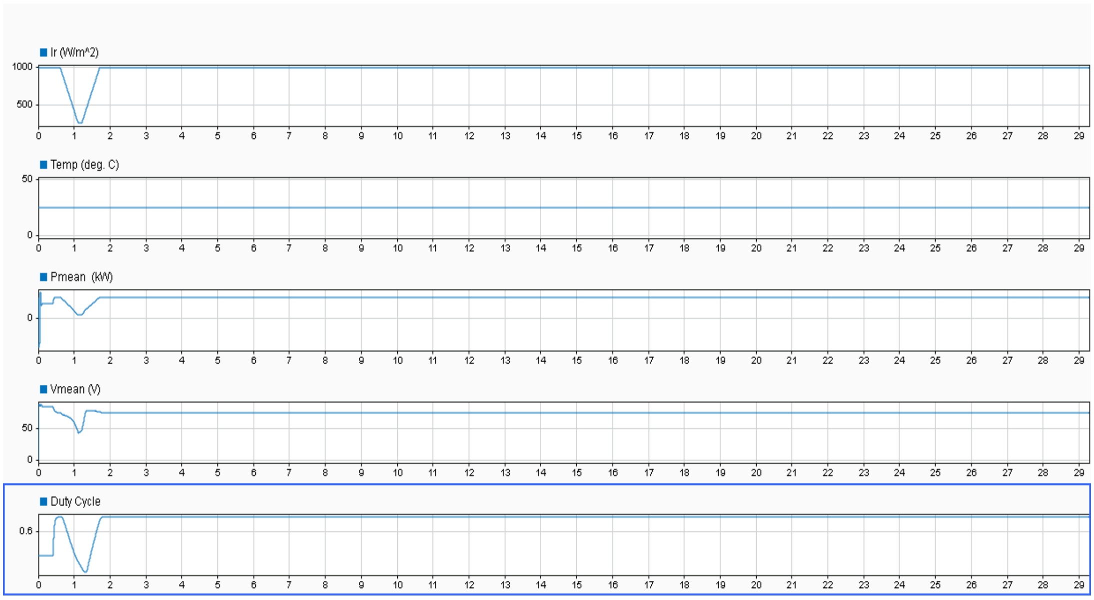

Fig.3.4. PV, irradiation, duty cycle, power, voltage signal.

When the battery is connected across the circuit, the duty cycle varies according to the voltage of the PV as seen in fig. 3.5 below. Indicating battery charging while maintaining operation at maximum operating point.

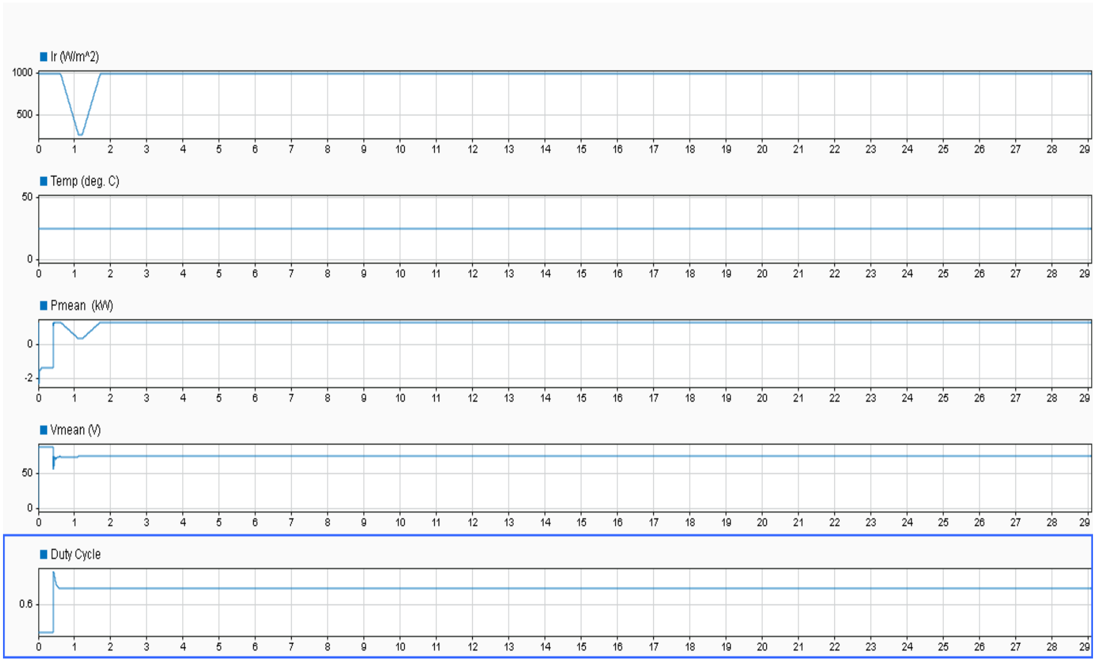

Fig. 3.5. Duty cycle varies according to voltage of PV.

The figure 3.6 below shows the charging of the battery initially at 50% state of charge (SOC). At 50% state of charge, the battery's voltage is below 49V at which point the generator of 4.8kW turns on to charge the battery up to the 49V mark and then gradually shuts down after exceeding 49V, leaving just the PV to charge the battery. From the State -of- Charge (SOC) graph it is observed that when the generator is ON the battery charges rapidly, but when the generator begins to shut down, the SOC of the battery increases slowly, this is because the power generated by the generator, 4.8kW is higher that the power generated by the PV which is 1.29kW.

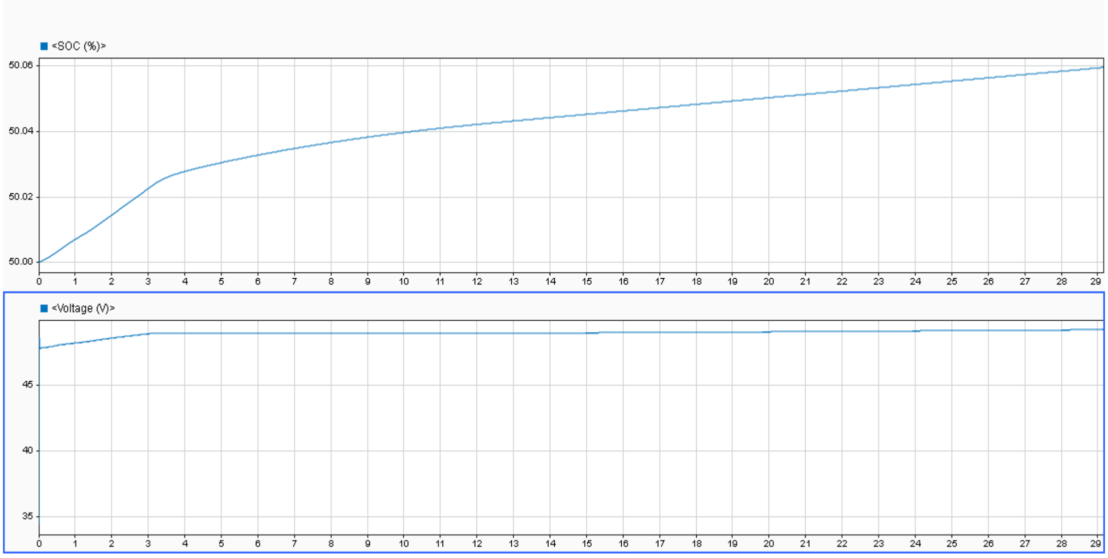

Fig. 3.6. Battery SOC and voltage.

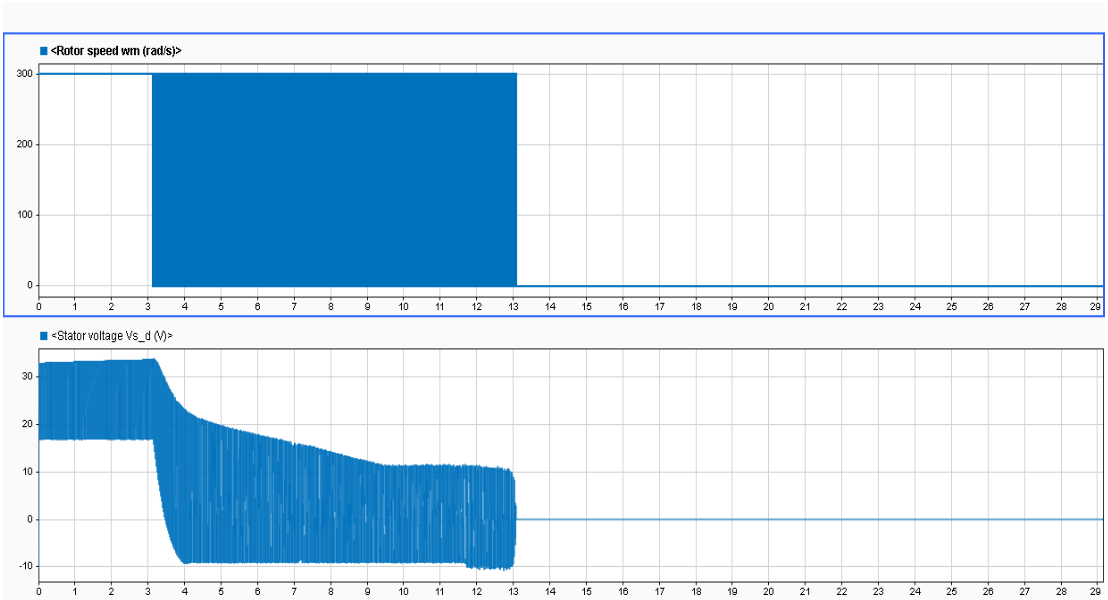

Fig. 3.7. Generator rotor speed and Stator voltage.

Figure 3.7 shows the rotor speed of the generator and stator voltage. The generator has a rotor speed of 300rad/sec. while the rotor speed is kept constant, the stator voltage increases gradually when the generator is charging the battery. At half load of

0.63kW, the generator only charges the battery for a short while before the voltage of the battery exceeds 49V and thereafter turns off. From the figure above, it can be seen that the signal changed drastically from 300rad/sec to 0 and from 33V to 0, this is because with half load there is more power going to the battery from the PV therefore the less time it will take for the voltage to exceed 49V and thereafter the generator turns off. The time at which the generator is operational is short compared to the full load scenario.

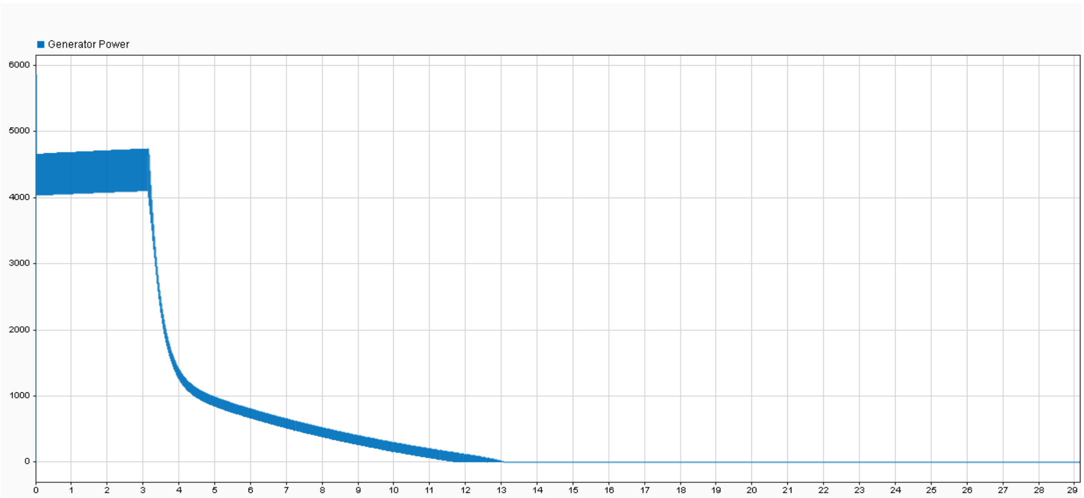

Fig. 3.8. Generator Power.

Figure 3. 8 shows the ON and OFF time of the generator at half load. It can be seen that the power supplied from the generator rated 4.8kW is but for a short while followed by a sharp drop. This is due to the fact that as soon as the battery exceed 49V, the control system of the battery immediately turns off the generator, and because its half load, the PV conveniently powers the load.

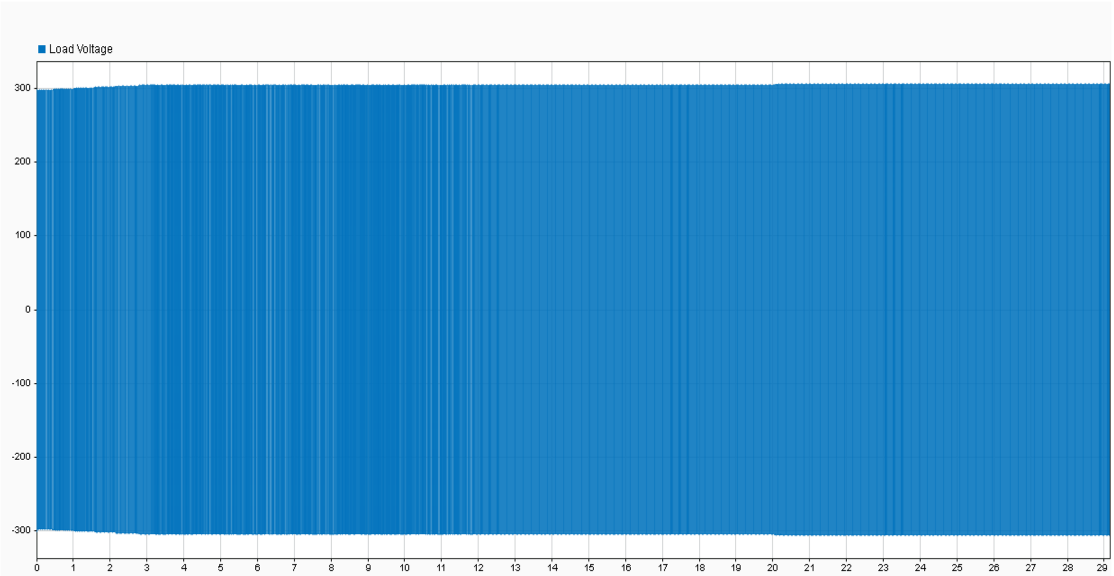

Fig.3.9. Load voltage.

Figure 3.9. above shows the load voltage of the system running at 220Vrms with peak at 311V.

3.4.2. Full load, 50% SOC, and Generator

With the full load, the generator charges the battery but not as fast as the half load scenario. After the voltage of the battery exceeds 49V, the generator turns off gradually leaving only the PV. The PV also charges the battery and supply power to the load. These results are shown in figure 3.10 below.

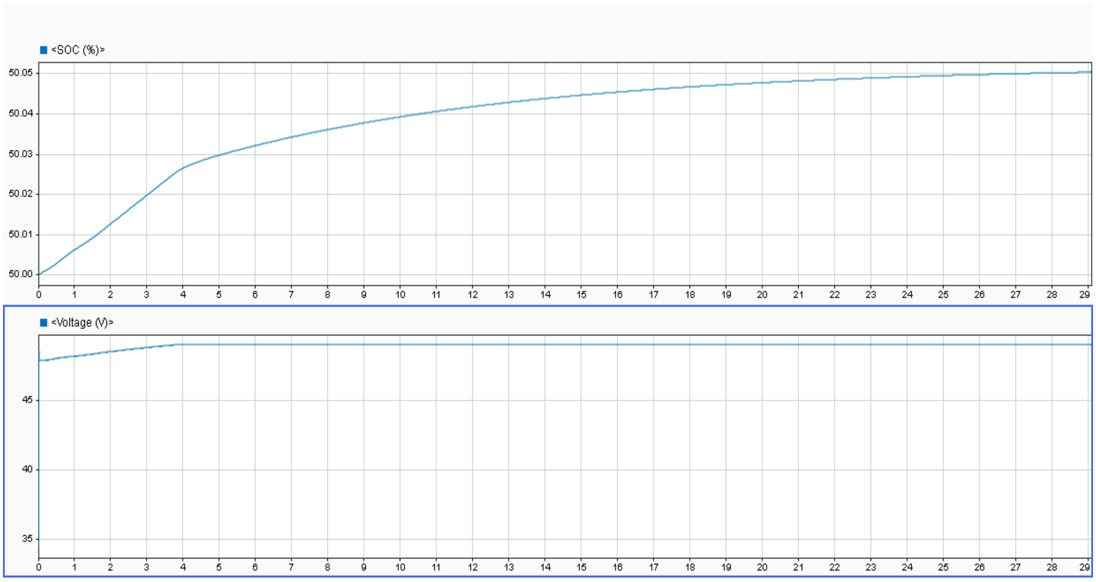

Fig. 3.10. Battery SOC and voltage.

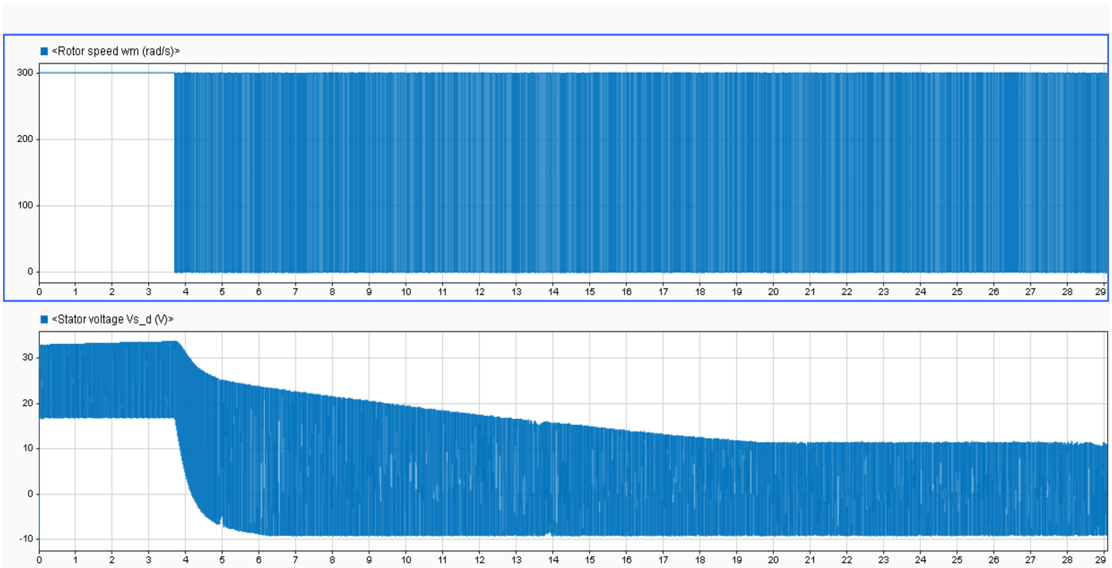

Fig. 3.11. Generator rotor speed and Stator voltage.

From the figure 3.11 above, it can be seen that the time at which the generator is operational is longer compared to the half load scenario this is because with full load there is less power going to the battery from the PV therefore the more time it will take for the voltage to exceed 49V.

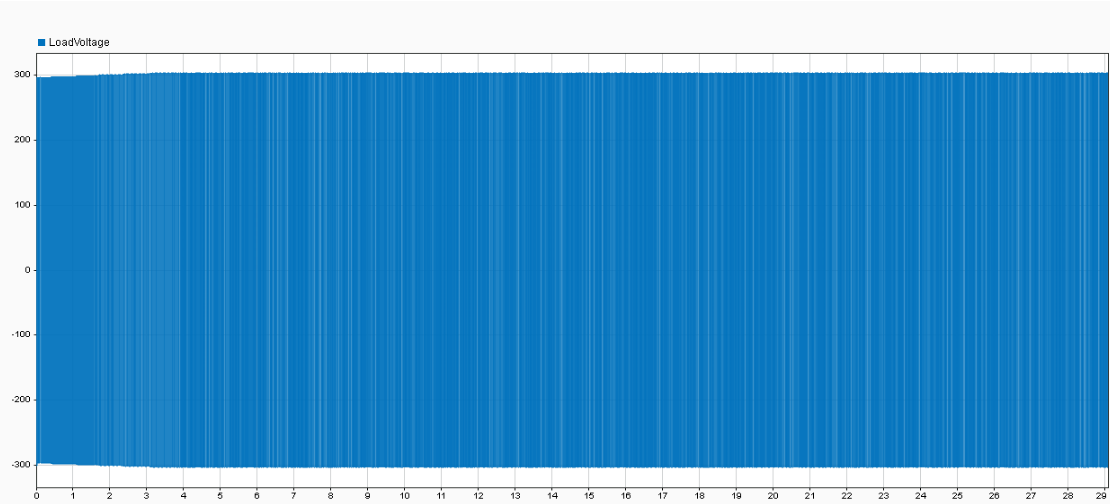

Fig. 3.12. Load voltage.

Figure 3.12 shows the load voltage of the system at full load capacity which is the same as that of half load scenario.

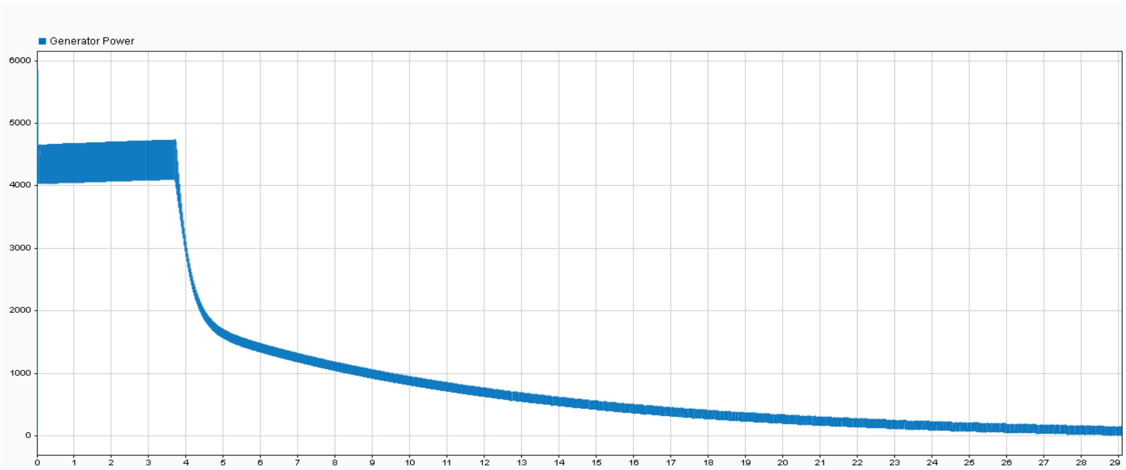

Fig. 3.13. Generator Power.

Figure 3.13. shows the generator power at full load, the generator is ON when the voltage is below 49V but short down gradually, it takes longer time for the power to reach zero as compared to the half load scenario.

3.4.3. Full load, 98% SOC, Generator

With full load, 98% SOC, the battery's voltage is above 49V and the Generator will be turned off leaving only the PV to charge the battery and supply power to the load. Because it is full load, and due to the fact that the Irradiation vary from 500kW/m^2/day to 1000kW/m^2/day, there is a sharp drop in the SOC of the battery when the Irradiance drops to 500kW/m^2/day and the gradually increases as the Irradiation goes back to 1000kW/m^2/day the PV conveniently charges the battery faster as compared to the full load scenario while also supplying power to the load. These results are shown in figure 3.14, 3.15, 3.16, and 3.17.

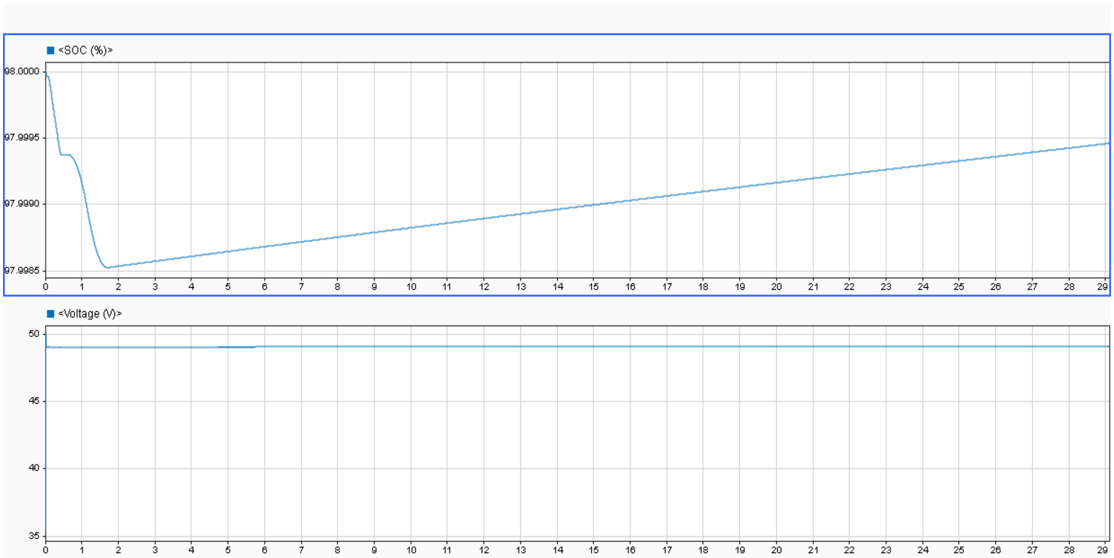

Fig. 3.14. Battery SOC and voltage.

Figure 3.14 above shows the state of charge of the battery beginning at 98%. In this scenario, the system is simulated in full load, and the graph shows a sharp drop in the state of charge of the battery when the irradiance of the solar resource reduced from 1000 kw/m^2/day to 500 kw/m^2/day. This is due to the fact that with reduction in solar irradiance there is a decrease in the power supplied from the PV, and also, since at 98% SOC the voltage of the battery is above 49V, the generator is totally OFF, so therefore, the power received by the battery comes solely from the PV and since the PV both supplies power to the battery and to the load at the same time, with full load, and reduction in solar irradiance, there is less power going to the battery at 500 kW/m^2/day, hence, a sharp drop in the SOC of the battery, but when the irradiance increases to 1000 kw/m^2/day there is a rapid rise in the SOC of the battery.

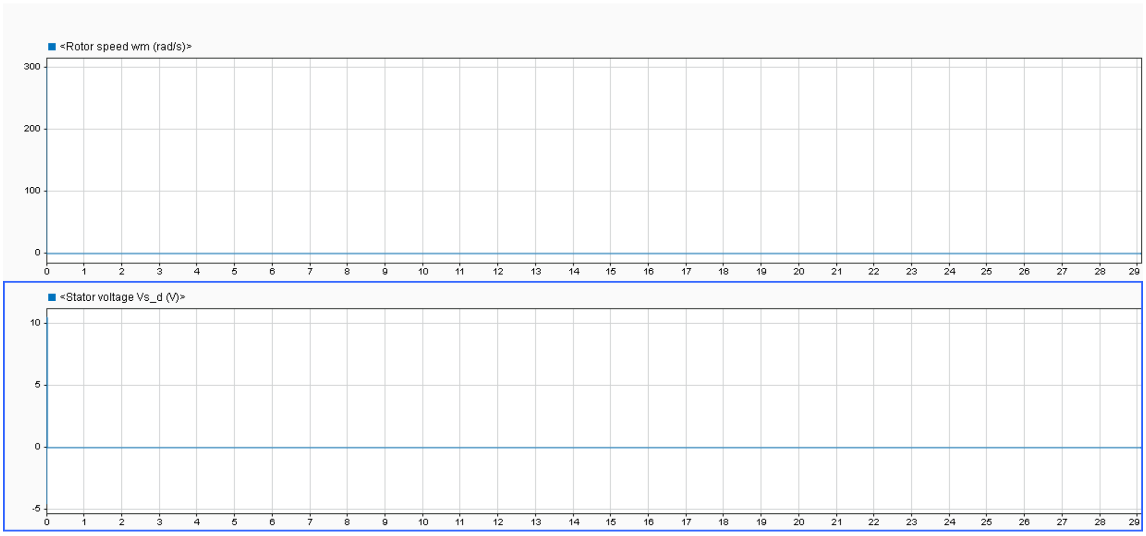

Fig. 3.15. Generator rotor speed and Stator voltage.

Figure 3.15 above shows the state of the generator at 98% SOC of the battery. At 98% SOC, the voltage of the battery is above 49V, and the control system of the generator is designed in such a manner that when the voltage is above 49V the generator turns off, hence, the generator voltage is zero.

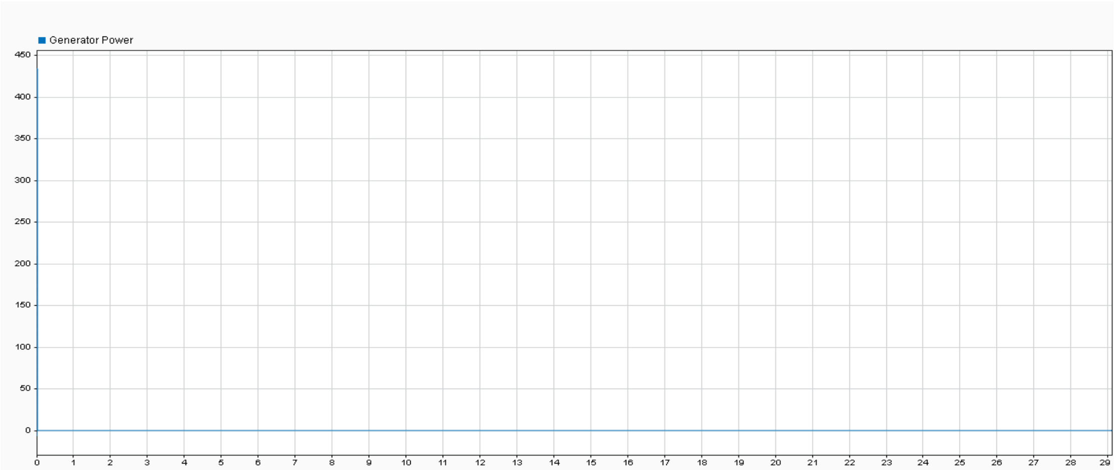

Fig. 3.16. Generator power.

Figure 3.16 shows the generator power at zero since the generator is not operational when the battery voltage is above 49V.

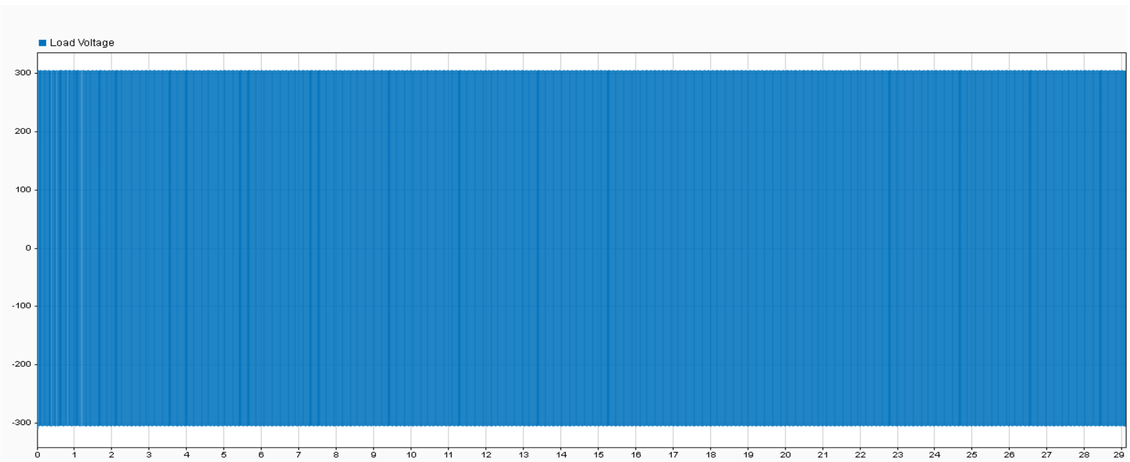

Fig. 3.17. Load voltage.

Figure 3.17 shows the load voltage of the system which is at 220Vrms (311V peak).

3.4.4. Half load, 98% SOC, Generator

With half load, 98% SOC, the battery's voltage is above 49V and the Generator will be turned off leaving only the PV to charge the battery and supply power to the load. Because it is half load, when the Irradiance drops to 500kW/m^2/day, the reduction in the SOC is minimal, and when the Irradiation goes back to 1000kW/m^2/day there is a rapid increase in the state of charge of the battery. The PV conveniently charges the battery faster as compared to the full load scenario while also supplying power to the load.

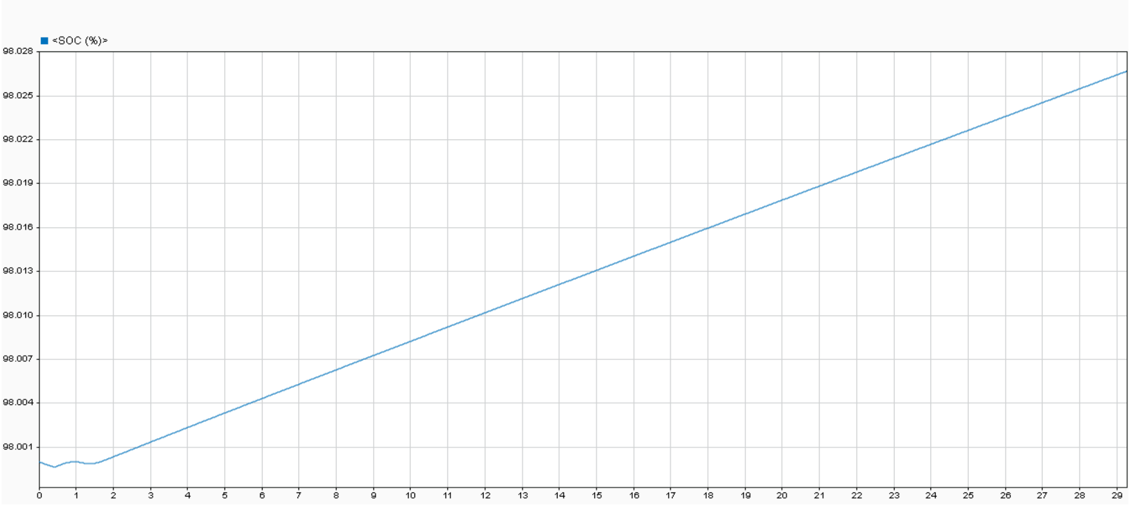

Fig. 3.18. Battery SOC.

Figure 3.18 above shows the SOC of the battery for a half load scenario when there is a variation in irradiation from 1000 kW/m^2/day to 500 kW/m^2/day. From the figure it can be observed that the SOC initially at 98% only decreased slightly in comparison to the full load scenario and thereafter a rapid increase in the state of charge. This is because for the half load scenario the power supplied to the battery is more compared to the full load case. With reduction in solar irradiation, the effect of discharge of the battery is very minimal and with increase in solar irradiation come rapid increase in the SOC of the battery.

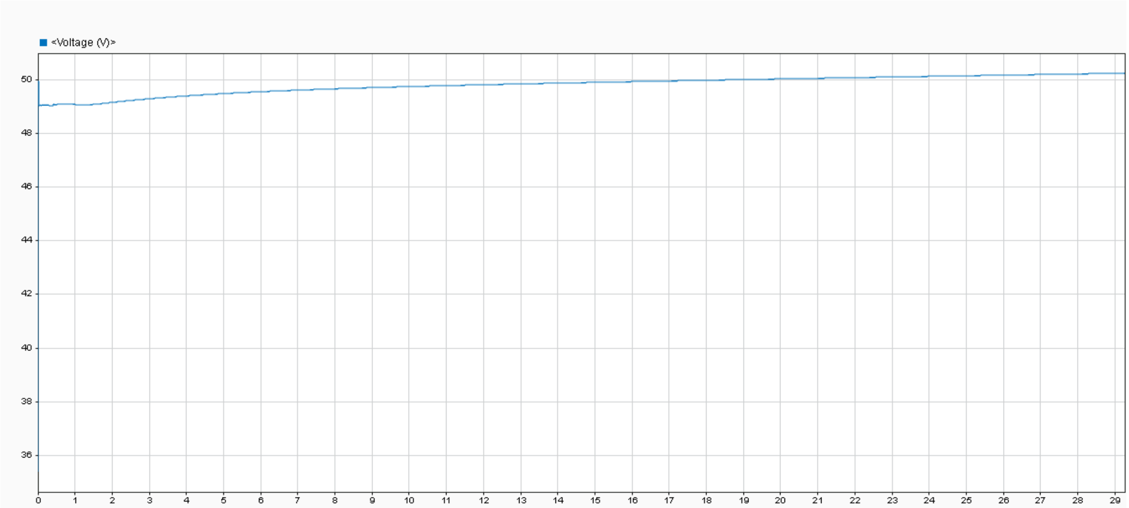

Fig. 3.19. Battery voltage.

Figure 3.19 shows the voltage of the battery when at 98% SOC with slight decrease when the irradiation reduced to 500 kW/m^2/day and a steady rise in voltage as goes back to 1000 kW/m^2/day.

3.5. Conclusion

This paper presented the dynamic simulation of a PV hybrid system with backup battery and generator for a remote area in Edo State, Nigeria. The simulation was tested in several conditions and configuration. The system was first simulated with the battery kept at 50% SOC and full load, it was observed that the PV charges the battery and supplies power to the load at the same time, in the condition were the voltage of the battery goes below 49V the emergency generator turns on and charges the battery until it exceeds 49V and then turns off. Another scenario shows the configuration of the battery kept at 98% SOC and the system was simulated in both full load and half load, result shows that in both scenarios the PV charges the battery and supplies power to the load, but the difference is that for the case of the full load the charging of the battery is slower in comparison to the charging of the battery in half load scenario. The system has been simulated and tested in different configurations and result shows that for a remote community, the configuration of PV, battery and emergency backup generator is the most suitable, economical, and reliable option to adopt.

Acknowledgment

The author would like to thank Soltech Nigeria Limited for providing graduate funding in support of his research.

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Chapter 4

Dynamic Simulation of an Off Grid Photovoltaic System with backup battery and generator for a Remote house in Nigeria.

Preface

*A version of this manuscript has been published in the **30th Annual IEEE Newfoundland Electrical and Computer Engineering Conference (NECEC) 2021. ID 7.** I am the primary author and carried out most of the research works, including the literature reviews, system design, dynamic simulation and result analysis. I prepared the original manuscript and also revised the final manuscript based on feedbacks from the co-author and the peer-review process. The Co-author, Dr. M. Tariq Iqbal, supervised the entire research work, reviewed, made corrections and contributed research ideas for the actualization of the manuscript.*

This chapter is a version of "Dynamic Simulation of an Off Grid Photovoltaic System with backup battery and generator for a remote house in Nigeria", J. C. Ozogbuda and M. T. Iqbal, *30th Annual IEEE Newfoundland Electrical and Computer Engineering Conference (NECEC)*. ID 7. 2021.

Abstract

This paper presents the simulation of an off grid Photovoltaic (PV) system with battery and generator backup for a house located in the remote areas of Edo State ,Nigeria. The case study is for a house with a peak load of 1.26kW and 3.4kWh daily energy consumption. The design was carried out using Homer Pro and simulation was performed in the Matlab Simulink software, the system is made up of 1.23kW PV comprised of 4 modules (325W, 2 in series, 2 in parallel), MPPT (maximum power point tracking), a DC –DC buck converter for stepping down the voltage, 4 batteries each of 12V, 350Ahr (48V, series connection), and a backup generator of 4.8kW. The system also incorporates a 1.6kW inverter which converts the output DC voltage from 48V to an equivalent AC. A step-up transformer connected directly to the inverter boosts the voltage from 48V AC to an output voltage of 220V AC for supply to the load. The dynamic simulation results and response to changing inputs are presented in this paper.

4.1. Introduction

The supply of electricity in non-electrified remote areas can be produced by distributed renewable energy [4]. Ankit proposed a Matlab based model of a standalone photovoltaic system for a small rural community of 15 households located in Subardan areas, with each household taking an average electricity demand of 1.7kWh/day, the total yearly load demand for the rural community was estimated to be 9800.632kWh. Using yearly metrological data to develop the model, simulated result shows that the system is exceedingly robust and can handle the dynamics associated with irradiance, temperature, and load demand [1].

Kartika performed simulation and development of Solar PV system for the fulfilment of load demand in isolated areas. The system comprised of PV solar panel, a DC-DC boost converter and a two-level inverter connected to the load. PI controller was used in controlling and maintaining the DC link constant regardless of variation in the input and output parameters which resulted to constant inverter output [2]. Wahyu proposed a PV hybrid with battery backup system for powering a Base Transceiver Station (BTS) telecommunication system to supply telecommunications system in rural communities with inaccessibility to electricity. To supply the BTS load by 43177.78Wh/day with 48V voltage system can be generated with 50 solar panels. From the simulated results it was found that PV modules which is the major generator to supply the base station is not sufficient due to inconsistency in supply, hence, to ensure continuity of electricity supply batteries and generator backup were integrated to the system [5]. Chaudry proposed an off grid PV system for a house in Pakistan having a load of 7.81kWh/day, the system comprised of 8 batteries and 36 PV. From the design, simulated result showed that the configuration is sufficient enough to power the house efficiently independently from the national grid [6]. Arif carried out a design for an off grid solar system for a house with average energy consumption of 40kWh per month located in a remote community in Pakistan, the system comprised of 4 solar panels of 140W, giving a total of 560W PV, 4 batteries each having 125Ahr and a 1kW inverter. Result showed the system provided better electrification solution with an energy production of 726kwh per annum [7].

This paper aims to present the Matlab dynamic simulation of stand-alone PV hybrid system representing a remote residence in Edo State, Nigeria having a peak load of 1.26kW and daily energy consumption of 3.4kWh/day. The system comprises of a 1.23kW PV (325W each), MPPT for maximum power tracking, DC –DC buck converter, a backup battery and generator system with a 1.6kW inverter which converts the output DC voltage of 48V from the converter to an alternating AC. The case study is for a typical house in remote Edo State, Nigeria. The objective of this research is the dynamic simulation of the system. This paper is divided into the following: section 2 shows the site location. Section 3 gives full the system components and specifications. Section 4 provides the dynamic simulation and result. Lastly, section 5 presents the conclusion.

4.2. Site Location

The selected site is situated in Edo State, Nigeria. The residence is a two-bedroom bungalow with no access to the utility grid. On Google maps the selected site has the following co-ordinates: Latitude: 6°17'22.2"N, Longitude: 5°59'31.8"E (6.28949409312645, 5.992154342254569). All system components were selected using Homer Pro. Figure 4.2 shows all components in a block diagram. Table 4.1 provides a list of all selected components.

Fig. 4.1. Location of remote site in Edo State Nigeria.

4.3. System Component

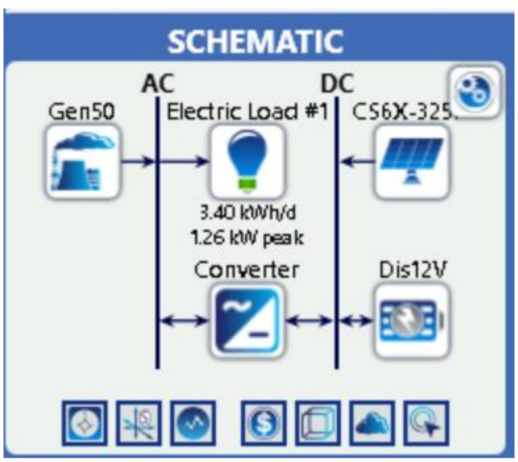

Fig. 4.2. Homer Block diagram of all selected components.

Table 4.1: List of system components and specifications.

Appliance	Quantity	Specification
PV	4, 325W modules	1.23kW
Battery	4, 12V, 350Ahr	48V
Generator	1	4.8kW
Inverter	1	1.6kW

4.4. Dynamic Simulation

The figure 4.3 below shows the dynamic system design carried out in the Matlab Simulink environment, the configuration of the system is made up of a PV system of 1.23kW comprised of 4 modules each of 325W, with 2 connected in series and 2 in parallel. MPPT is applied to the PV to ensure that the PV gives power at its maximum. The DC – DC buck converter is used to step down the voltage of the PV to the bus voltage of 48V, the PV charges both the battery and supplies power to the load. The system also incorporates a permanent magnet synchronous generator which serves as an emergency backup power system for charging the battery when the voltage of the battery goes below 49V due to inconsistency in solar resources. The output 48V DC from the buck converter is fed directly to the inverter which converts the DC to alternating AC. The 48V AC is stepped up by a transformer to 220Vrms AC which is used to power the load. A MPPT is used to control a DC-DC buck converter. Generator is a permanent magnet type, and its 3-phase output is connected to DC using a full bridge rectifier. Inverter produces 50Hz output that is stepped up to 220V using a transformer. Load is divided into two sets to represent a changing load. System simulation results are discussed in the following sections

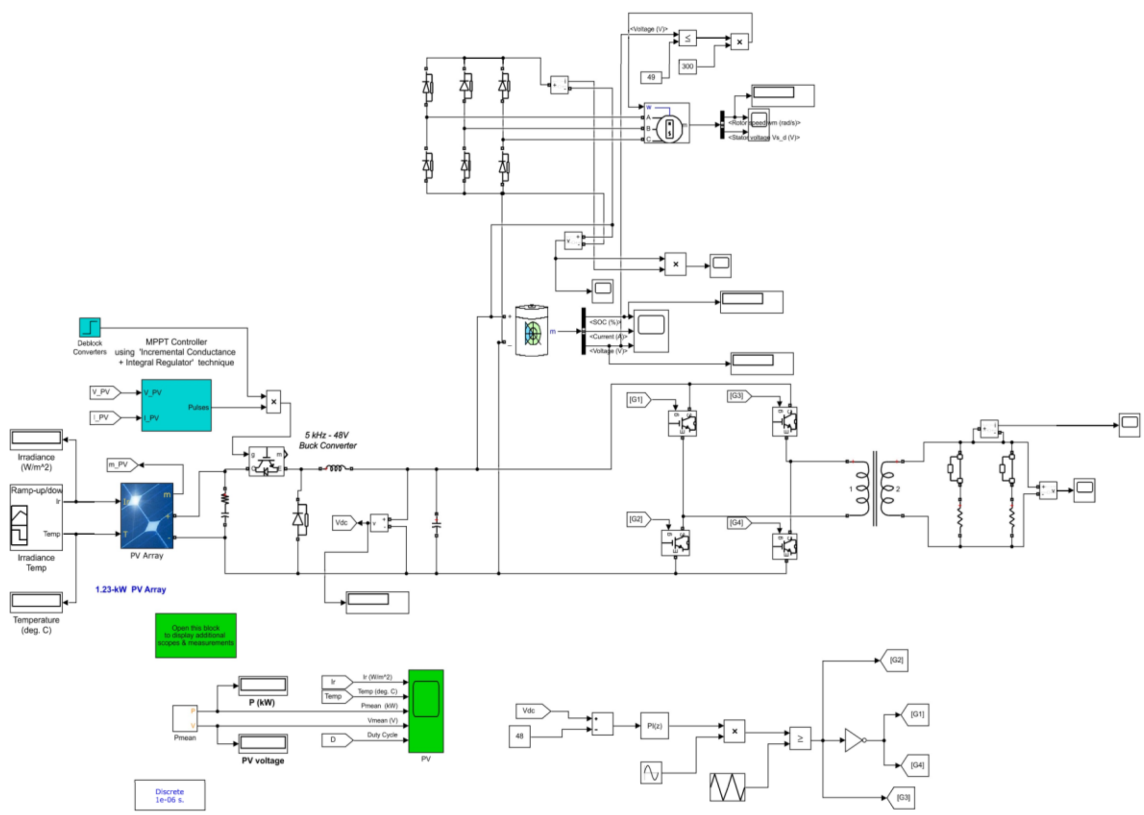

Fig. 4.3. PV-battery-generator hybrid system simulation in Simulink.

4.4.1. Half load, 50% State of Charge (SOC), and Generator

The figure below shows the Irradiation, Temperature, Power, Voltage, and duty cycle of the PV. The duty cycle varies according to the solar resources. The flow of the duty cycle follows the Irradiance and power of the PV when the battery is not connected. This result shows that the designed MPPT is able to track the input solar variation.

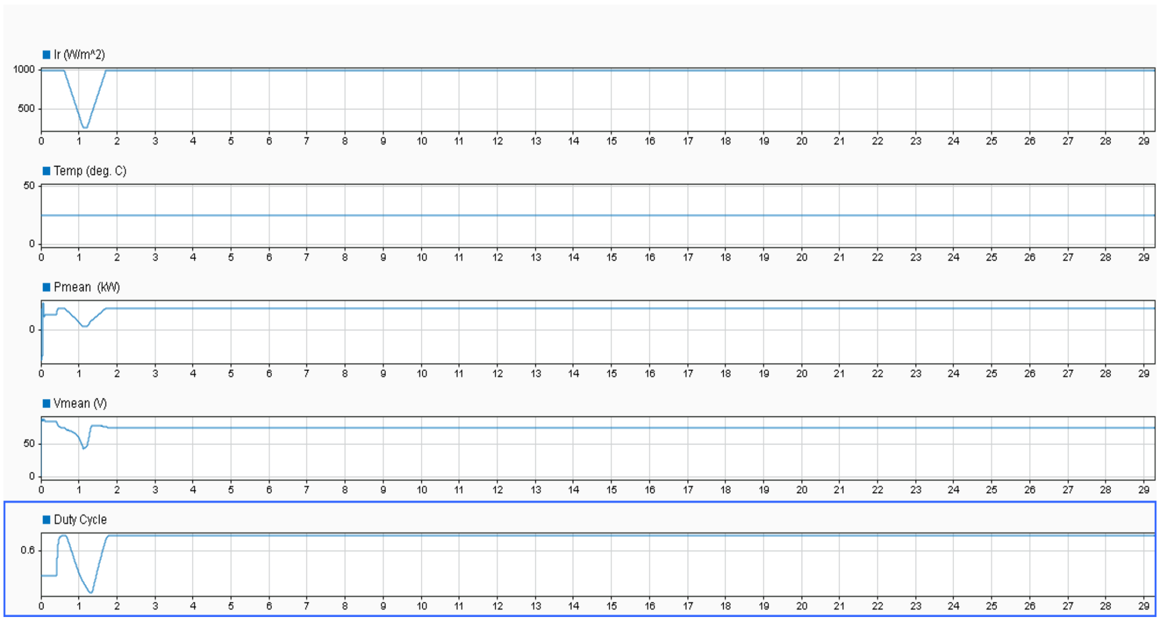

Fig. 4.4 PV, irradiation, duty cycle, power, voltage signal.

When the battery is connected across the circuit, the duty cycle varies according to the voltage of the PV as seen in fig. 4.5 below. Indicating battery charging while maintaining operation at maximum operating point.

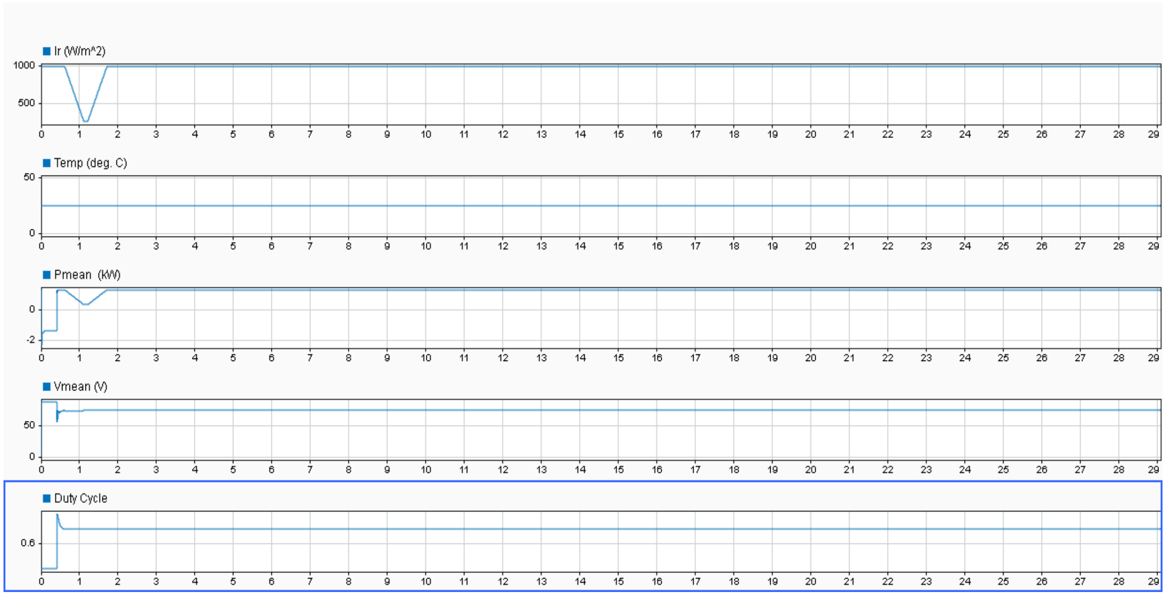

Fig. 4.5. Duty cycle varies according to voltage of PV.

The figure 4.6 below shows the charging of the battery initially at 50% state of charge (SOC). At 50% state of charge, the battery's voltage is below 49V at which point the generator of 4.8kW turns on to charge the battery up to the 49V mark and then gradually shuts down after exceeding 49V, leaving just the PV to charge the battery. From the State -of- Charge (SOC) graph it is observed that when the generator is ON the battery charges rapidly, but when the generator begins to shut down, the SOC of the battery increases slowly, this is because the power generated by the generator, 4.8kW is higher that the power generated by the PV which is 1.29kW.

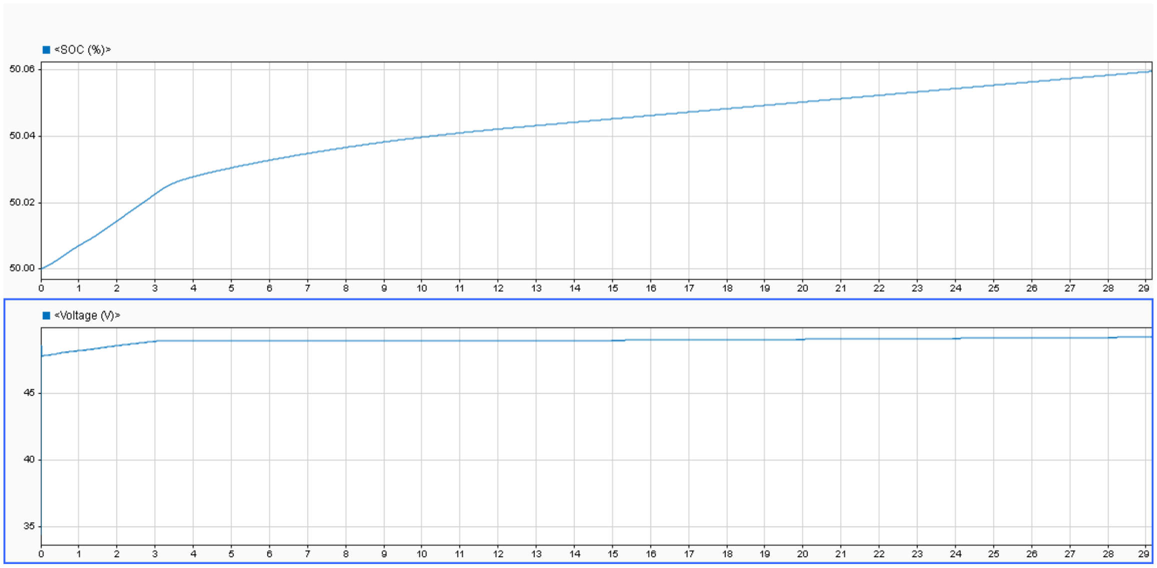

Fig. 4.6. Battery SOC and voltage.

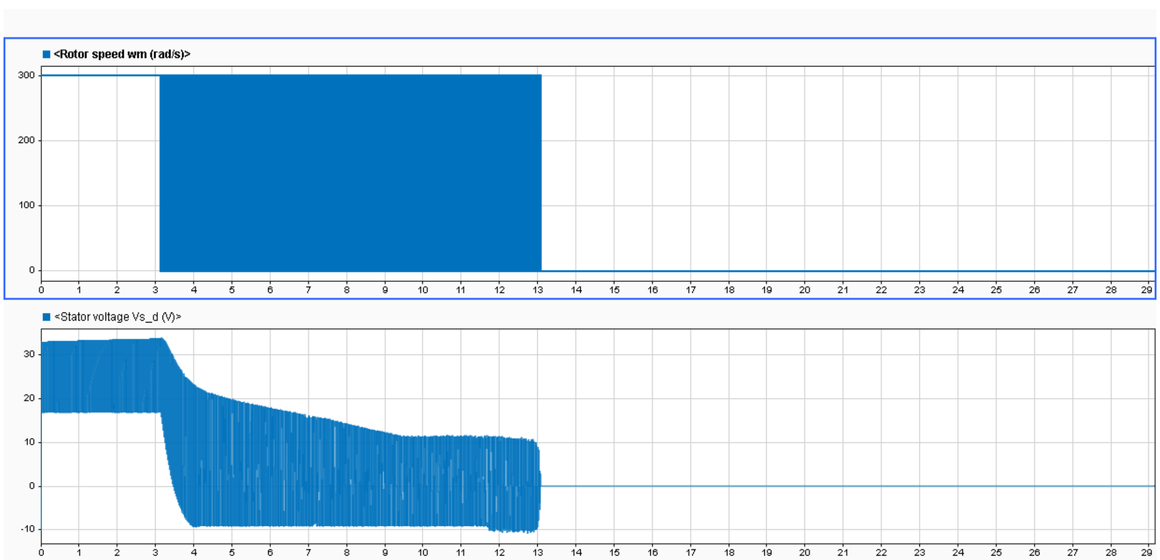

Fig. 4.7. Generator rotor speed and Stator voltage.

Figure 4.7 shows the rotor speed of the generator and stator voltage. The generator has a rotor speed of 300rad/sec. while the rotor speed is kept constant, the stator voltage increases gradually when the generator is charging the battery. At half load of 0.63kW, the generator only charges the battery for a short while before the voltage of the battery exceeds 49V and thereafter turns off. From the figure above, it can be seen that the signal changed drastically from 300rad/sec to 0 and from 33V to 0, this is because with half load there is more power going to the battery from the PV therefore the less time it will take for the voltage to exceed 49V and thereafter the generator turns off.

4.4.2. Half load, 98% SOC, Generator

With half load, 98% SOC, the battery's voltage is above 49V and the Generator will be turned off leaving only the PV to charge the battery and supply power to the load. Because it is half load, when the Irradiance drops to 500kW/m^2/day, the reduction in the SOC is minimal, and when the Irradiation goes back to 1000kW/m^2/day there is a rapid increase in the state of charge of the battery. The PV conveniently charges the battery faster as compared to the full load scenario while also supplying power to the load.

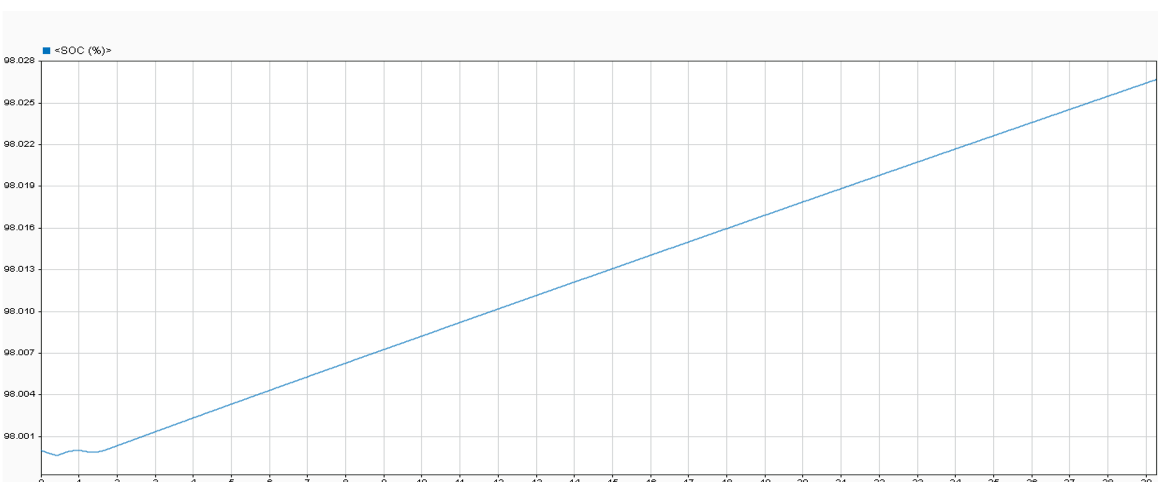

Fig.4 8. Battery SOC.

Figure 4.8 above shows the SOC of the battery for a half load scenario when there is a variation in irradiation from 1000 kW/m^2/day to 500 kW/m^2/day. From the figure it can be observed that the SOC initially at 98% only decreased slightly and thereafter a rapid increase in the state of charge. With reduction in solar irradiation, the effect of discharge of the battery is very minimal and with increase in solar irradiation come rapid increase in the SOC of the battery.

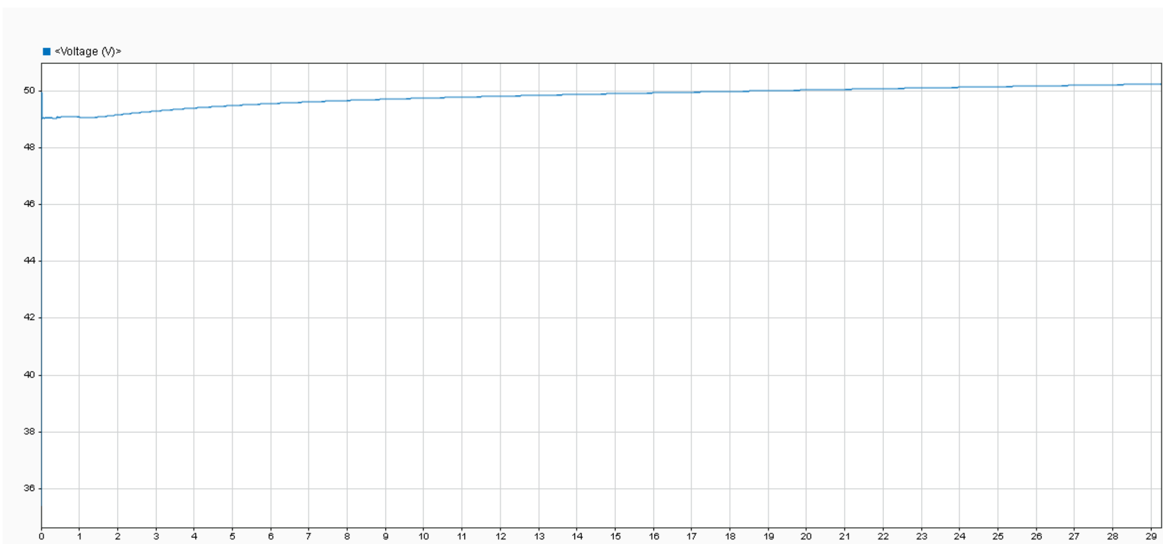

Fig. 4.9. Battery voltage.

Figure 4.9 shows the voltage of the battery when at 98% SOC with slight decrease when the irradiation reduced to 500 kW/m^2/day and a steady rise in voltage as goes back to 1000 kW/m^2/day.

4.5. Conclusion

This paper presented the dynamic simulation of a PV hybrid system with backup battery and generator for a remote area in Edo State, Nigeria. The simulation was tested in several conditions and configuration. The system was first simulated with the battery kept at 50% SOC and half load, it was observed that the PV charges the battery and supplies power to the load at the same time, in the condition were the voltage of the battery goes below 49V the emergency generator turns on and charges the battery until it exceeds 49V and then turns off. Another scenario shows the configuration of the battery kept at 98% SOC and the system was simulated in half load, result shows the PV charges the battery and supplies power to the load, but the difference is that for the case of the 98% SOC the generator is not operational because the battery voltage is above 49V. The system has been simulated and tested in different configurations and result shows that for a remote community, the configuration of PV, battery and emergency backup generator is the most suitable, economical, and reliable option to adopt.

Acknowledgment

The author would like to thank Soltech Nigeria Limited for providing graduate funding in support of his research.

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Chapter 5

Design of a DC Microgrid System for a Remote Community in Nigeria.

Preface

A version of this manuscript has been published in the ***European Journal of Electrical Engineeering and Computer Science Vol 5, No 6 (2021)*** *. I am the primary author and carried out most of the research works, including the literature reviews, system sizing and design, simulation and result analysis. I prepared the original manuscript and also revised the final manuscript based on feedbacks from the co-author and the peer-review process. The Co-author, Dr. M. Tariq Iqbal, supervised the entire research work, reviewed, made corrections and contributed research ideas for the actualization of the manuscript.*

This chapter is a version of "Design of a DC Microgrid system for a Remote Community in Nigeria", J. C. Ozogbuda and M. T. Iqbal, *European Journal of Electrical Engineering and Computer Science* **Vol.5 No.6.** 2021.

Abstract

This paper presents the design of a DC microgrid for a remote community in Edo State, Nigeria having a solar irradiance of 4.63kWh/m^2/day. The community is isolated and located far away from the city with no access to the electricity grid. There is need for lighting and running of electronics, as the main source of lighting presently is kerosene, which is not efficient and leads to health issues. The community is made up of 9 residence which are not more than 100m apart. House 1 was selected as the standard house with a load of 1kWh/day, while the other 8 houses have a load difference of ±10% with reference to house 1. Using a 48V DC bus, the designed PV system components comprise of a 100W solar photovoltaic (PV) panel and a 12V 45Ahr battery. The system was sized using Homer Pro. Optimization results presented various design for the various houses. The result obtained showed reasonable and feasible cost-effective solution in terms of the Net Present Cost in both installation and running of the hybrid system for the community. Sensitivity analysis was also carried out to test the adaptability of the system using a solar irradiation input of ±10%. Detailed result of the analysis is presented in the paper.

5.1. Introduction

The problems faced in increasing electrification are infrastructure and distribution of power plants, especially in remote areas [1]. Lack of electricity in most African countries has been an issue that is yet to be resolved; Nigeria is not an exception from this situation of lack of electricity/insufficient power supply. Most remote areas in the country suffer from total electrical blackout for days and in worse cases, no access to electricity grid. In these remote areas, Kerosene lantern is what is mostly used for lighting purpose. Due to the moderate temperature in these areas, there is usually no need for heating. Conventional approach to meet such needs is to connect these remote areas to the electrical grid, but this would be very expensive and unpractical because most of these remote residences are so far from the common cities that the line loss and maintenance cost would be too much and non-feasible to implement. Notwithstanding, Electricity in needed in this area for proper lighting and running of electronics. Renewable energy is the most appropriate solution to supply energy in isolated areas. Utilization of locally available resources is the best possible option to meet the energy requirement. Single technology-based system (solar photovoltaic/wind/small hydro) is a viable option to supply energy in isolated areas. Un-electrified rural areas like village hamlets or small villages that are far away from the utility grid can be electrified by single technology,[2]. One solution that can be done is to build a power generation using off-grid power system. Off grid power system can consist of PV-Battery or Genset-Battery to supply the communal load [3]. STANDALONE Photovoltaic (PV) systems are designed and sized to supply certain AC and/or DC electrical loads [4].

Adithya designed a small off-grid PV system for a rural home. The system comprised of a 5W PV, and a 6V, 7Ah lead acid battery. The system was used to power small loads like LED (Light emitting diode) lamp and mobiles. Simulation result shows the system was efficient in powering the resident [5]. Sini designed a system for a rural residence in Bhilai, Chattigarh which experiences breakdown and tripping in power supply. The house has an estimated energy consumption of 30.41kWh/d and 3.24kW peak power. Simulation was carried out using Homer Pro. The result showed that among other possible configuration, the PV-battery system has the lowest Net Present Cost (NPC) and COE and would yield reasonable returns in the long run [6]. Nunu designed a solar PV system for Mapetja rural village having a solar radiation of 5.96kWh/m^2. The village is located far away from the National grid. The total load consumption of a single house in the village was found to be approximately 11kWh/d. The PV system required for sufficient supply comprised of 728 modules (7 series, 104 parallel), a charge controller, 18 deep cycle batteries of 12V and an inverter. Result showed that the use of the designed stand-alone PV system would be the best suitable sustainable solution for the village in terms of electricity supply [7]. Chin designed and optimised a PV hybrid system for residential community of Basco island in Philippines to replace the diesel generator only system. the proposed energy system is made up of 4611kW PV, 116 batteries of 12823kWh, 10kWh wind generators, 1000kW diesel generator and 1500kW converter. The system was found to be both power efficient enabling the use of electricity supply for 24-hours and cost-effective with cost of energy (COE) equals to $0.409/kWh for $1/litre diesel fuel cost [8]. Chaudry proposed an off grid PV system for a house in Pakistan having a load of 7.81kWh/day, the system comprised of 8 batteries and 36 PV. From the design, simulated result showed that the configuration is sufficient enough to power the house efficiently independently from the national grid [9]. Arif carried out a design for an off grid solar system for a house with average energy consumption of 40kWh per month located in a remote community in Pakistan, the system comprised of 4 solar panels of 140W, giving a total of 560W PV, 4 batteries each having 125Ahr and a 1kW inverter. Result showed the system provided better electrification solution with an energy production of 726kwh per annum [10].

The selected site is located using the Google earth pro, with coordinates (6.182863, 5.933505) Latitude:6°10'58.3"N Longitude: 5°56'00.6"E. Having a solar irradiance value of 4.63kWh/m^2/day. The community is made up of 9 households which are completely cut off from the utility grid. The houses are not more than 100m apart as shown in figure 5.1.

The purpose of this research is to design a system where each house has a photovoltaic (PV) panel and a battery. The loads are all connected with a 48V bus. All loads are DC loads. The sizing of the system has been done using the Homer Pro optimization software.

Fig. 5.1. Location of the remote community in Nigeria.

5.2. Electrical Load

Each household in the community has few loads to be powered, comprising mostly of lighting points, table fan, radio, and TV. A detailed breakdown of the load of each household is presented in the table 5.1 below. Some residents have cell phones that they take to nearby villages for charging.

Table 5.1. daily energy requirement for house 1 in the community.

Appliances	Quantity	Wattage (W)	Total Wattage (W)	Daily usage (hours)	Energy (Wh/day)
LED bulb	3	18	54	10	540
Fan	2	10	20	9	180
Radio/cell phone	1	5	5	8	40
Television	1	30	30	8	240
Total:			**109**		**1000**

The figure below shows the percentage load distribution of the 9 households in the community for a converter less isolated DC microgrid. With house 1 as a reference and a load variation of ±10%, the load distribution from house 1 to house 9 are 1kWh/day,1.1 kWh/day, 1.2 kWh/day,1.3 kWh/day,1.4 kWh/day,0.9 kWh/day,0.8 kWh/day,0.7 kWh/day and 0.6 kWh/day. Each house has a PV system, a battery bank, and an ON/OFF switch to connect/disconnect from the microgrid if they decide to do so.

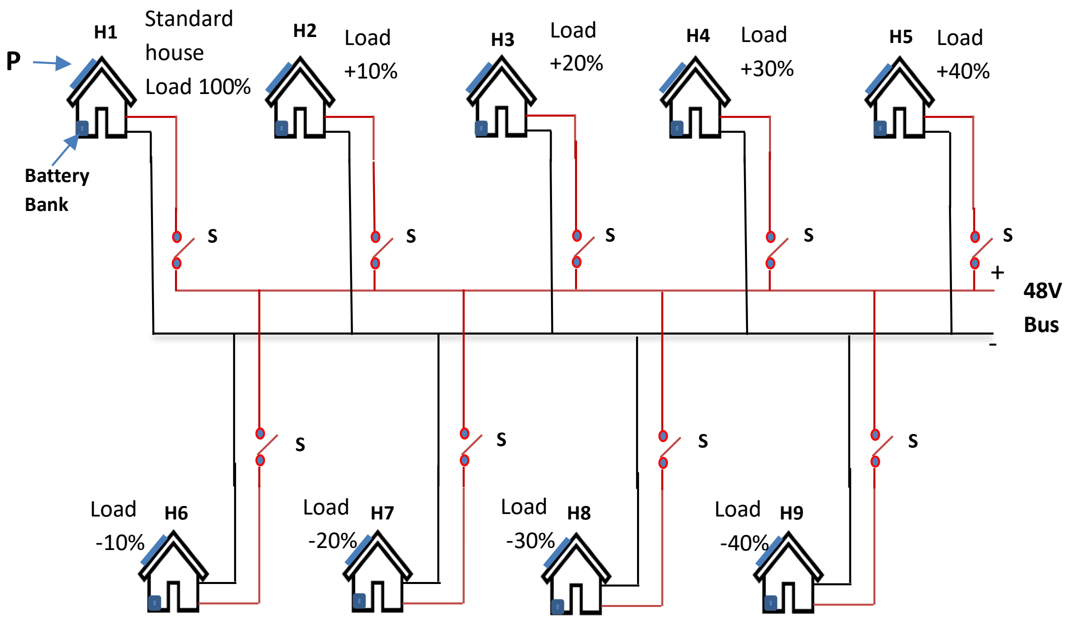


Fig.5.2. block diagram showing load distribution of households in the community.

5.3. System Components Design

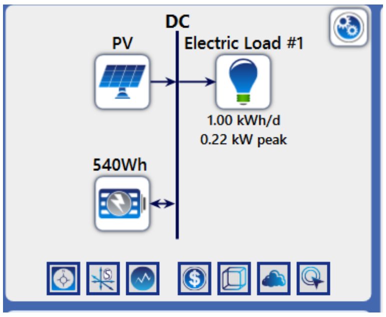


Fig.5.3. Homer Pro system block diagram.

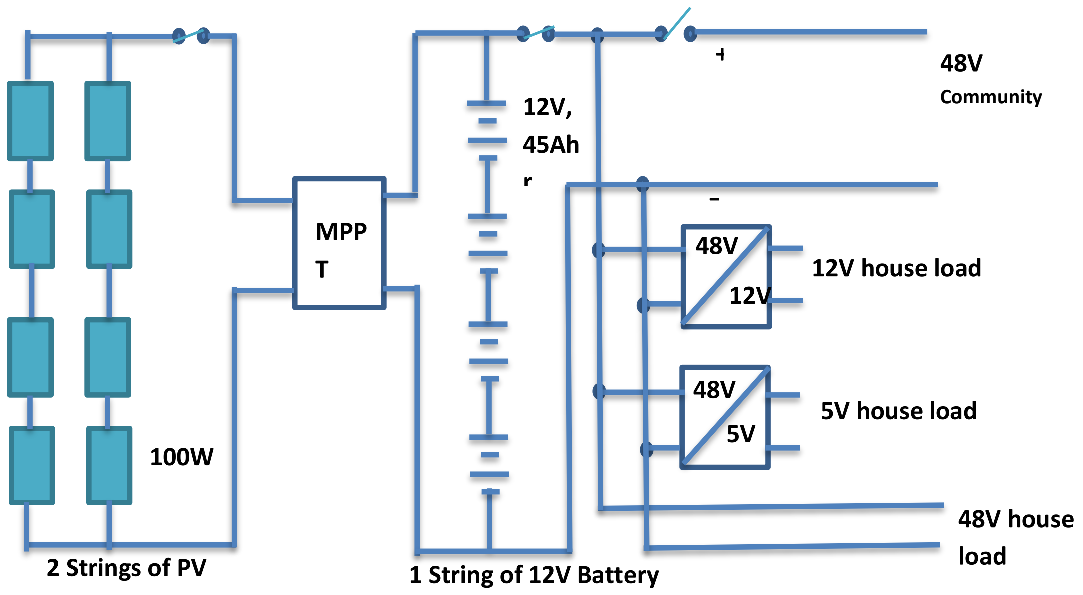


Fig.5.4 System component in a house.

The system comprises of a Donghui High efficiency 100W Mono solar panel, and a PowerStar battery of 12V, 45Ahr all connected to the 48V bus, there is no inverter in the system. the MPPT ensures the PV reaches maximum power point. House load is 48V/12V/5V. Two DC-DC converters are used to get 12V and 5V from 48V. TV and some lights are 48V. Some lights and fan run on 12V. Radio/cell phone needs 5V for charging.

Sensitivity	Architecture			Cost				System		PV		540Wh	
Electric Load #1 Scaled Average (kWh/d)	PV (kW)	540Wh	Dispatch	NPC (US$)	COE (US$)	Operating cost (US$/yr)	Initial capital (US$)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost (US$)	Production (kWh/yr)	Autonomy (hr)	Annual Through (kWh/yr)
0.600	0.417	4	CC	$2,407	$0.851	$108.49	$1,004	100	0	304	569	51.8	131
0.700	0.323	8	CC	$3,780	$1.15	$165.90	$1,636	100	0	236	440	88.9	160
0.800	0.396	8	CC	$3,928	$1.04	$173.22	$1,689	100	0	289	540	77.8	182
0.900	0.863	4	CC	$3,310	$0.780	$153.13	$1,330	100	0	630	1,178	34.6	191
1.10	1.21	4	CC	$4,015	$0.774	$188.00	$1,585	100	0	885	1,654	28.3	231
1.20	0.827	8	CC	$4,799	$0.848	$216.29	$2,003	100	0	603	1,128	51.8	263
1.30	0.958	8	CC	$5,066	$0.827	$229.47	$2,100	100	0	700	1,308	47.9	283
1.40	0.759	12	CC	$6,226	$0.943	$276.33	$2,654	100	0	554	1,036	66.7	314
1.00	0.576	8	CC	$4,293	$0.911	$191.27	$1,821	100	0	421	787	62.2	223

Fig. 5.5. System design for each house in the community.

The system was designed in Homer Pro. The figure 5.5 above represents the optimization result for the 9 houses with various electrical loads. Using a 100W PV and 12V, 45Ahr lead acid battery, For the house with 0.6kWh/d of load, the required components would be 0.417kW PV and 4 batteries. For the house with 0.7kWh/d of load, the required components are: 0.323kW PV and 8 batteries with this configuration comes the highest autonomy of 88.9hr, which means in the absence of solar power the backup battery can run for up to 4 days. For the house with 0.8kWh/d of load, the required components are: 0.396kW and 8 batteries. For the household with 0.9kWh/d of load consumption, required components include: 0.863kW PV and 4 batteries. For house with 1.10kWh/d of energy consumption, required components: 1.21kW PV and 4 batteries. For house with 1.20kWh/d of load, required components are: 0.827kW PV and 8 batteries. For house with 1.30kWh/d of load, required components would be: 0.958kW PV and 8 batteries. For the house with 1.4kWh/d of load, required components are 0.759kW PV and 12 batteries. For the house with 1kWh/d of load, required components are 0.576kW PV and 8 batteries. All houses show a renewable fraction of 100% and the initial cost, capital cost and operational cost varies from one house to another. Say a house needs 0.759kW PV and each PV module is 100W, 12V then four modules will be used in series (800W total) to have a 48V system. Small PV modules and batteries were selected that could be carried and moved around without any need for a vehicle and road that does not exist in the community.

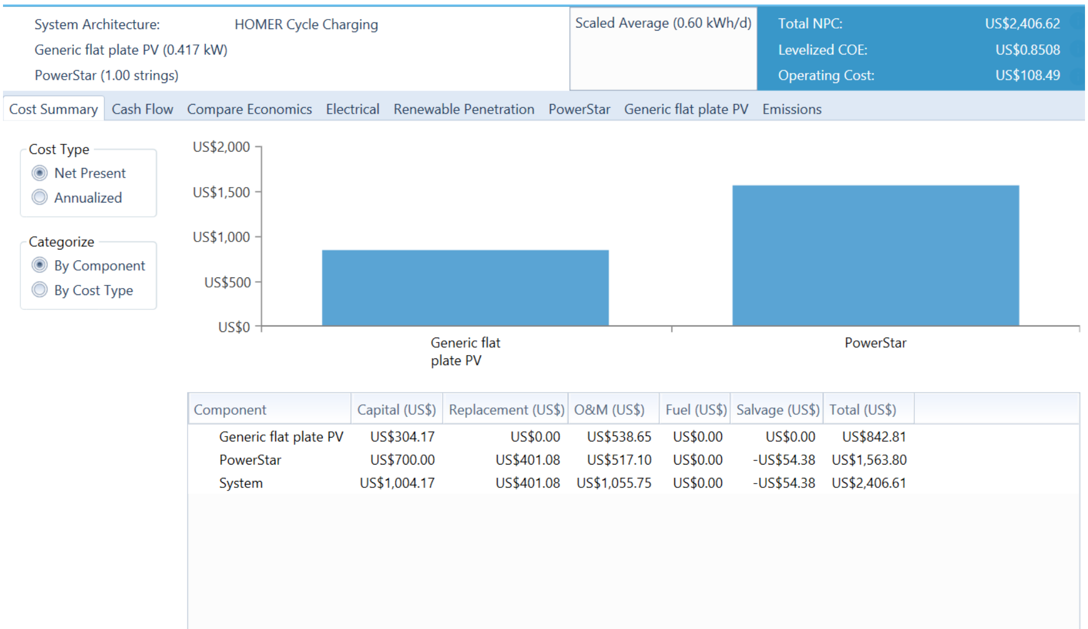
5.4. Economic Analysis

Homer Pro also performs economic analysis to determine the feasibility implementing the system with financial considerations. From the cost summary of the simulated result shows the detailed breakdown of the cost of the system which comprises of the capital cost, replacement cost, operation, and maintenance (O&M) cost, salvage cost and total cost of each component. The total cost of all the components gives the Net Present Cost (NPC) of the system per household. Table 5.2 below provides all cost details for all houses in the community.

Table 5.2. Optimized cost for each residence in the community.

Household	Electric Load (kWh/d)	PV (kW)	Batt. 12V	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Capital Cost ($)	Autonomy (hr)
House 1	1.0	0.576	8	$4,293	$191.27	$1,821	$421	62.2
House 2	1.1	1.21	4	$4,015	$188.00	$1,585	$885	28.3
House 3	1.2	0.827	8	$4,799	$216.29	$2,003	$603	51.8
House 4	1.3	0.958	8	$5,066	$229.47	$2,100	$700	47.9
House 5	1.4	0.759	12	$6,226	$276.33	$2,654	$554	66.7
House 6	0.9	0.863	4	$3,310	$153.13	$1,330	$630	34.6
House 7	0.8	0.396	8	$3,928	$173.22	$1,689	$289	77.8
House 8	0.7	0.323	8	$3,780	$165.90	$1,636	$236	88.9
House 9	0.6	0.417	4	$2,407	$108.49	$1,004	$304	51.8

House 9 with an electrical load of 0.6kWh/d, Homer Pro analysis shows that the Net Present Cost (NPC) for installation, operation and running of this system is $2,407, initial capital cost of $1,004, operational cost of $108.49. the figure 5.6 below shows the cost summary and break down of the cost for the components.



Component	Capital (US$)	Replacement (US$)	O&M (US$)	Fuel (US$)	Salvage (US$)	Total (US$)
Generic flat plate PV	US$304.17	US$0.00	US$538.65	US$0.00	US$0.00	US$842.81
PowerStar	US$700.00	US$401.08	US$517.10	US$0.00	-US$54.38	US$1,563.80
System	US$1,004.17	US$401.08	US$1,055.75	US$0.00	-US$54.38	US$2,406.61

Fig.5.6. Cost summary of house 9.

The figure 5.6 above shows the cost summary of House 9. It also shows the capital cost, replacement cost, operational cost, salvage, and total cost for each component of the system. for the PV it shows a capital cost of $304.17, operation and maintenance (O&M) cost of $538.65, and this gives a total cost of $842.81. the Battery have a capital cost of $700, replacement cost of $401.08, O&M cost of $517.10, salvage cost of $54.38, which gives a total cost of $1,563.80. the total cost of both components (PV and battery) gives the NPC of the system. Information on capital costs, initial capital, operational cost, and NPC for other houses in the community can be found in table 5.2 above.

5.5. Electrical Output

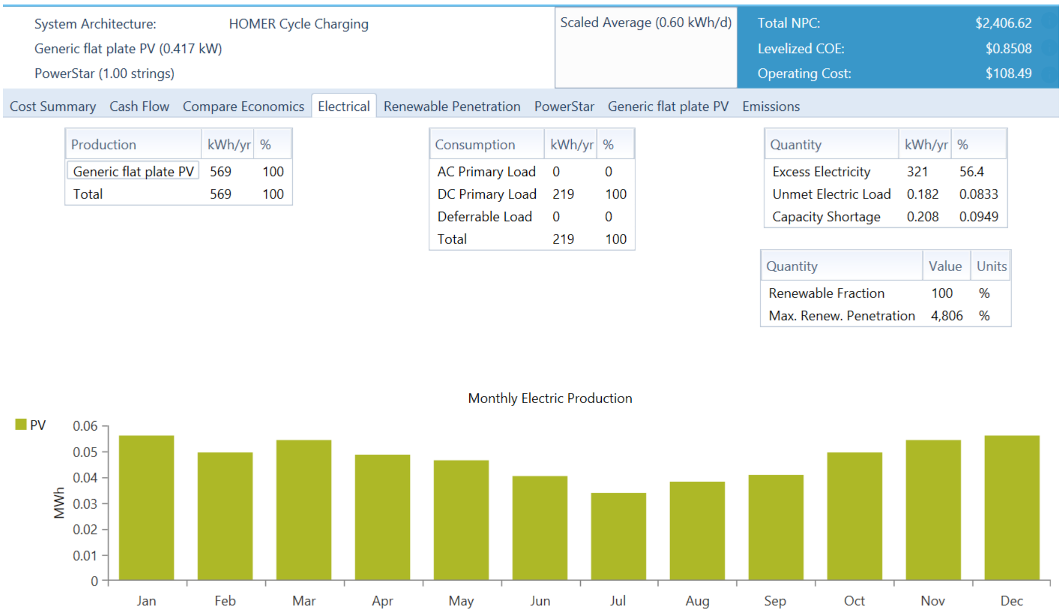


Fig. 5.7. Electrical output of a house in the community.

The figure 5.7 above shows the electrical output for house 1 having a load of 0.6kWh/d. the homer optimization result showed the most efficient system for the resident is 0.417kW PV and 1 string of Power battery. For the PV component, a 12V 100W PV was selected whereas for the battery a 12V, 45Ahr PowerStar battery was selected. The system has been simulated using a 48V bus system, which will require 4 of the selected PV modules connected in series and 4 of the selected battery components connected in series to give 1 string of battery. The result also shows a 100% renewable fraction and excess electricity of 321kWh/y. Optimization result shows autonomy of the system to be 51.8 hr, which means in the case of no solar resource due to rainy days the battery system can supply power for up to 2 days. The monthly electrical production for the year is also shows the monthly production of PV power for the span of one year, the graph showed peak production in the months of

January, March, November, and December, while the lowest production in the month of July (days are larger in July and house lighting needs are reduced).

Each house has a PV system that could be connected to the community DC microgrid through a switch. In the selected community of PV system with no measurement system is difficult to maintain due to poor know how and lack of knowledge. Battery may over discharge due to carelessness. If all houses are connected through DC microgrid then people can share excess production with neighbours and that will lead to a more reliable system. If a house owner forgot to clean PV modules, then for a time being power can come from neighbours. Therefore, a community system connected through 48V bus as shown in the figure 5.2 is recommended and designed.

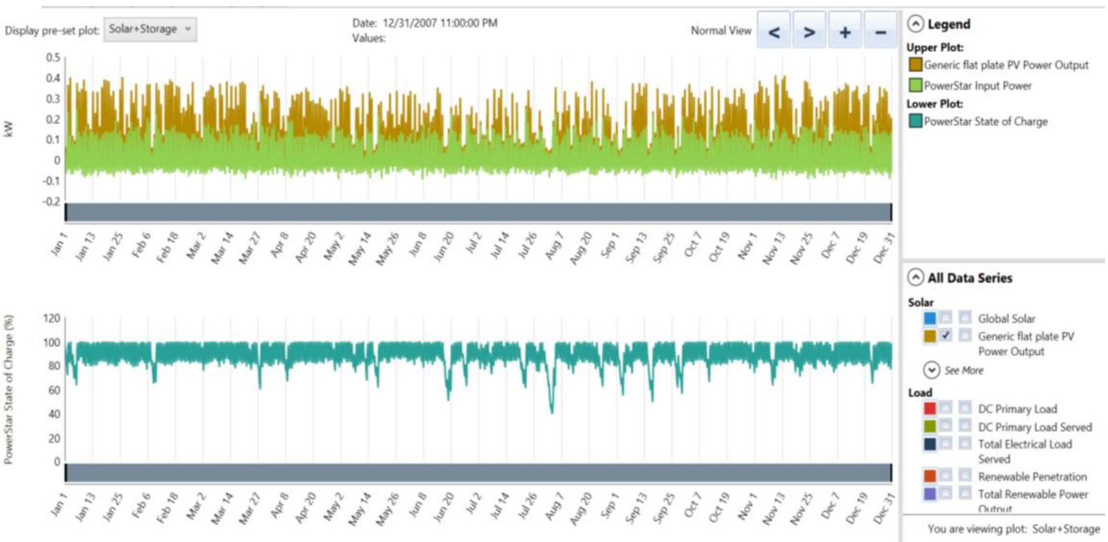


Fig.5.8. Time series detail analysis of PV power output for a resident.

The figure 5.8 above also shows the hourly time series detailed analysis of the battery State of charge and the Solar PV power output for the span of 1 year. From the graph is can be deduced that the period of sharp decline in the state of charge of the battery from 100% to 40% is between the month of June to September, whereas power output of the solar PV varies almost throughout the year. In a DC microgrid such sharp decline is less likely due to power sharing among neighbours.

5.6. Sensitivity Analysis

Sensitivity analysis also called the “what if analysis” is critical in understanding the robustness of a design. It allows you to understand how a changing input will affect the choice of least cost system.

In this design model, sensitivity analysis is performed on the solar irradiation. Inputting a range of solar irradiation from 4.14kWh/m^2/day to 5kWh/m^2/day due to climate change factors such as less cloudiness in certain times of the year (summer/dry season) causes the solar irradiation to increase and dust accumulation on PV leads to decrease in PV efficiency.

Due to climate change factors such as less cloudiness in certain times of the year (summer/dry season) the solar irradiation increases, so therefore the optimization result also takes this variable into consideration by optimizing the system with a solar irradiation value of 5.00kWh/m^2/day. The optimization result shows the different house loads and best possible configuration for optimal and efficient supply of power to the residence in the community. Figure 5.9 below shows system sensitivity analysis results obtained from Homer Pro.

Export... Export All...

Sensitivity Cases

Left Click on a sensitivity case to see its Optimization Results.

Compare Economics Column Choices...

Sensitivity		Architecture					Cost				System		PV		
Electric Load #1 Scaled Average (kWh/d)	Solar Scaled Average (kWh/m²/day)			PV (kW)	540Wh	Dispatch	NPC (US$)	COE (US$)	Operating cost (US$/yr)	Initial capital (US$)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost (US$)	Production (kWh/yr)	Autonom (hr)
0.600	4.14			0.469	4	CC	$2,512	$0.888	$113.69	$1,042	100	0	342	571	51.8
0.600	4.63			0.417	4	CC	$2,407	$0.851	$108.49	$1,004	100	0	304	569	51.8
0.600	5.00			0.385	4	CC	$2,343	$0.828	$105.34	$981.18	100	0	281	568	51.8
0.700	4.14			0.364	8	CC	$3,865	$1.17	$170.07	$1,666	100	0	266	444	88.9
0.700	4.63			0.323	8	CC	$3,780	$1.15	$165.90	$1,636	100	0	236	440	88.9
0.700	5.00			0.299	8	CC	$3,732	$1.13	$163.50	$1,618	100	0	218	440	88.9
0.800	4.14			0.437	8	CC	$4,011	$1.06	$177.31	$1,719	100	0	319	532	77.8
0.800	4.63			0.396	8	CC	$3,928	$1.04	$173.22	$1,689	100	0	289	540	77.8
0.800	5.00			0.364	8	CC	$3,865	$1.02	$170.07	$1,666	100	0	266	537	77.8
0.900	4.14			0.530	8	CC	$4,199	$0.990	$186.62	$1,787	100	0	387	645	69.1
0.900	4.63			0.863	4	CC	$3,310	$0.780	$153.13	$1,330	100	0	630	1,178	34.6
0.900	5.00			0.450	8	CC	$4,037	$0.951	$178.59	$1,728	100	0	328	663	69.1
1.10	4.14			0.777	8	CC	$4,699	$0.906	$211.32	$1,967	100	0	567	946	56.6
1.10	4.63			1.21	4	CC	$4,015	$0.774	$188.00	$1,585	100	0	885	1,654	28.3
1.10	5.00			0.650	8	CC	$4,443	$0.857	$198.68	$1,875	100	0	475	959	56.6

Fig. 5.9. Sensitivity analysis of system design in Homer Pro.

The figure 5.9 above shows some of the sensitivity results for the community. For the house with a load of 0.6kWh/day, the sensitivity cases show three results; case 1 for a solar irradiation of 4.14, case 2 for a solar irradiation of 4.63 and case 3 for a solar irradiation of 5.00. from these three cases it can be observed that as solar irradiation increases number and cost of component reduces. For example, for 4.14 solar irradiation the required component would be 4 batteries, 0.469kW PV, and the NPC of the system would be $2,512. Whereas, for the 5.00 solar irradiation case required components would involve 4 batteries and 0.385kW PV, which shows an NPC of $2,343. The same applies to all other sensitivity cases.

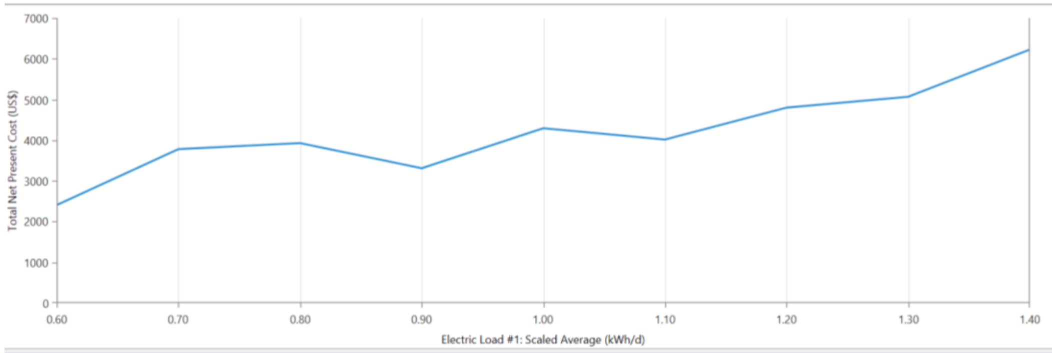


Fig 5.10. Optimization surface plot with NPC and COE superimposed for remote Edo community for 4.145.00kWh/m^2/day solar scaled average.

Figure 5.10 represents the graph for total Net present Cost (NPC) against Electrical load for 4.63kWh/m^2/day solar scaled average. The result shows that as the load increases, there in a non-linear increase in system cost. This is because with increase in load demand comes increase in the required components needed to meet the demand of the system. Result for solar scaled average of 4.14 kWh/m^2/day and 5.00 kWh/m^2/day also shows similar results.

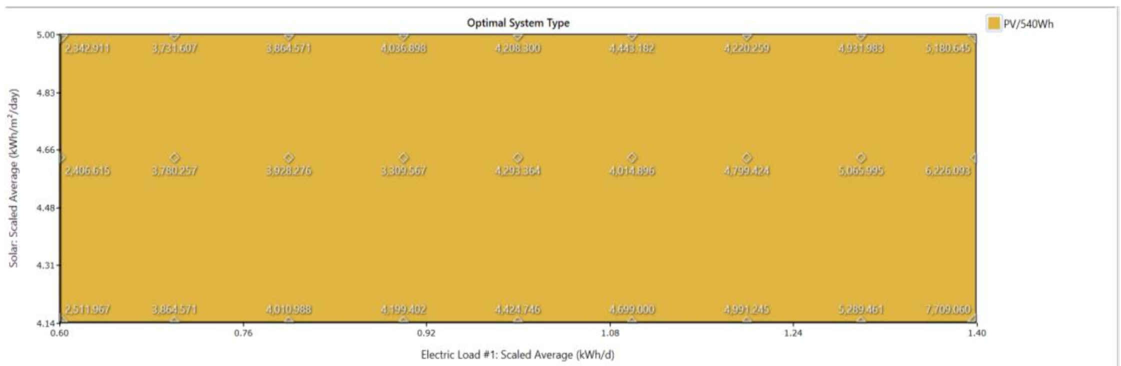


Fig 5.11. Optimization surface plot with NPC and COE superimposed for remote Edo community for 5.00kWh/m^2/day solar scaled average.

Figure 5.11 above is a plot of solar scaled average against average electrical load. this graph shows that if solar energy is more, then system cost is going to be low.

For instance, in the case of 0.6kWh/d, the NPC of the system at 4.14kWh/m^2/day is \$2,511.967, whereas at a solar scaled average of 5.00 kWh/m^2/day the NPC is \$2,342.911, this shows a decrease in cost of about \$170. For electrical load of 0.90, NPC at 4.14kWh/m^2/day is 4,199.402, whereas at 5.00 the NPC reduces to \$4,036.898.

5.7. Conclusion

The study involved the sizing of a remote community in Edo State, Nigeria having 9 houses located far away from the utility grid and the city. The cost of running electric cables to connect this remote community to the city utility grid would be far more expensive and would lead to huge losses alone the line, which would be counterproductive. For this research, a solar energy was considered due to the abundance in supply of solar resources in the region. From simulated result a PV microgrid DC system is the best solution in terms of cost and optimization of energy. Factors such as variation in solar resources, unequal use of energy in the community can be balanced out by sharing of excess energy among residence in the community. With increase or decrease in solar irradiation from 4.14kWh/m2/day to 5kWh/m2/day due to climatic factors, there would be little to no change in system cost because houses having less energy consumption will share excess energy with residence with more need for energy. This system is far better than a standalone system for each resident as it would require much more PV components leading to more cost in installation, operation, and maintenance.

5.8. Reference

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Chapter 6

Dynamic Simulation Of DC Microgrid PV System For A Remote Community In Nigeria

6.1. Introduction

Microgrid technology is a small power generation, distribution and utilization system comprising of distributed generation, energy storage system, conversion devices, protection and monitoring devices [1]. This technology can be classified into DC microgrid, AC microgrid and AC/DC hybrid microgrid system [2].Many researchers have carried out studies in the control and operation of DC microgrids [3]. The absence of reactive power in DC microgrid, makes the DC bus the only indicator in monitoring the stable operation of the DC microgrid system [4]. The stability of the DC microgrid system includes both static and transient stability [5]. In [6] Uttar Pradesh authorities used a 24V solar powered DC microgrid for powering lighting loads. Detailed stated-of-art DC microgrid systems have been discussed in [7]. There is flexibility in integration of storage system(s) such as batteries for DC microgrid [8]. Off grid power system can be comprised of a PV-battery or Generator Set-Battery combination for supply of power to community load [9]. The selected site in the figure below is an isolated community in the remote areas of Edo State, Nigeria. In Google map its coordinates are Latitude: 6°10'58.3"N Longitude: 5°56'00.6"E (6.182863, 5.933505). The community is completely cut off from the grid and solely depend on kerosene lamps for lighting purposes, there isn't much need for heating since they have a temperate weather. This site was chosen and it consists of 9 residences with no access to electricity. The system proposed is a solar PV and battery microgrid system. The system is designed in such a way that, Using a 48V common bus system power is been shared among the houses in the community. Each house has its own solar PV and battery and can connect/disconnect to the grid using a switch. When houses are connected to the grid power is been shared among the various houses. In the event where there is excess power in any of the houses, the excess power is fed to the microgrid and is being utilized by houses in need of more energy to power their loads. This system was designed using the Homer Pro tool and comprised of a 100 Watt 12V Solar PV, 12V 45Ahr lead acid battery and switches. The system was simulated in Simulink at different switching times and results shows the responds of the system when houses connect and disconnect from the microgrid.

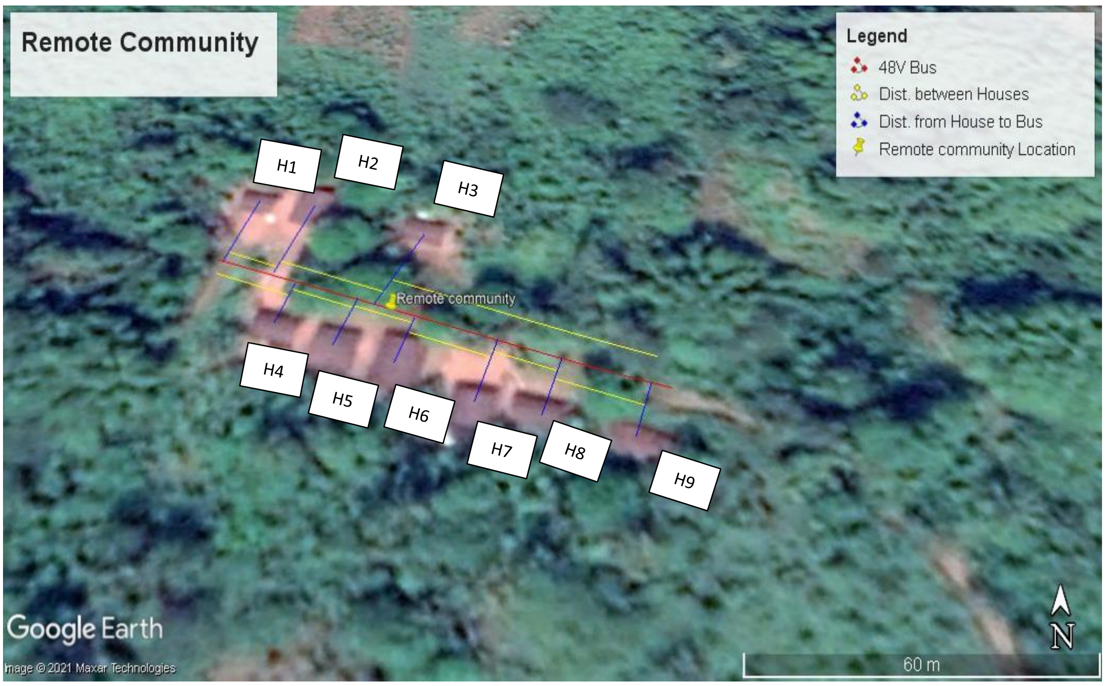

Fig.6.1. Distance between houses in remote community.

6.2. Design Of Microgrid

Design of the microgrid is comprised of various components, which includes connection of the microgrid (this accounts for line losses between houses and from houses to bus), calculation of DC load, calculation and configuration of solar PV, battery design configuration.

6.2.1 Connection Of Microgrid

The proposed microgrid connection is shown in the figure below. The community is comprised of nine (9) residences. Taking reference from house 1, other houses have a load variation from ±10% to ±40%. Each house is connected to another through a 48V DC common bus system. The distance from the houses to the bus and from the house to another have been taken into account as shown in table 6.1 and 6.2. Using a 10 gauge wire the resistance between the houses and the 48V bus was commuted with respect to the distances as shown in tables 6.1 and 6.2. Table 6.3 shows the datasheet of American Wire Gauge (AWG) cable/conductor size and properties. From the table, using a 10 AWG wire, Resistance (ohms/km) is given as: 3.276392. Using this value, the resistance across the wire for the figure above is calculated using the formula:

$R = 3.276392 \times 10^{-3}$ (ohms/m) × distance (m)

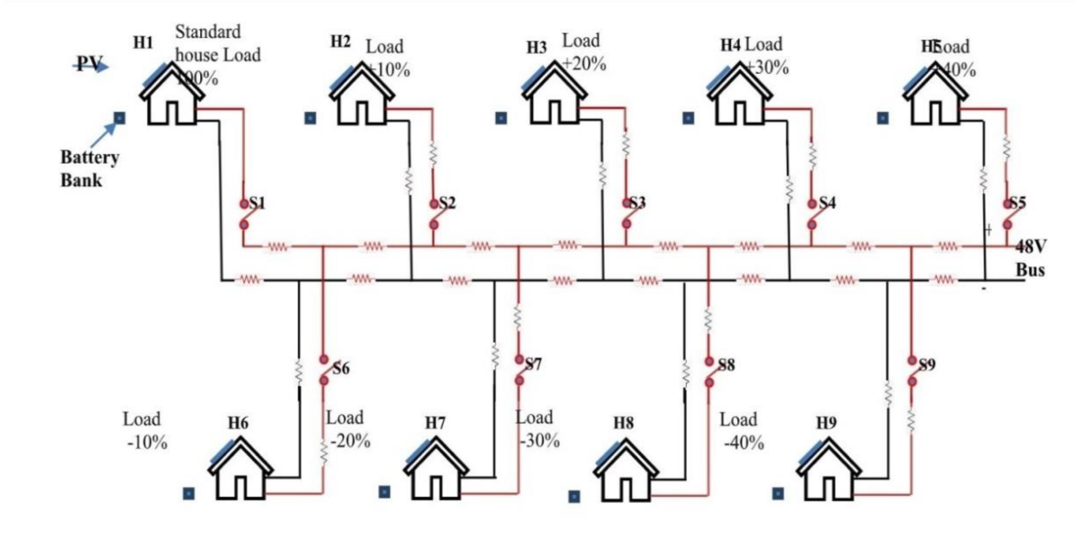

Fig.6.2 Block diagram of line resistance between houses in the community.

Figure 6.2 above shows the communal microgrid connection with all wire resistances. These resistances represent line losses along the wire from one house to another and from each house to the 48V bus. The circuit also shows that each house having switches S1 to S9. These switches are used to connect/disconnect from the microgrid.

Table 6.1: Distance and resistance from Houses to Bus (Blue line).

Houses	**Distance**	**Line Resistance**
House 1	18.7m	0.0613 Ω
House 2	21.2m	0.0695 Ω
House 3	22m	0.072 Ω
House 4	11.2m	0.0367 Ω
House 5	12.8m	0.0419 Ω
House 6	12m	0.0393 Ω
House 7	15.5m	0.0508 Ω
House 8	14.1m	0.0462 Ω

House 9	13m	0.0426 Ω

Table 6.2: Distance and resistance between Houses (Yellow Line).

Houses	**Distance between houses**	**Line Resistance**
House 1 – House 2	12.7m	0.0416 Ω
House 2 – House 3	25.7m	0.0842 Ω
House 1 – House 4	17.7m	0.0579 Ω
House 4 – House 5	15m	0.0491 Ω
House 5 – House 6	13.7m	0.0449 Ω
House 6 – House 7	18.5m	0.0606 Ω
House 7 – House 8	14.9m	0.0488 Ω
House 8 – House 9	19.7m	0.0645 Ω

Table 6.3: American Wire Guage (AWG) Cable/conductor Sizes and Properties.

AWG	Diameter [inches]	Diameter [mm]	Area [mm^2]	Resistance [Ohms / 1000 ft]	Resistance [Ohms / km]	Max Current [Amperes]	Max Frequency for 100% skin depth
0000 (4/0)	0.46	11.684	107	0.049	0.16072	302	125 Hz
000 (3/0)	0.4096	10.40384	85	0.0618	0.202704	239	160 Hz
00 (2/0)	0.3648	9.26592	67.4	0.0779	0.255512	190	200 Hz
0 (1/0)	0.3249	8.25246	53.5	0.0983	0.322424	150	250 Hz
1	0.2893	7.34822	42.4	0.1239	0.406392	119	325 Hz
2	0.2576	6.54304	33.6	0.1563	0.512664	94	410 Hz
3	0.2294	5.82676	26.7	0.197	0.64616	75	500 Hz
4	0.2043	5.18922	21.2	0.2485	0.81508	60	650 Hz
5	0.1819	4.62026	16.8	0.3133	1.027624	47	810 Hz
6	0.162	4.1148	13.3	0.3951	1.295928	37	1100 Hz
7	0.1443	3.66522	10.5	0.4982	1.634096	30	1300 Hz
8	0.1285	3.2639	8.37	0.6282	2.060496	24	1650 Hz
9	0.1144	2.90576	6.63	0.7921	2.598088	19	2050 Hz
10	0.1019	2.58826	5.26	0.9989	3.276392	15	2600 Hz
11	0.0907	2.30378	4.17	1.26	4.1328	12	3200 Hz
12	0.0808	2.05232	3.31	1.588	5.20864	9.3	4150 Hz
13	0.072	1.8288	2.62	2.003	6.56984	7.4	5300 Hz
14	0.0641	1.62814	2.08	2.525	8.282	5.9	6700 Hz
15	0.0571	1.45034	1.65	3.184	10.44352	4.7	8250 Hz
16	0.0508	1.29032	1.31	4.016	13.17248	3.7	11 k Hz
17	0.0453	1.15062	1.04	5.064	16.60992	2.9	13 k Hz
18	0.0403	1.02362	0.823	6.385	20.9428	2.3	17 kHz
19	0.0359	0.91186	0.653	8.051	26.40728	1.8	21 kHz
20	0.032	0.8128	0.518	10.15	33.292	1.5	27 kHz
21	0.0285	0.7239	0.41	12.8	41.984	1.2	33 kHz
22	0.0254	0.64516	0.326	16.14	52.9392	0.92	42 kHz
23	0.0226	0.57404	0.258	20.36	66.7808	0.729	53 kHz
24	0.0201	0.51054	0.205	25.67	84.1976	0.577	68 kHz
25	0.0179	0.45466	0.162	32.37	106.1736	0.457	85 kHz
26	0.0159	0.40386	0.129	40.81	133.8568	0.361	107 kHz
27	0.0142	0.36068	0.102	51.47	168.8216	0.288	130 kHz
28	0.0126	0.32004	0.081	64.9	212.872	0.226	170 kHz
29	0.0113	0.28702	0.0642	81.83	268.4024	0.182	210 kHz
30	0.01	0.254	0.0509	103.2	338.496	0.142	270 kHz
31	0.0089	0.22606	0.0404	130.1	426.728	0.113	340 kHz
32	0.008	0.2032	0.032	164.1	538.248	0.091	430 kHz
33	0.0071	0.18034	0.0254	206.9	678.632	0.072	540 kHz
34	0.0063	0.16002	0.0201	260.9	855.752	0.056	690 kHz
35	0.0056	0.14224	0.016	329	1079.12	0.044	870 kHz
36	0.005	0.127	0.0127	414.8	1360	0.035	1100 kHz
37	0.0045	0.1143	0.01	523.1	1715	0.0289	1350 kHz
38	0.004	0.1016	0.00797	659.6	2163	0.0228	1750 kHz
39	0.0035	0.0889	0.00632	831.8	2728	0.0175	2250 kHz
40	0.0031	0.07874	0.00501	1049	3440	0.0137	2900 kHz

6.2.2. Calculation Of Current For Solar PV

For this project, the Renogy RNG-100D-SS solar panel was used; the Renogy 100 Watt 12 Volt monocrystalline Panel provides high efficiency per area and is perfect for off-grid applications. In other to conform to the 48V DC common bus voltage, the panel was connected with a minimum of 4 in series in other to reach the required nominal voltage. The table below shows the properties of the RNG-100D-SS Solar PV.

Table 6.4: Datasheet of RNG-100D-SS solar PV.

Properties	**Value**
Maximum Power at STC	100W
Open Circuit Voltage (V_{oc})	22.3V
Short Circuit Current (I_{sc})	5.86A
Optimum Operating Voltage (V_{mp})	18.6V
Optimum Operating Current (I_{mp})	5.38A
Temperature Coefficient of V_{oc}	-0.28%/^{o}C
Temperature Coefficient of I_{sc}	0.048%/^{o}C
Module Efficiency	18.3%
Number of Cells	33 (3×11)

Load between each house differs so the various PV configuration and calculation is shown below.

Given that:

PV rated power = 100watt

Voltage at maximum power point (Vmp) = 18.6V

For 4 PV (connected in series):

At 1000W/m^2, 25^{oc},

P = VI

I = P/V = 400/74.4 = 5.376A

For 8PV (4 in series, 2 in parallel configuration)

I = P/V = 800/74.4 = 10.75A

For 12PV (4 Series, 3 Parallel configuration)

I = P/V = 1200/74.4 = 16.13A

6.2.3. Load Calculation

In other to design the microgrid in Matlab Simulink, the load for the houses which ranged from 1kW to 600W was converted to their equivalent resistances as shown in the calculation below using the formula given below:

$$P = V^2/R \quad 6.1$$

$$R = V^2/P \quad 6.2$$

Using equation 6.2 to calculate the resistance of each residence.

Where:

P = Power (Watts)

V = Voltage (Volts)

R = Resistance (Ohms)

House 1: P = 1kW, V = 48V

$P = V^2/R$

$R = V^2/P = 48^2/1000 = 2.304\ \Omega$

House 2: P = 1.1kW, V = 48V

$R = V^2/P = 48^2/1100 = 2.095\ \Omega$

House 3: P = 1.2kW, V = 48V

$R = V^2/P = 48^2/1200 = 1.92\ \Omega$

House 4: P = 1.3kW, V = 48V

$R = V^2/P = 48^2/1300 = 1.772\ \Omega$

House 5: P = 1.4kW, V = 48V

$R = V^2/P = 48^2/1400 = 1.645\ \Omega$

House 6: P = 0.9kW, V = 48V

$R = V^2/P = 48^2/900 = 2.56\ \Omega$

House 7: P = 0.8kW, V = 48V

$R = V^2/P = 48^2/800 = 2.88\ \Omega$

House 8: P = 0.7kW, V = 48V

$R = V^2/P = 48^2/700 = 3.29\ \Omega$

House 9: P = 0.6kW, V = 48V

$R = V^2/P = 48^2/600 = 3.84\ \Omega$

6.2.4. Battery Design Configuration

The battery used for the design is 12V, 45Ahr. Using a 48V bus, the table below shows the configuration of each house in the remote community.

Table 6.5: Battery configuration for each house load.

Household	Electric Load (kWh/d)	Number of Batt. (12V)	Design Configuration
House 1	1.0	8	48V, 90Ahr
House 2	1.1	4	48V, 45Ahr
House 3	1.2	8	48V, 90Ahr
House 4	1.3	8	48V, 90Ahr
House 5	1.4	12	48V, 135Ahr
House 6	0.9	4	48V, 45Ahr
House 7	0.8	8	48V, 90Ahr
House 8	0.7	8	48V, 90Ahr
House 9	0.6	4	48V, 45Ahr

6.3. Dynamic Simulation And Results

The Matlab Simulink is a tool used for modelling and dynamic simulation of system. The microgrid was carried out in the Matlab Simulink environment to show dynamic behaviour of the system to depict how the system would responds in real time. The figure below shows the design of the system in the Matlab Simulink environment.

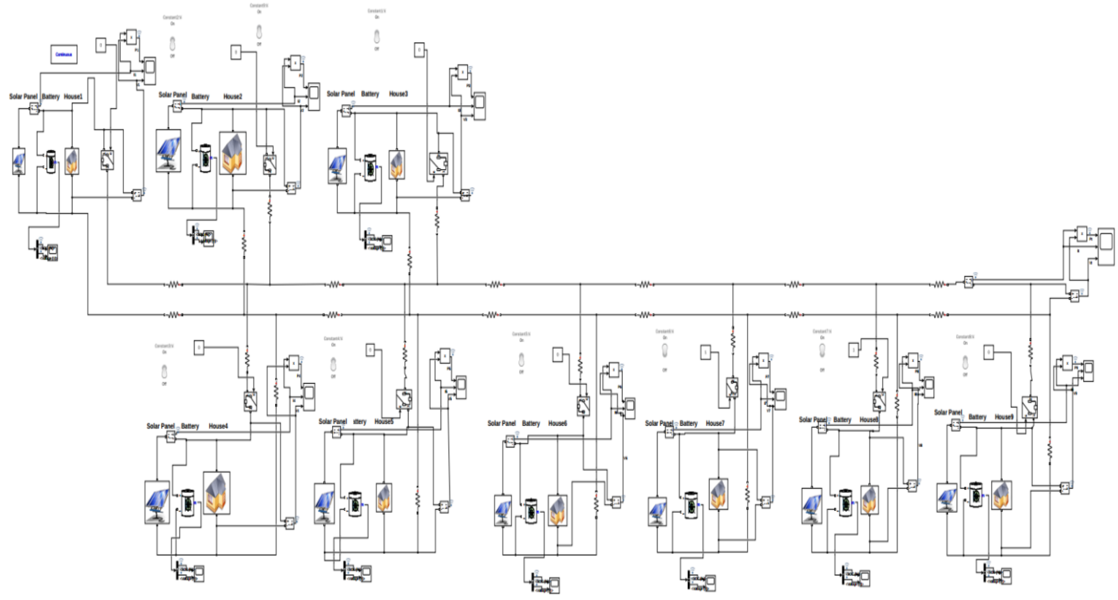

Fig. 6.3. Design of communal microgrid system in Simulink.

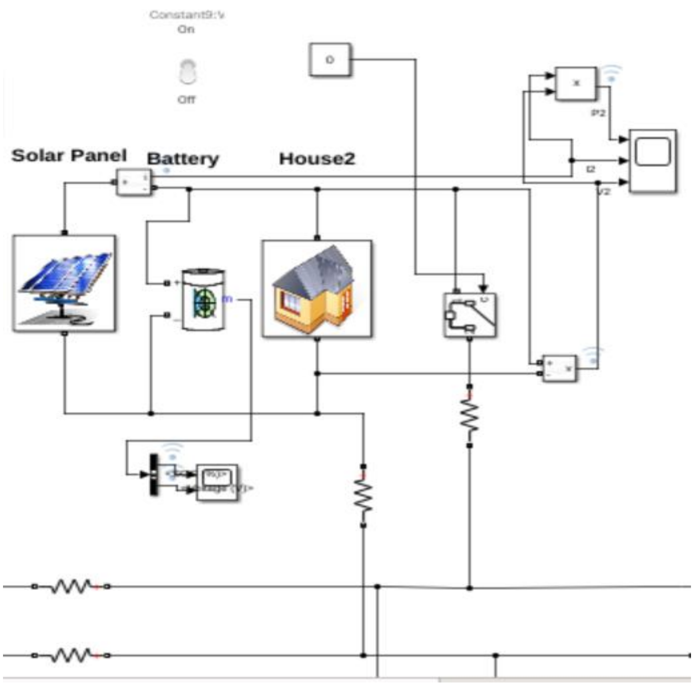

Fig. 6.3.1. Design connection of House 2 to Microgrid.

The figure 6.3 above shows a DC micro grid distribution system comprising of PV and battery. Figure 6.3.1 shows the detailed design of house 2 and its connection to the microgrid. Just like every other residence in the community, house 2 comprises of PV, Battery, and a switch that connect/disconnects to the communal grid, design also shows line resistance between the house and bus and also between each residence. The DC voltage generated by the PV from each house is distributed throughout the community grid. For this reason, there is no need for inverter for common bus connection. The houses are separated from each other by varied distance. Based on the distance, the line resistance is computed between the houses. The batteries connected to the various houses also have the nominal bus voltage of 48V. If the DC bus voltage of 48V is kept stable, future connections to the communal micro grid are easy because no inverter is required hence no modification necessary. The community microgrid operation works in a way that excess energy from a house can be sent back to the grid and be utilized by another house with less energy. With this form energy sharing there is efficient use of energy. Each house also has a breaker to disconnect from the 48V common bus voltage, which, by disconnecting from the grid affects the power, voltage and current output of the grid as seen from the simulation results below.

The following results show the Power, current and voltage of each house, Battery voltage, SOC of the battery, and effect on bus voltage when all houses were disconnected, connected, and also when some houses disconnect and connect at different times using the toggle switch.

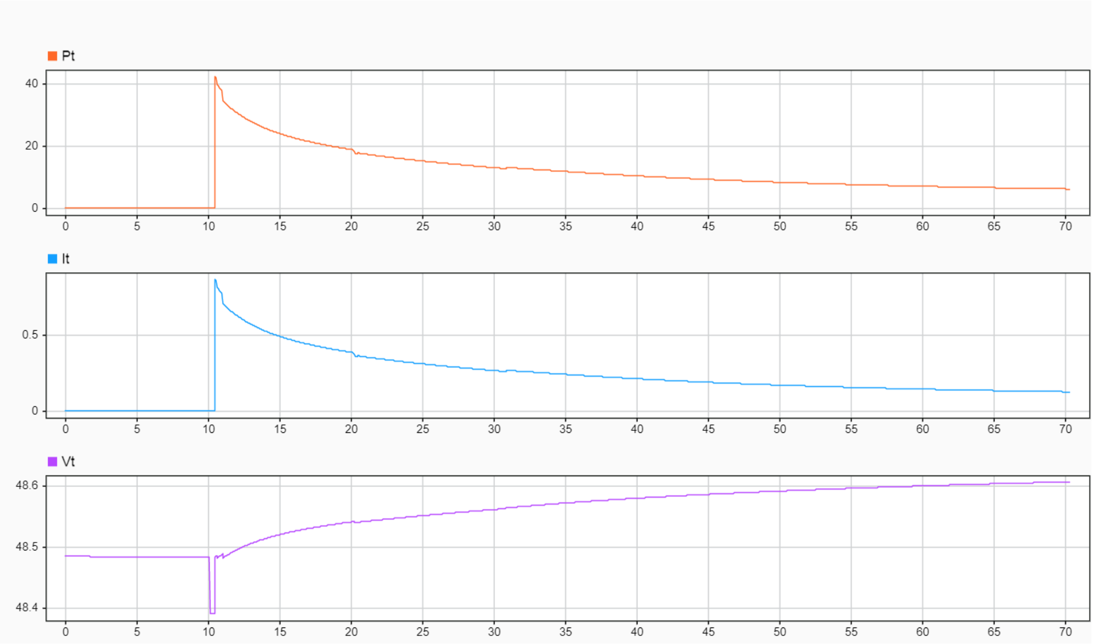

Fig. 6.4. Common bus voltage, current and power.

Figure 6.4 above shows the common bus voltage, current and power of all houses (House 1 – House 9) of the microgrid. At t = 10 there was a sharp drop in voltage as this represents disconnection of all houses due to routine maintenance, after which 5 residences (house 5 – house 9) were reconnected signifying the sharp rise in both voltage, current and power in the microgrid bus voltage. At t = 20, 3 other houses where connected to the grid and at the same time two other houses were disconnected (house 1 and house 2), which is shown by the steady rise in voltage, at t = 30, the remaining two houses were connected to the grid, which contributes to the steady increase in voltage. At t = 50, two houses where disconnected and reconnected at t = 60, but there wasn't much difference in voltage drop, since all other houses were still connected to the grid.

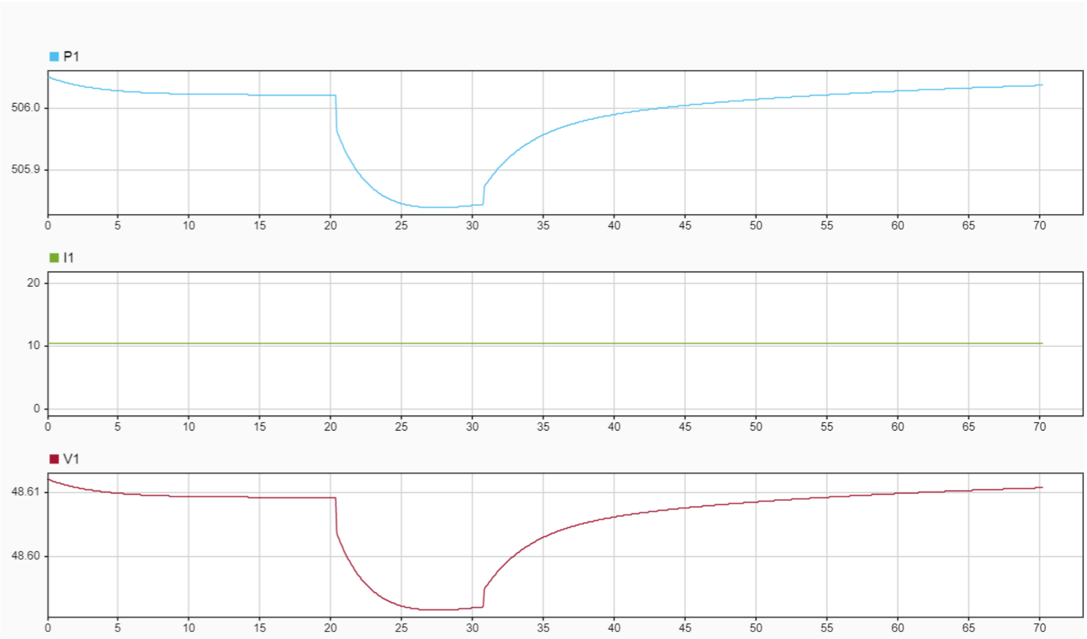

Fig.6.5. Power, Current of voltage of House 1.

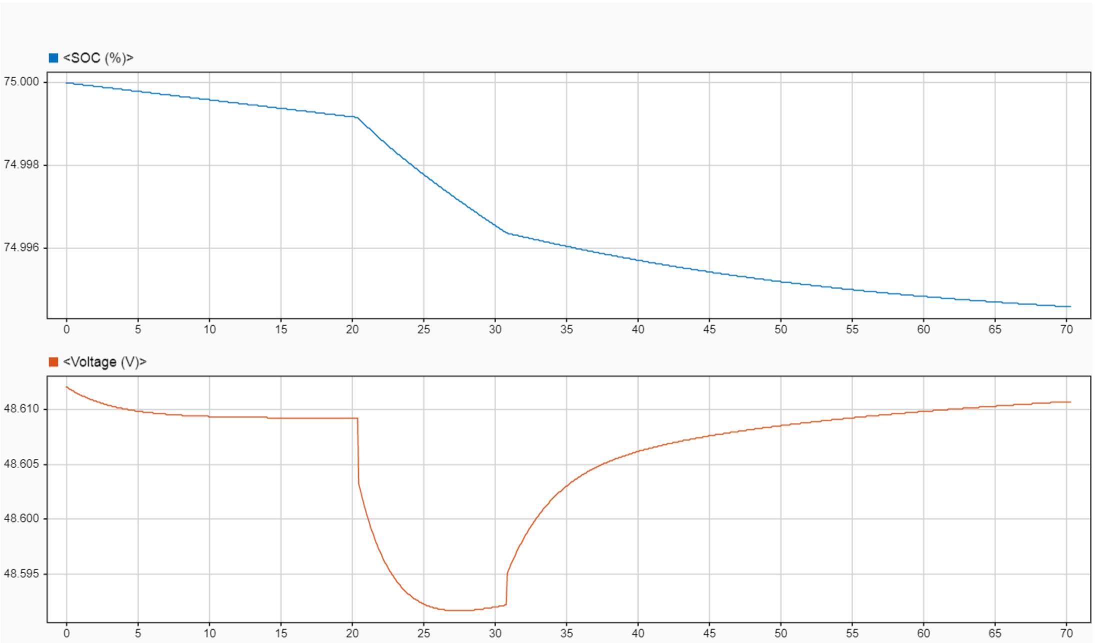

Fig.6.6. Shows the SOC of the battery and voltage.

Figure 6.5 above shows the load voltage, current and power response of house 1 for the different switching times during simulation. The graph shows significant drop in voltage and power at t = 20 and at t = 30 there was gradual increase which signifies when house 1 was disconnected from the grid and reconnected respectively. Figure 6.6 shows the voltage and State of Charge (SOC) of battery for house 1. The initial SOC of the battery begins at 75% and then there is a gradual decrease in SOC from t = 0 to t = 20 and also a further decrease till it reaches t = 70. This decrease is due to connection of other house loads in the microgrid. As more houses connect, power is being shared between the houses leading to more energy utilized from the battery.

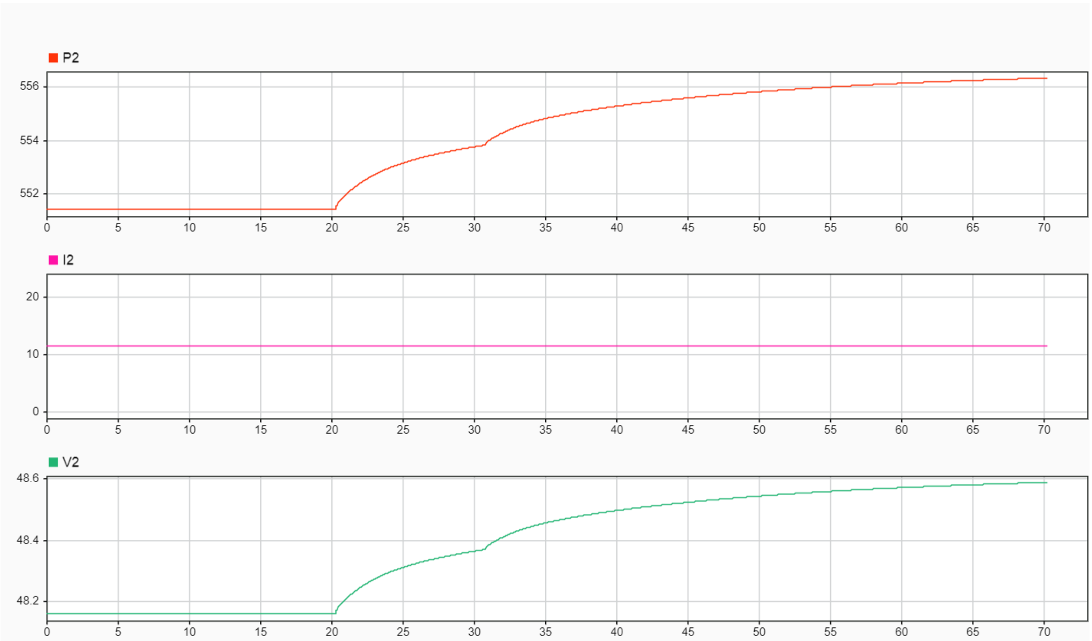

Fig 6.7. Power, current and load voltage of House 2.

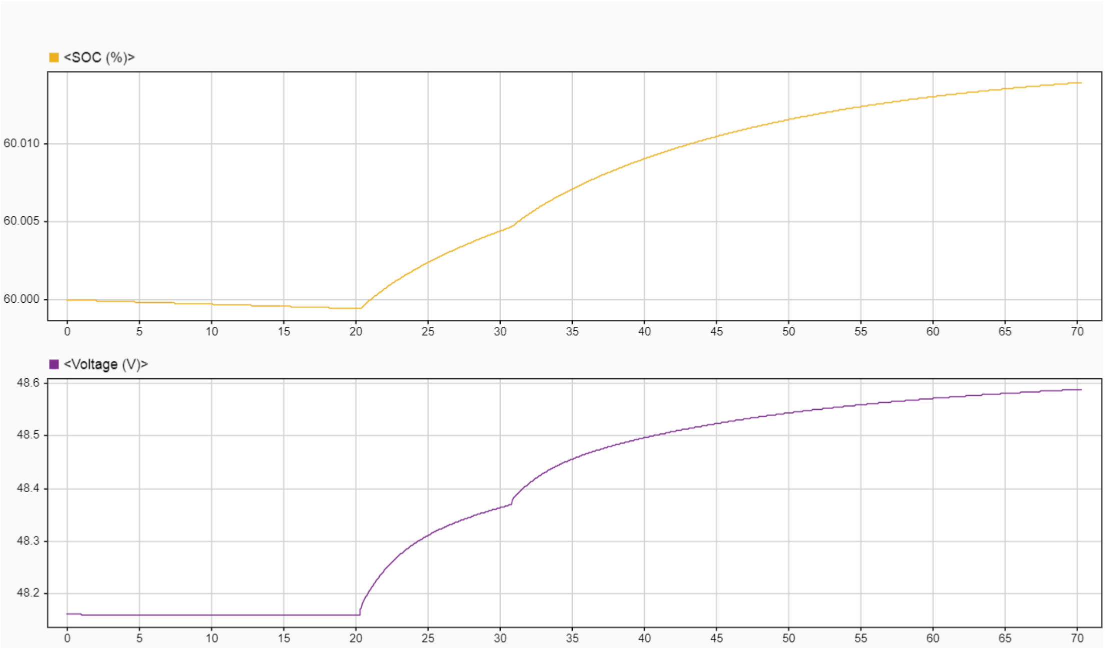

Fig. 6.8. Battery Voltage and SOC of house 2.

Figure 6.7 above shows the load voltage, current and power response of house 2 for the different switching times during simulation. The graph shows significant rise in voltage and power at t = 20 and at t = 30 there was gradual increase which signifies when the house was receiving excess power from the microgrid. Figure 6.8 shows the voltage and State of Charge (SOC) of battery for the house. The initial SOC of the battery begins at 60% and then there is a significant increase in SOC from t = 20 to t = 30 and also a further increase till it reaches t = 70. This decrease is due to connection of other house loads in the microgrid. As more houses connect, power is being shared between the houses and therefore excess power from the grid increases battery charging.

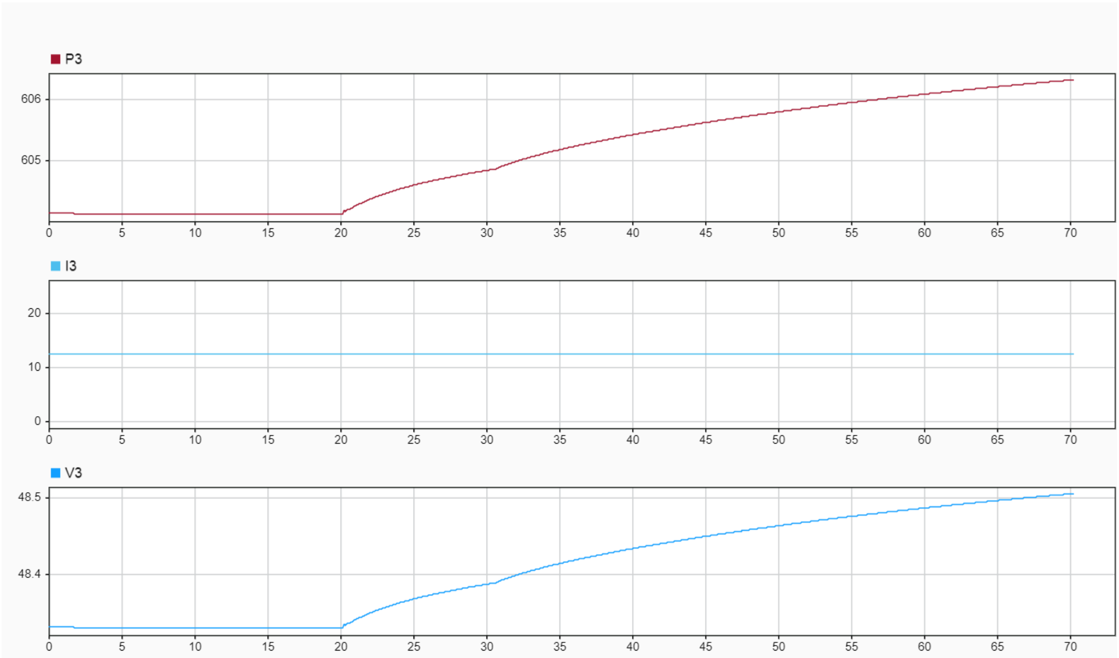

Fig.6.9. Power, current, and load voltage of house 3.

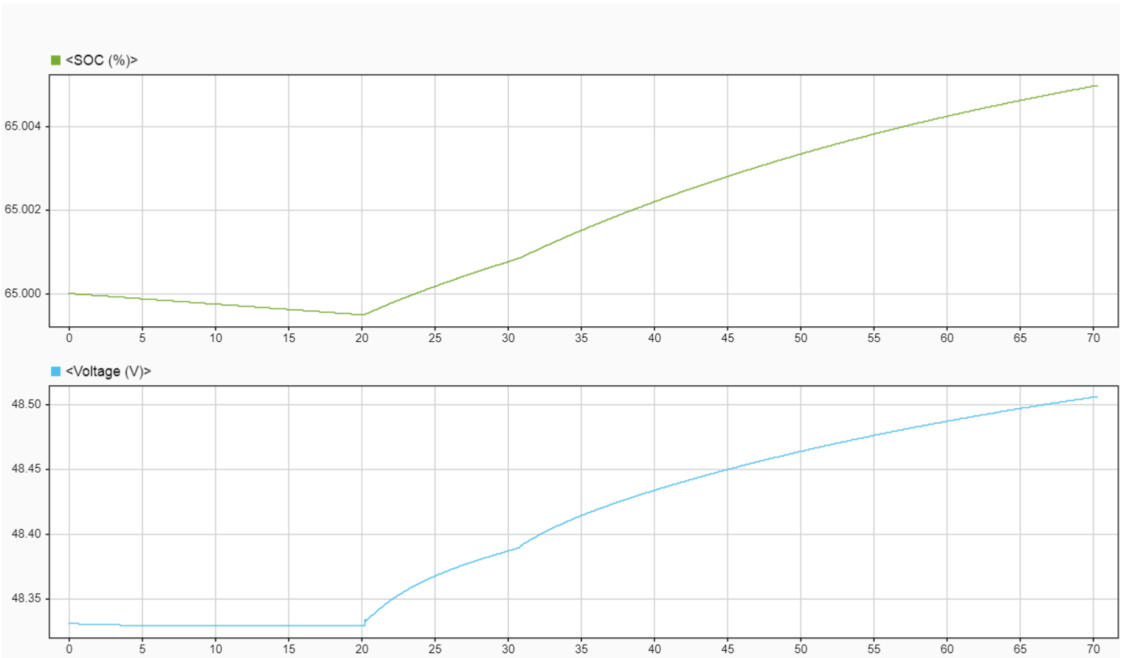

Fig 6.10. Battery SOC and voltage.

Figure 6.9 above shows the load voltage, current and power response of house 3 for the different switching times during simulation. The graph shows significant rise in voltage and power at t = 20 and at t = 30 there was gradual increase which signifies when the house was receiving the excess power and voltage from the micro grid. Figure 6.10 shows the voltage and State of Charge (SOC) of battery for the house. The initial SOC of the battery begins at 65% and then there is a significant increase in SOC from t = 20 to t = 30 and also a further increase till it reaches t = 70. This decrease is due to connection of other house loads in the microgrid. As more houses connect, power is being shared between the houses and therefore excess power from the grid increases battery charging.

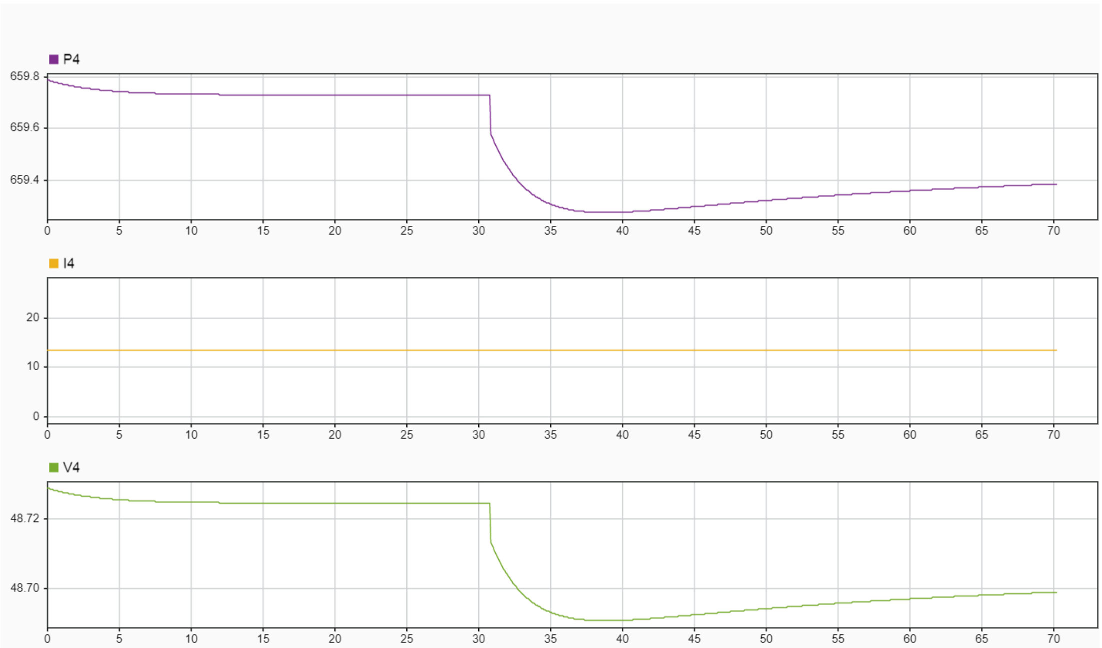

Fig. 6.11. Power, Current and Voltage of house 4.

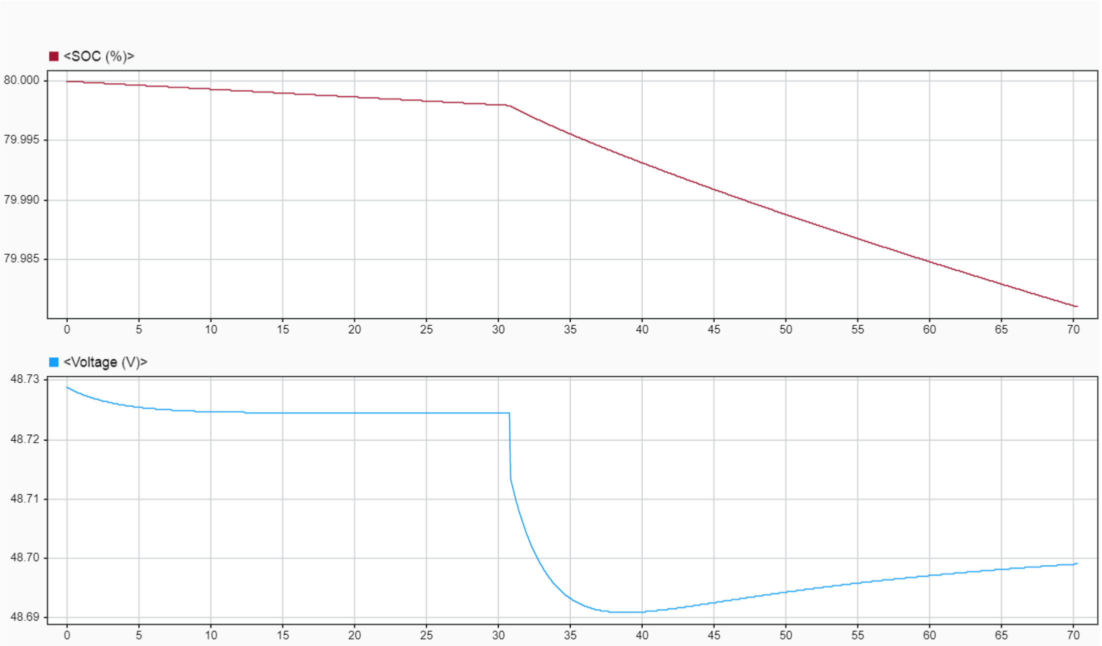

Fig 6.12. Battery SOC and voltage of House 4.

Figure 6.11 above shows the load voltage, current and power response of house 4 for the different switching times during simulation. The graph shows significant drop in voltage and power at t = 30 and at t = 40 there was gradual increase which signifies when the house load was significant than the power at t=30, but at t=40 there was a gradual increase in voltage and power due to excess energy from other houses being fed into the grid. Figure 6.12 shows the voltage and State of Charge (SOC) of battery for the house. The initial SOC of the battery begins at 80% and then there is a significant increase in SOC from t = 0 to t = 30 and also a further increase till it reaches t = 70. This decrease is due to connection of other house loads in the microgrid. As more houses connect, power is being shared between the houses.

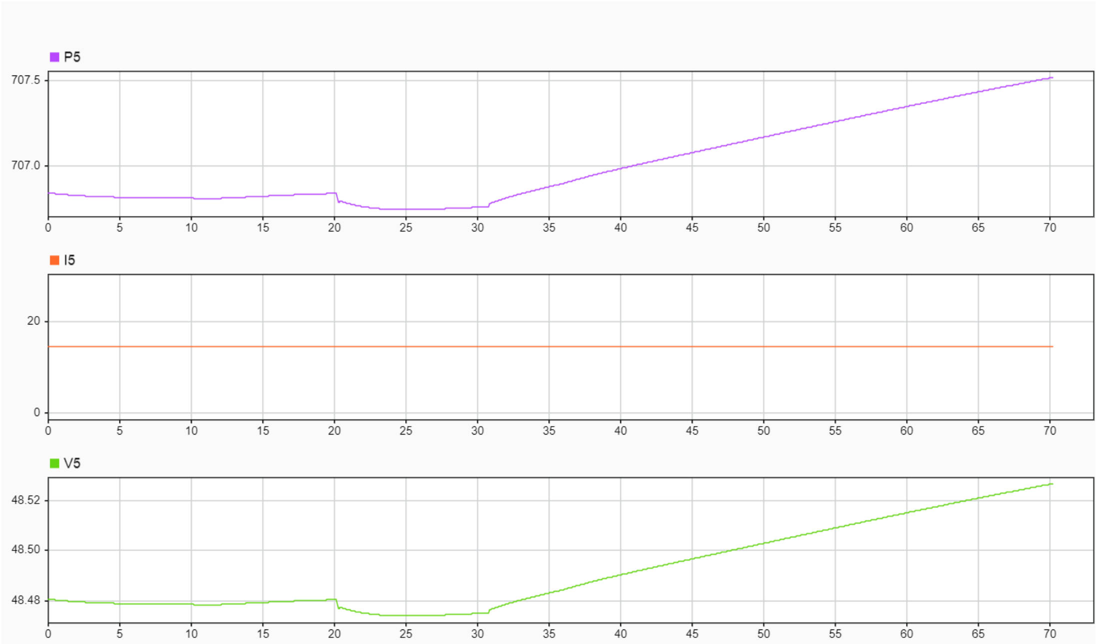

Fig 6.13 House 5. Power, current and load.

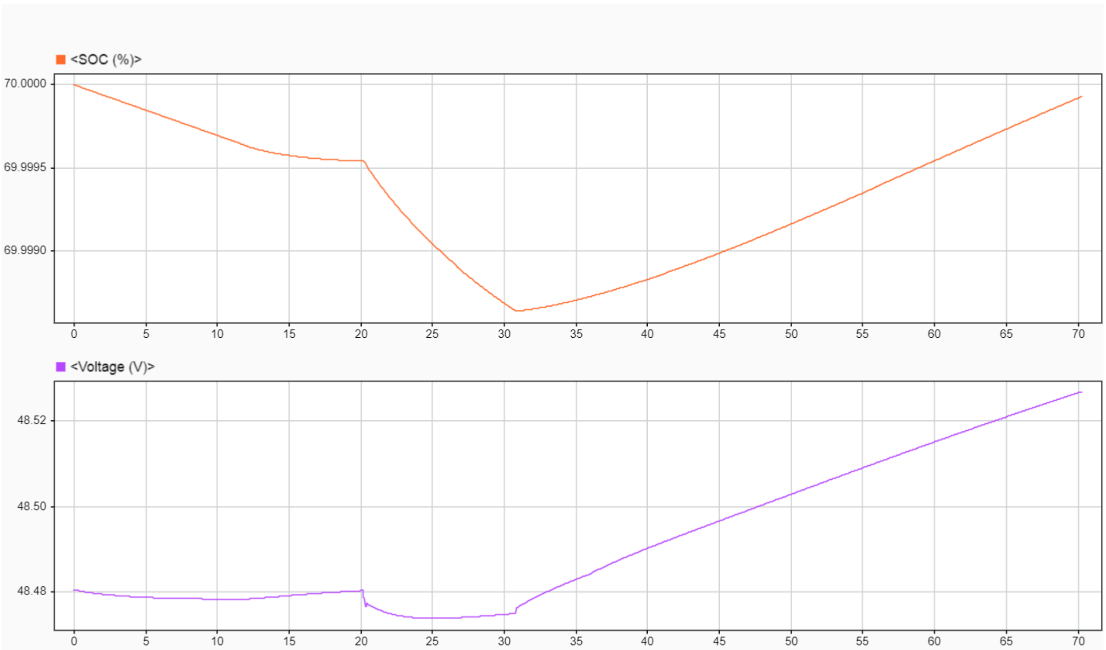

Fig. 6.14. House 5. Battery SOC and voltage.

Figure 6.13 above shows the load voltage, current and power response of house 5 for the different switching times during simulation. The graph shows significant drop in voltage and power at t = 20 which signifies when the house load was significant than the power supplied by the solar PV, but at t=30 there was a rapid increase in voltage and power due to excess energy from other houses being fed into the grid. Figure 6.14 shows the voltage and State of Charge (SOC) of battery for the house. The initial SOC of the battery begins at 70% and then there is a significant decrease in SOC from t = 0 to t = 30 which marks the period the battery supplied additional power to the house when the house was disconnected from the grid, and as it reaches t = 30, the battery SOC begins to increase rapidly as excess power from the microgrid charges the battery.

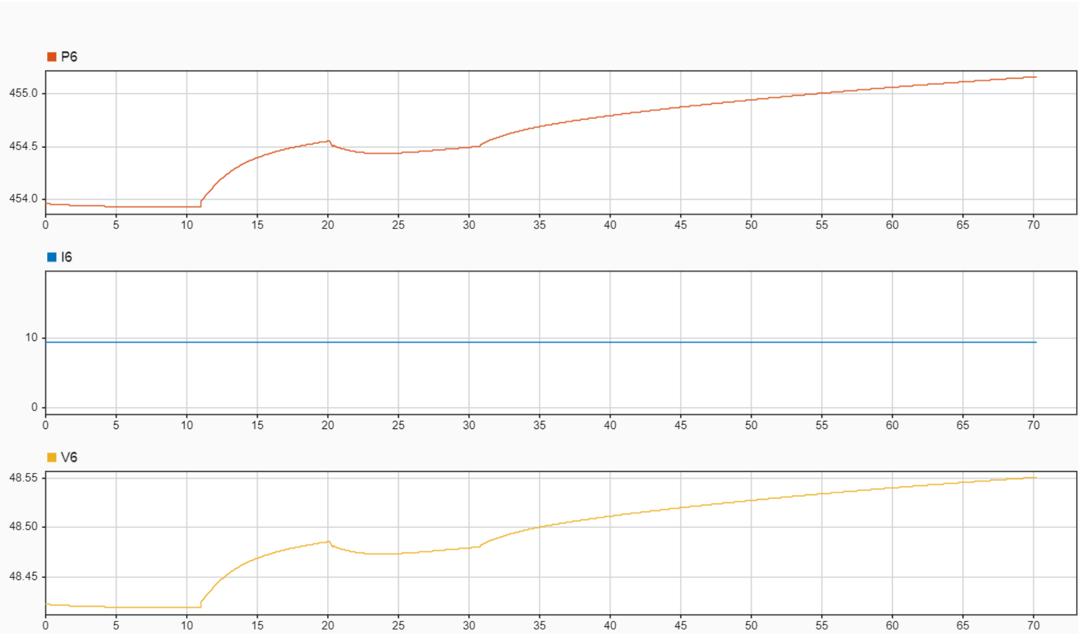

Fig. 6.15. House 6, Power, Current and voltage.

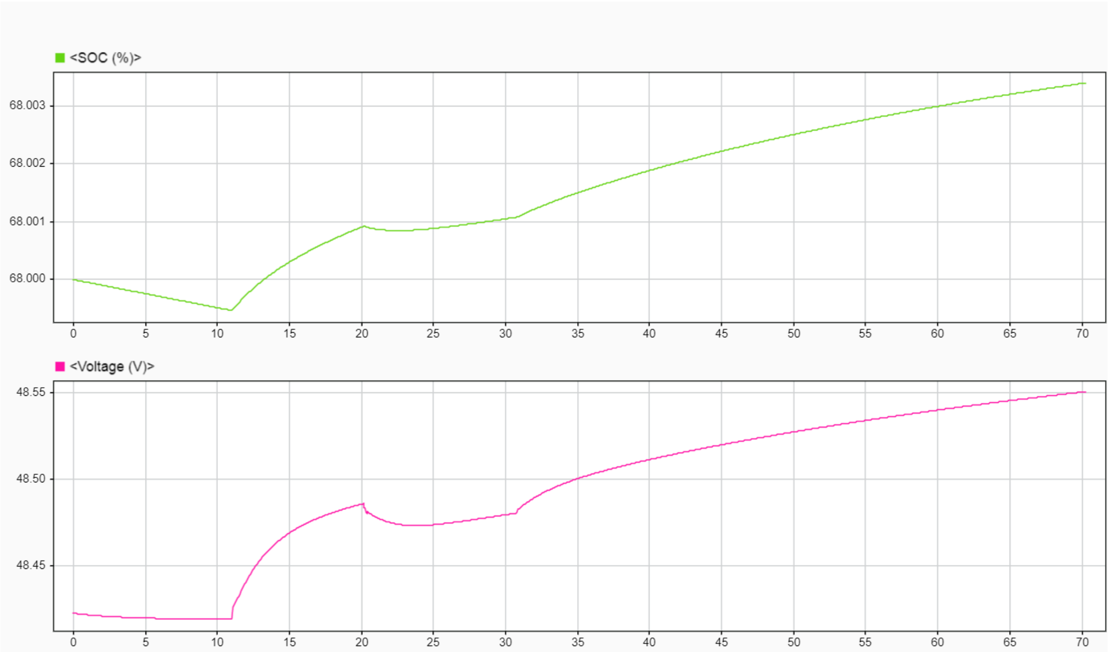

Fig. 6.16. House 6, Battery SOC and voltage.

Figure 6.15 above shows the load voltage, current and power response of house 6 for the different switching times during simulation. The graph shows increase in voltage and power from t = 10 to t = 20 which signifies the period the house was connected to the microgrid, but from t=20 to t = 30 there was decrease in voltage and power, this marks the period the house was disconnected from the microgrid, and at t = 30 it was reconnected back to the microgrid which resulted in steady increase in voltage and power due to excess power from the grid. Figure 6.16 shows the voltage and State of Charge (SOC) of battery for the house. The initial SOC of the battery begins at 68% and just like the load responds, the SOC of the battery also discharges when the house disconnects from the microgrid as power and charges when reconnected back to the microgrid.

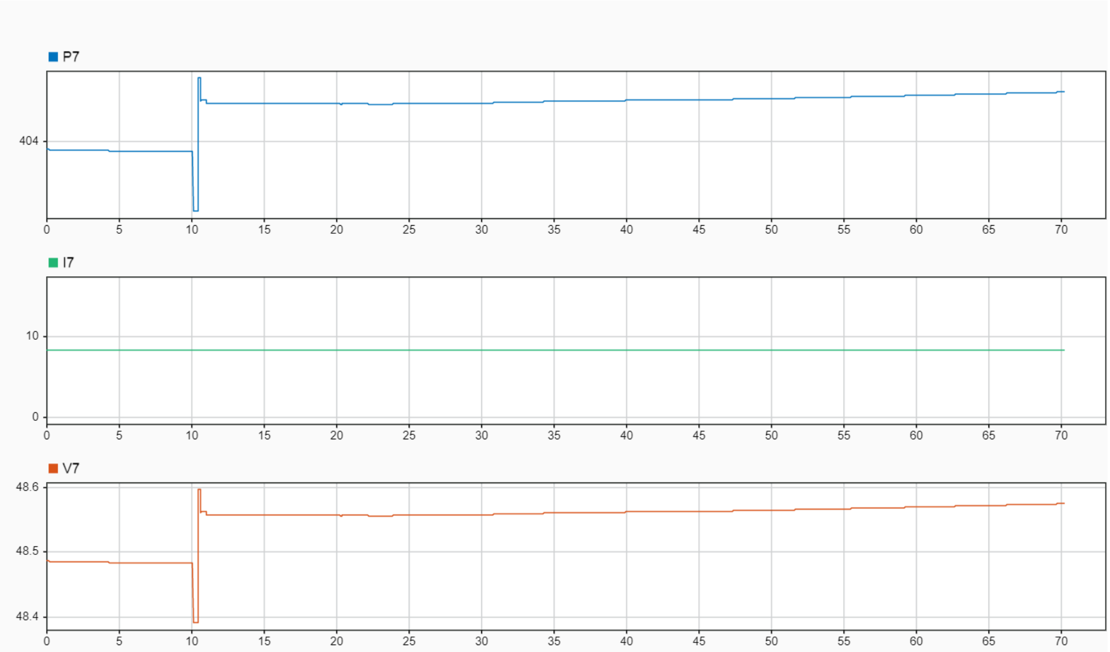

Fig. 6.17. House 7. Power, Current and Voltage.

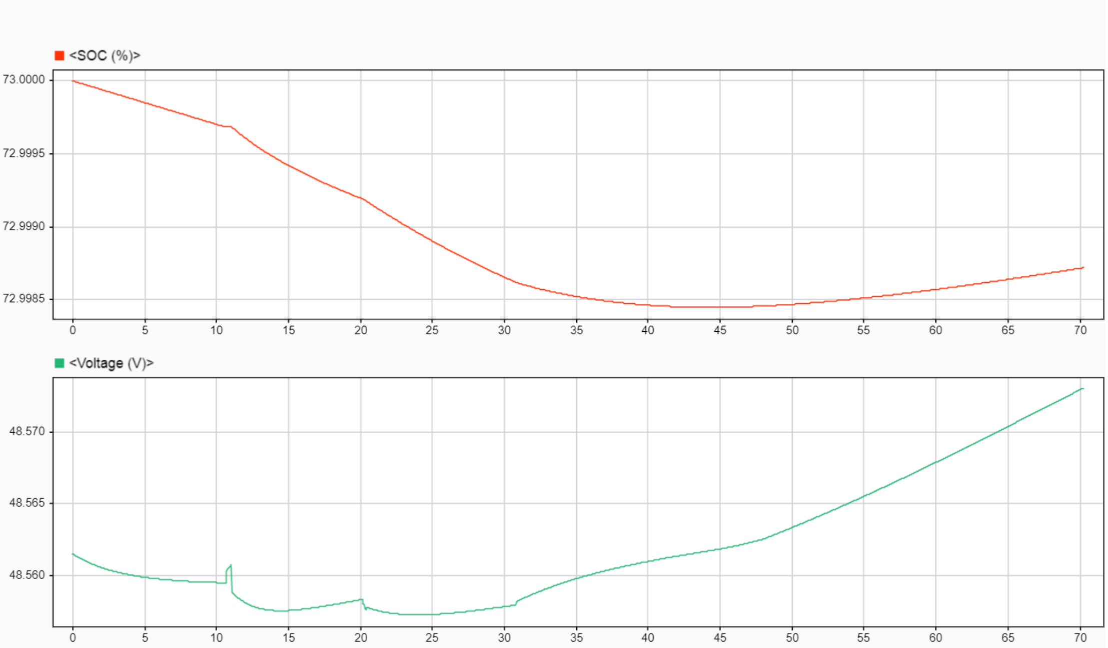

Fig. 6.18. House 7, Battery SOC and Voltage.

Figure 6.17 above shows the load voltage, current and power response of house 7 for the different switching times during simulation. The graph shows drop in voltage and power at t = 10 which signifies the period the house was disconnected from the microgrid, but also reconnected along with other houses to the microgrid to bring about a sharp rise in voltage and power, and also slight decrease in voltage and power up until t = 30, due to disconnection of other houses from the microgrid and from t = 30 up until t =70 shows a gradual increase in voltage and power as other houses reconnects back to the grid. Figure 6.18 shows the voltage and State of Charge (SOC) of battery for the house. The initial SOC of the battery begins at 73% and just like the load responds, the SOC of the battery also discharges when other houses disconnects from the microgrid as seen in t = 10 and t =20, and at t = 30 the SOC increases when they reconnected back to the microgrid.

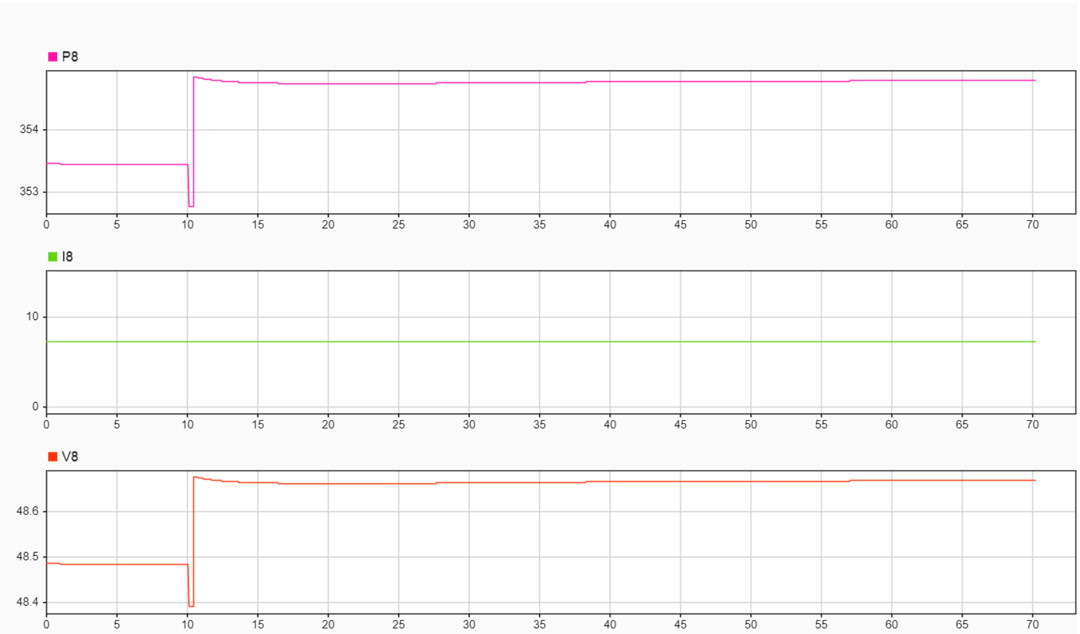

Fig 6.19. House 8. Power, Current, and Load voltage.

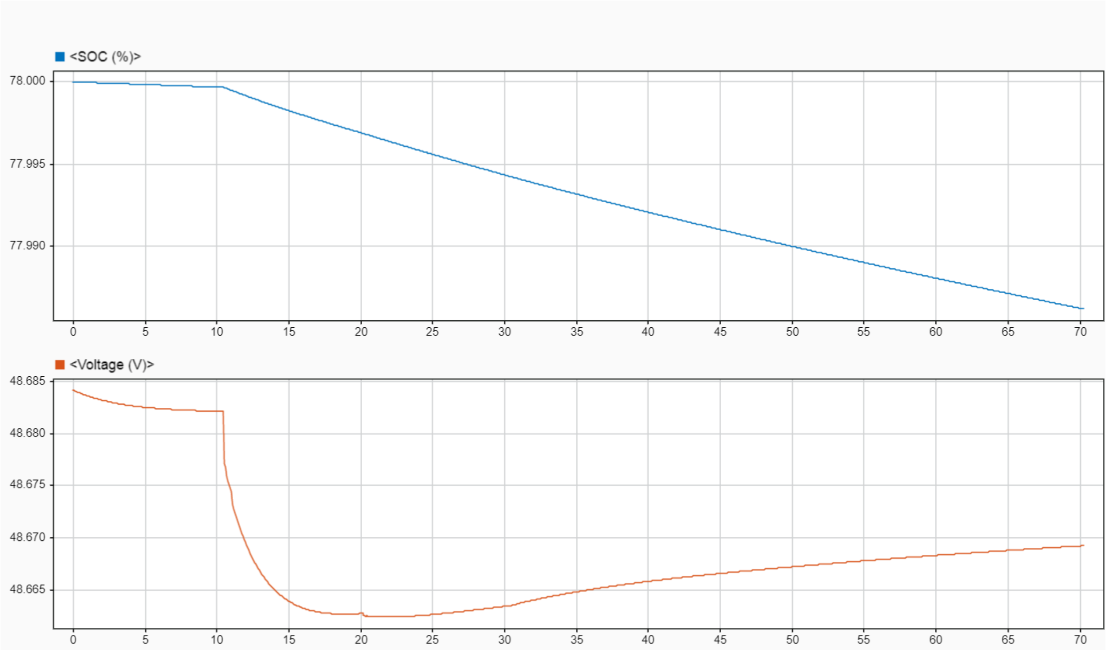

Fig. 6.20. House 8. Battery SOC and voltage.

Figure 6.19 above shows the load voltage, current and power response of house 8 for the different switching times during simulation which have a similar response as house 7. The graph shows drop in voltage and power at t = 10 which signifies the period the house was disconnected from the microgrid, but also reconnected along with other houses to the microgrid to bring about a sharp rise in voltage and power, and also slight decrease in voltage and power up until t = 20, due to disconnection of other houses from the microgrid and from t = 20 up until t =70 shows a gradual increase in voltage and power as other houses reconnects back to the grid. Figure 6.20 shows the voltage and State of Charge (SOC) of battery for the house. The initial SOC of the battery begins at 78% and just like the load responds, the SOC of the battery also discharges when other houses disconnects from the microgrid as seen in t = 10 and t =20, and at t = 20 the SOC increases when they reconnected back to the microgrid.

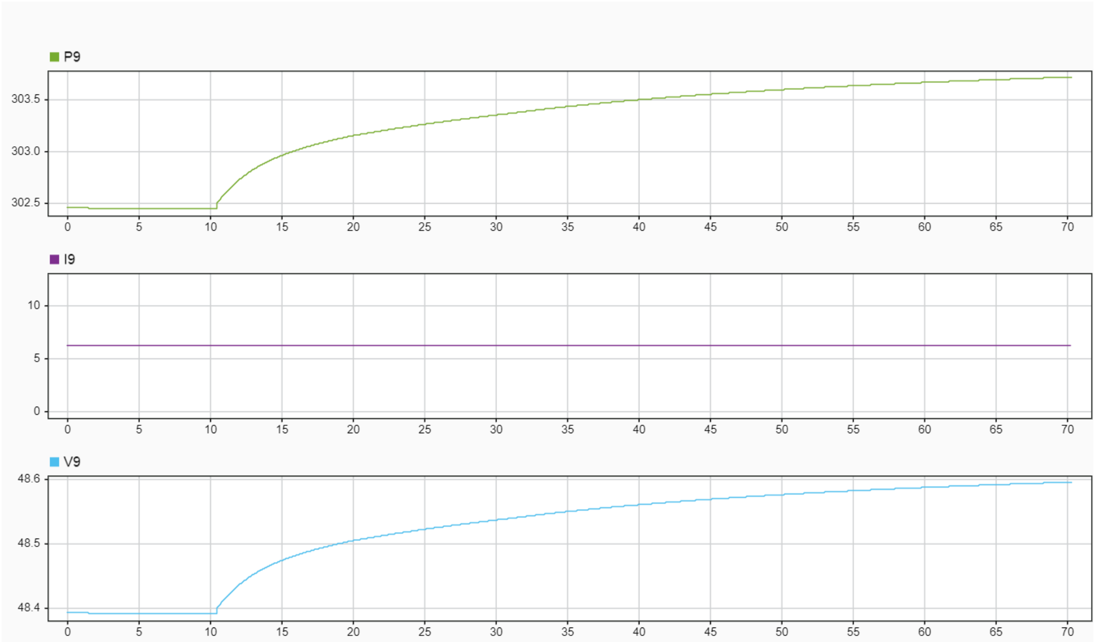

Fig 6.21. House 9, Power, Current and Load Voltage.

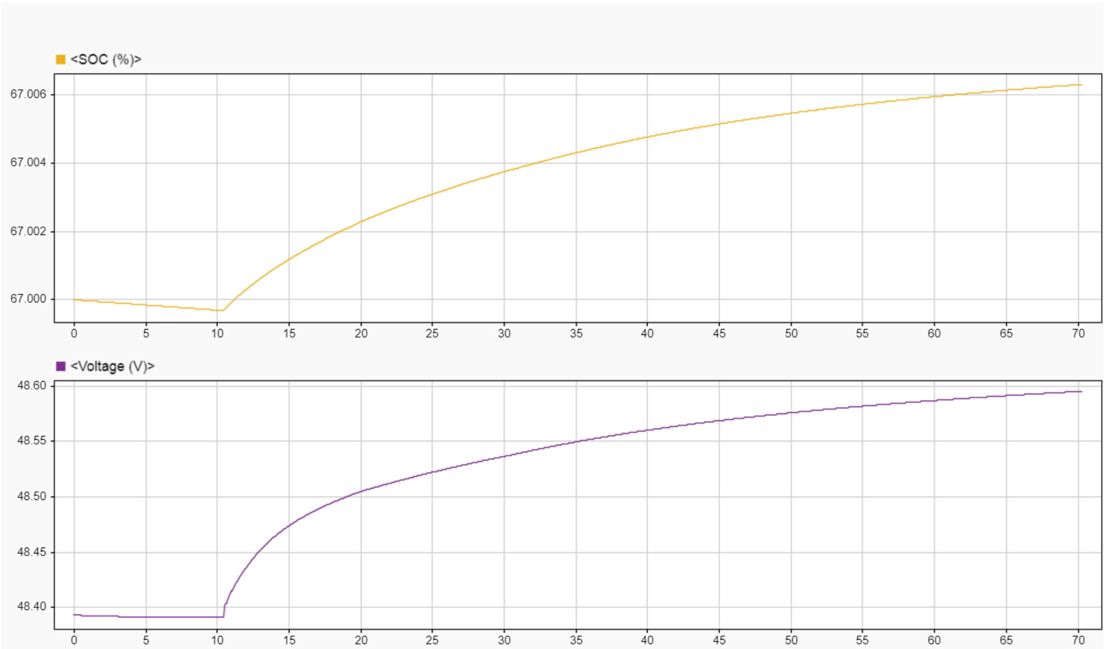

Fig 6.22. House 9, Battery SOC and voltage.

Figure 6.21 above shows the load voltage, current and power response of house 7 for the different switching times during simulation. The graph shows drop in voltage and power from t= 0 to t = 10 which signifies the period the house was disconnected from the microgrid, but also reconnected at t = 10 along with other houses to the microgrid to bring about a rapid rise in voltage and power up until t =70. Figure 6.22 shows the voltage and State of Charge (SOC) of battery for the house. The initial SOC of the battery begins at 67% and just like the load responds, the SOC of the battery also discharges when the house disconnects from the microgrid as seen in the period from t = 0 to t =10, and from t = 10 up until t = 70 the SOC increases when reconnected back to the microgrid signifying sharing of excess power between houses in the community.

6.4. Conclusion

The study involved the dynamic simulation of an off grid microgrid system for a remote community in Edo state, Nigeria. From economic point of view, the proposed microgrid design comprising of solar PV and battery, was connected in such a way that power would be shared among the 9 houses in the community through a common 48V DC bus for optimal utilization of energy and reduction in cost. Simulated result showed that at different times the switch is being toggled on and off for different houses, power is being fed into the microgrid and utilized by other houses as seen from the simulation results. For instance, comparing the results between house 1 and house 2, it can be seen that for house 1, at t = 20, there is significant drop in voltage and power and at t = 30 there was gradual increase which signifies when the house was disconnected from the grid and reconnected respectively, whereas for house 3, at t = 20, there is constant rise in voltage and power, as it remains connected to the grid and at t = 30 there was significant increase which signifies when the house was receiving excess power from the microgrid. This simply means that for the period t=30 when house 1 was reconnected, both voltage and power of house 2 began to experience increase due to the excess power fed into the microgrid due to reconnection of house 1. The results show that for a remote community of this size, a power sharing DC microgrid is the best option for the community. The selected 48V DC bus is 100% safe and simple solution avoiding any need for inverters.

6.5 References

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Chapter 7

Conclusions and Recommendations

7.1 Conclusions

Small scale renewable energy system is becoming very necessary in current power system design, especially in under developed countries such as Nigeria. The reason for this is most households and communities in the remote part of the country have inadequate supply of electricity and in most cases are completely cut off from the grid. By implementing small scale renewable energy system we will be able to combat reduction in pollution caused by diesel generator and also aid in promotion of greener environment. Economically, application of this system would reduce cost significantly as connection of household and community which are located far away from the utility grid would involve much cost in infrastructure and running of cables. In terms of optimization of energy, this option is the most preferred as energy is utilized in the most efficient way with little loss as compared to long distance wiring from these remote areas to the grid leading to great line loss, there is also the issue of maintenance, small scales renewable energy design are much easier in terms of maintenance in comparison to integration to the main grid system.

In this thesis a small scale solar hybrid system has been designed. Four studies were done and were implemented using solar photovoltaic system. Firstly, sizing and analysis was carried out for an off grid resident in remote area in Edo State Nigeria having a solar irradiance of 4.63kWh/m^2/day, this was done in order to determine the most cost efficient and optimal system in fulfilment of load requirement for the house having an average energy consumption of 3.4kWh/day and total load of 1.26kW. The sizing was carried out using Homer Pro, a system sizing tool. Using a 48V bus system, design was carried out using the software and consisted of a 1.23kW solar with 325W each (4 modules), 4 batteries of 12V, 1.60kW inverter, and a 4.80kW generator. After simulation, using the compare economic tool, details of the analysis showed the Net Present Cost (NPC) of the base system (A generator) and the current system (A configuration of PV, Generator, Battery, and Inverter), result proved that the current system is most cost efficient and the better option as compared to the base system economic comparison between the two systems shows that the NPC of generator is $10,785, while for the hybrid power system the NPC is $4,146 that is much lower than existing arrangement. Sensitivity analysis was also carried out to determine the robustness of the system in terms of adaptation to various changing environmental and economic parameters.

Chapter 3 includes the dynamic simulation of the system designed for the remote residence using Matlab Simulink. The design consisted of 1.23kW PV made up of 4 modules (325W each with 2 in series and 2 in parallel), A MPPT (maximum power point tracking), a DC –DC buck converter, 4 backup battery of 12V, 350Ahr connected in series and a 4.8kW emergency generator system with a 1.6kW inverter which converts the output DC voltage of 48V from the converter to an alternating AC. The system also incorporates a control system that turns off the emergency generator when the voltage of the backup battery goes below 49V. The system was simulated in various configurations to determine the reliability of the system. Simulated result shows that in various configurations the system proved to be both stable and reliable.

Chapter 4 includes the simulation of an off grid Photovoltaic (PV) system with battery and generator backup for a house. The house having a load of 1.26kW was optimized Homer Pro to give the most efficient and cost effective system. Simulation was also performed in the Simulink to show stability of power supply in various configurations.

Chapter 5 includes the sizing and design of a remote community consisting of 9 residences with no more than 100m apart in distance. The community is completely cut off from the grid, with the load of the household ranging from 0.6kW to 1.4kW. Using the Homer Pro tool, the system was sized on a 48V bus system and comprised of the following components: A 100W solar photovoltaic (PV) panel and a 12V 45Ahr battery. After simulation was carried out the system presented the most cost efficient and optimal system for each house in the community. Further simulation was done to determine the robustness of the system by inputting sensitivity variables, which resulted in more configurations that best fits the changing variables. From simulated result a PV-Battery microgrid DC system is the best solution in terms of cost and optimization of energy for the community in comparison to the cost of running long distance cable and infrastructure for integration to the utility grid in the city. This also would reduce huge line losses along the line and maintenance cost.

Chapter 6 includes the dynamic simulation of the DC microgrid system for the community; the system was design in the Matlab Simulink environment and consists of 100 Watt 12V Solar PV, 12V 45Ahr lead acid battery and switches. The system was simulated by switching ON and OFF different houses from the microgrid at different times and results shows the system response when houses connect and disconnect from the microgrid. Simulated result shows that with each house connected to a common 48V bus system, there is sharing of power among the houses which helps in the optimization and efficient use of energy among the residence in the community. Excess energy is being shared when houses having excess power being fed into the microgrid are utilized by houses in need of additional power to meet their load demand.

7.2 Recommendations

1. Addition of low cost open-source SCADA system for small scale renewable energy system.
2. Application of wind energy system especially in Northern Nigeria where there is high wind energy and solar resources.
3. DC Microgrid renewable energy system for Northern Nigeria in areas with spatial residential/communities.
4. Large Scale Grid-tied Hybrid system implementation in Nigeria.
5. Implementation of Solar farms and Solar water pumps for communities in Northern Nigeria for agricultural and ranching purposes for improved agricultural experience and development in the agricultural sector.

Publications

- J.C. Ozogbuda and M.T. Iqbal, “Dynamic Simulation of a Standalone Photovoltaic Hybrid System of a Remote house in Nigeria”. *2021 IEEE 12th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON).* 10.1109/IEMCON53756.2021.9623160.

- J.C. Ozogbuda and M.T. Iqbal, “Dynamic Simulation of an Off Grid Photovoltaic System with backup battery and generator for a Remote house in Nigeria”. *30th IEEE NECEC conference* Nov. 18, 2021.

- J. C. Ozogbuda and M. T. Iqbal “Design of a DC Microgrid System for a Remote Community in Nigeria” Vol 5, No 6, 2021.

- J. C. Ozogbuda and M. T. Iqbal, “Sizing and Analysis of an Off-Grid Photovoltaic System for a House in Remote Nigeria”, *Jordan Journal of Electrical Engineering* Vol.8 No.1, Pages 17-26, 2022.