Design and Control of a Hybrid Power System for a Remote Telecommunication Facility in Nigeria

by

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Abstract

The proliferation of mobile base transceiver station sites in Nigeria comes with a growing need to address those sites' source of power. Sustainability and mitigating harmful environmental impact caused by the diesel-only method of power generation is of great concern. This thesis examines the design, optimal sizing, and control of a Hybrid Power system to replace the current diesel-only option on the site. An outdoor base station site in Agbaja, a rural settlement in Kogi State, Nigeria is used as a case study. HOMER pro is used to size the system based on the measured load and available renewable resources. The PV/Diesel/Battery configuration resulted in the least Net Present Cost (NPC), Cost of Energy (COE), and unmet energy. The system is sized as DC for better performance and elimination of multiple energy conversion experienced in the AC system. A comparison between this proposed system and the current system shows a reduction in operating expenditure (OPEX) by 75% with zero unmet energy. Each component of the system is designed and simulated in a MATLAB/Simulink environment and connected to form the whole system. The transient behaviour of the system is studied under varying solar irradiation to ascertain the stability of the power supplied to the sensitive telecommunication load. The result shows a stable power output to the load at rated voltage of 48 V. Also, a low-cost open source Internet of Things (IoT)-based Supervisory Control and Data Acquisition (SCADA) system using ESP32 and Arduino IoT Cloud for monitoring and control of the system using a widget-based dashboard is also presented. Current, voltage, temperature, and humidity sensors are programmed to measure relevant parameters of interest, and the measured Data is processed and parsed to the Arduino IoT Cloud via a Wi-Fi network communication channel. A mobile application is also deployed to aid remote monitoring and control as well. LEDs are used to implement a high temperature and low voltage control logic. The prototype used to demonstrate this only cost $88.34 USD.

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Chapter 1

Introduction and Literature Review

1.1 Introduction

Energy is an indispensable commodity in the world today and no society can thrive without it. It is intrinsically connected to human existence and the standard of development of any society is directly corelated to the quantity available to that society. The trend in energy consumption has continued to be on the rise and there is no sign of going down. Part of the reason for this trend is the need for technological advancement that is currently on the rise and, the increase in population is the other reason.

Nigeria has experienced unstable grid generated electricity for a very long time. This problem has been persistent for various reasons ranging from over-reliance on oil and gas generated electricity and seasonal variations in water head experienced in hydro power generating stations [1, 2]. The other notable reason for this unstable grid has to do with grossly inadequate installed generating capacity [3]. The country only generates 14% of the total electrical energy demand and this is grossly inadequate and not acceptable for any country that desires sustainable industrial growth [3]. Another well-documented reason for the poor grid power availability in the country is the deplorable transmission and distribution power facilities [4]. They are reported cases of power stations generating below its capacity because the transmission lines cannot evacuate the power to the substation where they can be distributed. Distribution lines are very old and poorly planned. This has led to transformers blowing up because they are overloaded and distribution lines are heated up above tolerable limits. All these have contributed to the current electrical quagmire in the country.

The above-mentioned situations have affected the level of production and development in the country. The cost of running a functional business is very high because of having to provide for the power needs of the business independently. In a survey carried out by The World Bank enterprise survey [5], 27.2% of the firms surveyed chose lack of electricity as the biggest obstacle to doing business in the country. The only obstacle that was ranked higher than this was access to finance and, that was 30.2%. In another report from International Monetary Fund (IMF) [6], they concluded that the lack of reliable grid electricity cost the country's economy $29 billion annually. Other than the monetary aspect, there is an environmental risk as well associated with the current generation means. Most government establishments, private small and medium enterprises as well as individual rely solely of diesel generators to provide the needed power to carry out their everyday businesses and activities. These have severe health effects both on human and the environment as millions metric tons of CO_2 are produced each year from these generators alone. CO_2 is a key constituent of greenhouse gas that leads to the much talked about global warming which is something that must be combated to a standstill as much as possible.

To solve this peculiar power shortage problem in Nigeria, government can increase the generation capacity significantly and overhaul the entire transmission and distribution lines. These solutions are not feasible at this point because of the enormous cost involved in carrying out these tasks. Also, the current issues involved with the unsustainable power generation in relation to shortage of oil and gas, variation in water head and above all, damage to the environment as a result of greenhouse gas emission, makes these options unattractive. It also negates the global trend of finding lasting solutions to greenhouse gas emissions by promoting green, reliable and sustainable means of energy generation.

The other solution which is viable and achievable is investing significantly in distributed energy generation system. This takes the pressure off the already dilapidated national grid and ensure that power supply is reliable and available when needed. One of the major advantages of distributed energy system is the fact that it can be designed for a specific application and can be scaled up appropriately when needed to meet any growing energy need that may arise in the nearest future. The other advantage is the shorter time it takes to build a distributed energy generation station compared to the traditional power station that takes so many years to build.

Globally, there have been significant attempts at diversifying the energy generation mix by integrating renewable energy to the generation mix. This has continued to evolve over the years with different levels of innovations. This option has been viable in regions where grid availability is not constant, where there are abundance renewable resources and, where technologies that aids utilisation of these energy are in place [7].

1.2 Nigerian Current Telecommunications Sector

As the telecommunication industry continues to experience tremendous level of growth and penetration, especially in a developing country like Nigeria, there is a growing demand for the energy that powers these mobile base stations to be reliable, efficient and above all, be generated in an environmentally friendly manner [8]. Base stations have the highest power requirement in a telecommunication chain. According to [9], 60% of the power needed in a mobile network chain is consumed in the base station and, providing this power could be very expensive. For rural areas with bad-grid and off-grid telecommunication base station sites, the current operational status in

Nigeria is using diesel generators to power these sites. The era of using these diesel generators as the primary, and sometimes the only source of power generation for these sites are long gone due to the well-documented challenges associated with this approach. Some of which include, reliability of the generator sets (gen-sets), high cost of operation and maintenance of these gen-sets, and the negative environmental impact associated with the green house gases (GHG) produced from its operations [10, 11]. As the number of base stations continue to increase, there is a corresponding increase in the operational expenditure (OPEX) of these mobile service providers and in order to break even, the cost is being transferred to the subscribers through increased tariff. Figure 1 shows the number of subscribers and teledensity of the country between 2002 and 2019.

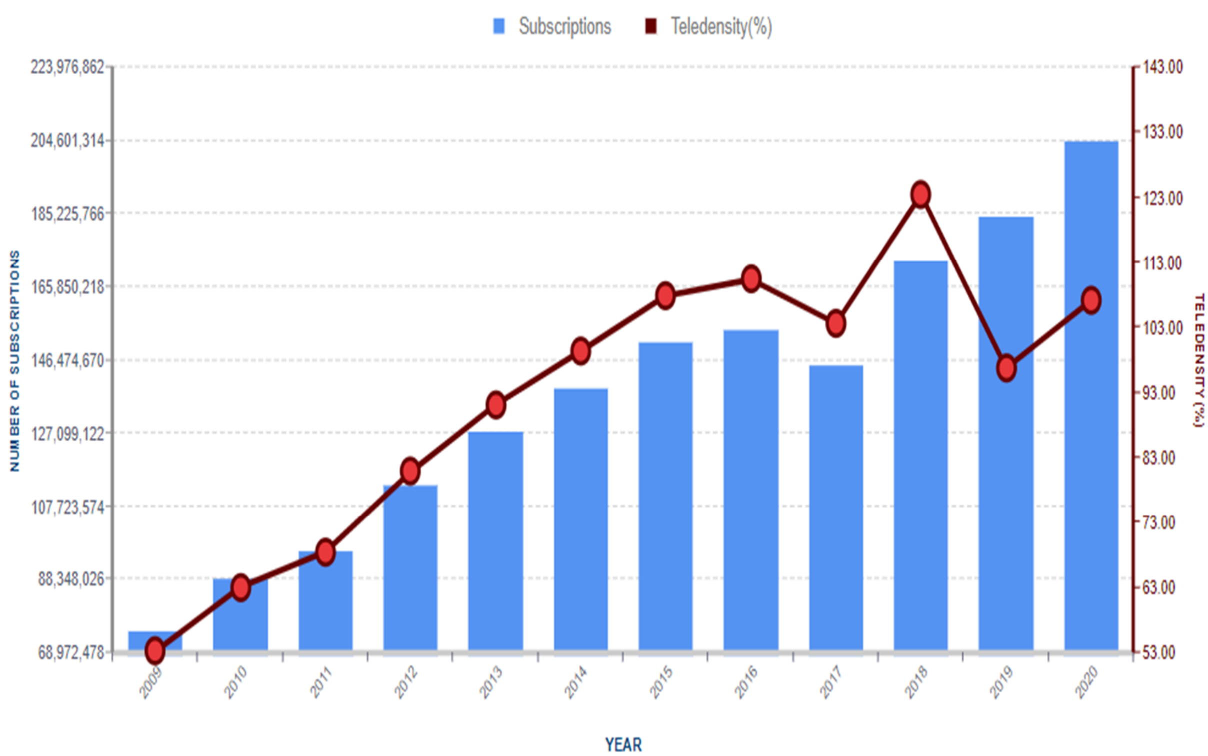

Figure 1. 1: Number of subscribers and teledensity of Nigeria between 2002 – 2020

The proliferation of mobile subscribers and user equipment in the telecommunication market has cause an unprecedented increase in the base transceiver station needed to support this growth, and this number is expected to continue growing. In a report released by the Nigerian Communications Commission, an agency of government saddled with the responsibility of regulating the telecommunication sector in the country, there were 52,160 base transceiver stations (BTS) and colocation towers in the country by the end of 2018 most of which still depended on diesel generators for their power.

For any base station, the reliability of the power supply is the first requirement that must be considered to maintain continuous service availability and good quality of service (QoS). Since the introduction of the green telecommunication network, there has been a significant level of research into sustainably powering these mobile base stations to eliminate the use of diesel generators and the associated disadvantaged with it [12]. In the light of the foregoing, green network renewable energy solutions only would be considered.

Renewable energy sources (solar and wind predominantly,) have been in use in the telecommunication sector since the 1970s. These were used to power microwave repeaters in remote areas to connect those areas with radio, television and telephone services [13]. The major reason for using these sources is the fact that they are readily available in different parts of the world [12]. The fact that these systems can easily be designed, installed, disassembled and scaled when there is a change in power requirements makes the solution economically feasible and practical for this application [11].

Some of the major drawbacks of renewable energy sources are the fact that they are highly unpredictable, intermittent, and constantly dynamic in nature. Therefore, to ensure reliability and continued operation of a base station, a single renewable energy source cannot be used in isolation, but integrated with other renewable or non-renewable sources (grid or diesel generator as a backup power source) and/or an energy storage (mostly batteries in the case of base stations) [13, 14]. This is the basis of a Hybrid Renewable Energy System (HRES).

Hybrid Renewable Energy System (HRES) is preferred in powering off-grid sites because of the nature of the load on the site. This load needs to be supplied continuously and the constantly changing atmospheric conditions would pose a challenge to a single source of alternative energy. Integrating different renewable energy sources, a conventional means of power generation for backup and a battery storage to store excess energy that can be used to power the load when the alternative energy sources are not generation at all or not generating enough to power the load on the site.

1.3 Literature Review of Related Work

There has been a significant level of research into the concept of powering base station sites with renewable energy sources both in standalone applications and hybrid systems. These researches have been championed by both the academics and industry expert who daily strive to reduce the carbon footprint of telecommunication networks.

In [15], a comparative analysis of a Solar-Powered base station for different generations of mobile communication technologies was examined. The analysis was based on the system's architecture, the amount of energy produced and the cost optimization of the system. A feasibility study was also carried out to compare the proposed system to the conventional sources of power generation with regards to cost. HOMER was used for the simulation and the battery autonomy was more than 2 days in each case. The OPEX saving was between 32% for 3G Node B 4/4/4 and 66% for

2G BS 2/2/2. In all the generations of mobile technologies examined, the energy requirements were met with the proposed solar powered system in a sustainable and cost-effective manner with varying percentage of excess energy. The author concluded that renewable energy solutions was a viable means of power generation for a mobile telecommunication site with low load requirements.

In another study carried out in [16], an off-grid hybrid power system for a specific remote mobile base station located in Oromia, Ethiopia is considered. HOMER is employed for the modelling, simulation and techno-economic study. The study showed the optimal system configuration to be PV/Battery system with a net present cost (NPC) of $57,508 and cost of electricity (COE) of $0.355/kWh. A feasibility study between the optimized system as well as PV/Wind/Battery hybrid system is carried out in comparison to the conventional diesel generator (DG). The result indicates that using the conventional diesel generator to power the site will cost the mobile operator three times more than what it would cost to deploy the optimized system on the site. Also, 15,341 kg of CO_2 per year and 37.9 kg of CO emissions per year will be prevented from the atmosphere if this system is implemented. A sensitivity analysis is also carried out to examine the effect of change in solar insolation, wind speed, the price of diesel and the energy demand of the site. Deploying this system to the site will reduce the OPEX of the site significantly.

In study [17], the energy requirement for the site was 241.10 kWh/day and a peak load demand of 20.31 kW with an average daily solar radiation of 5.4645 Wh/m^2/day and a clearness index of 0.605. HOMER was employed for the simulation and sizing of the system while the dynamic behaviour of the system was studied using MATLAB/Simulink. The effect of cost and environmental benefits amongst three different power generation configurations were studied. PV/Battery hybrid configuration showed a NPC of $255,812, LCOE of $0.23/kWh and operating cost of $9111.

The other option simulated was PV/Battery/Diesel generator (DG) configuration which showed a NPC of $248,260, LCOE of 0.22/kWh and operating cost of $10,273. The NPC and LCOE is lower in this case than the PV/Battery configuration but has downside is the release of 3061.235 kg of GHG into the atmosphere per year. When compared to the conventional diesel generator set, which has a NPC of $633,633, LCOE of $0.559/kWh and operating cost of $47,624 and releases 90,295.90 kg of GHG into the atmosphere annually.

From the result, the Solar/Battery configuration is more economical and environmentally friendly compared to the conventional DG configuration. The downside about this configuration is an unmet energy of 25.2kWh/year and because of the critical nature of BS load, the PV/Battery/DG hybrid configuration would meet this shortcoming to increase the quality of service (QoS). This study only carried out simulation in HOMER without any experimental verification. Also, the PV size of 75.6 kW will require about 378 m^2 of land area for installation in places where there is competition for land, the system will not be feasible.

In another study carried out in [18], industry professionals came together to propose a turnkey hybrid solution to a site that had hitherto been operated using two diesel generators that run alternately. A single diesel generator and a cyclic battery system was proposed. Both a laboratory experiment and a field test showed a reduction of 66% in the OPEX of the proposed hybrid system and a carbon footprint reduction of more than 60%. According to the field test result, the hybrid configuration has a potential to yielding a return on investment within 2 years. An introduction of renewable energy resource would increase the cycling time of the battery and further reduce the OPEX.

In another related study, the design and operational experience of powering BTS in Girisari village in Bali island of Indonesia was examined in [19]. The 96 kWh/day of energy for powering this

BTS was obtained by combining Solar PV, wind and the utility grid as back-up. A battery bank of 1200 Ah with autonomy of 24 hours is used to store the energy for emergency purposes. Solar PV showed more promise when compared to the wind as the sunshine hours in this location ranges from 7-8 hours per day during dry season and 5-6 hours during rainy season. The system performed as expected with the bulk of the energy coming from solar PV. The drawback of this system was in optimization of the design to maximise the use of renewable energy resources.

In yet another related study conducted in [20], a mathematical model to determine the operational cost and total expenditure of base station is first proposed by the authors. A generic MATLAB tool is then used to design and optimize a fully hybrid system to minimize the cost taking cognisance of the CO_2 emission from the diesel generator. The compound model was finally optimized for both minimum OPEX and CO_2 emission annually while ensuring optimal power supply to the base station. This was achieved by calculating the cycling time for the RE resources, diesel generator and the utility grid from the algorithm. In addition, the design parameters for the RE sources are determined from directly from this algorithm. The authors simulated real-life cases with 1000 base station sites in Lebanon and Mali with power requirement that ranges from 1 kW to 5 kW based on the site configuration and concluded that a fully-hybrid power system was beneficial both in terms of CO_2 emission and OPEX saving.

In [10], the authors studied the chances of decreasing both operational expenditure (OPEX) and greenhouse gas emissions in a rural base station site in Malaysia while ensuring that reliability is maintained. Solar PV was used in addition to diesel generator to form the hybrid system and the analysis was done based on energy yield, the cost and benefit of this system as well as on the greenhouse gas emission of the system. The result showed a 43% to 47% reduction in OPEX annually. The study also analysed the possibility of deploying this system configuration in

Germany, a country that experiences summer, winter, fall and spring months and compares the result to that of Malaysia, a tropical climate country. Due to the solar radiation received in Malaysia all year round, this hybrid system has a better long-term cost benefit in Malaysia over Germany.

In [21], the authors studied the potential of optimized hybrid system in powering an off-grid macro base transceiver station in Ikwerre, a location in Rivers state of Nigeria. HOMER was used for modeling the system, and the optimized system was composed of PV/hydro/diesel generator system with battery for energy storage. From the optimized result, the mobile operator would save $15,961,777 and 70,553 tonnes of CO_2 over the 20 years lifecycle of the system when compared to the diesel only system.

In yet another study carried out in [11], the possibility of using hybrid PV/wind to power a base transceiver station in three rural locations in Democratic Republic of Congo was examined. The three locations had a similar solar radiation and wind data which prompted the authors to concentrate the analysis in Kabinda, the worst case amongst the three locations. This hybrid system was compared with the stand-alone diesel generator system, pure wind energy system and a pure PV energy system to evaluate the technical performance, the economics and environmental impact. The indices used for these comparisons were, the initial cost of the system, total net present cost for the 20 years project lifecycle, the cost of energy and the capacity shortage off the various systems. The authors concluded that the hybrid PV/Wind was the most viable option when measured based on the indices used for comparison. The sizing and optimization were done using HOMER.

In [22], a case study for the optimal sizing of a hybrid energy system to power a remote telecommunication tower was carried out. This case study was carried out in a site located in Doka-Shaaria nature reserve in Kaduna State, Nigeria. With an average solar insolation of 5.75

kWh/m^2/day and a wind speed of 3.2 m/s, a solar PV/wind/diesel generator hybrid system was proposed with a battery system for storage. From the analysis done using HOMER, PV/diesel generator with battery storage proved to be the optimal configuration for the system with COE $0.420/kWh and 78% renewable fraction. Sensitivity analysis was carried out to determine the effect of change in solar radiation, fuel price and wind speed. The result showed that for a wind speed that is less than 3.7m/s, wind turbine is not a feasible energy generation option.

In a comprehensive study carried out by the authors in [8], the cost of energy for a hybrid system configuration was considered for different diesel generator schedule for a base transceiver station in 12 locations across Nigeria. A load of 4 kW to 8 kW was considered for different BTS configuration. The three generator schedule studied were an optimised case, forced-on and generator-only. The result obtained showed an optimal levelized cost of energy (LCOE) that range from $0.156/kWh to $0.172/kWh depending on the BTS load. Solar PV contributed as much as 47% of energy in a 4 kW optimised system in Sokoto. The savings in OPEX ranged from 41.68% to 47% and carbon emission saving of 4222 kg to 31,428.36 kg per year depending on the generator schedule and site load. The authors concluded that a hybrid energy system will yield a better result than a conventional diesel generator.

The authors in [9] enumerated some of the current scenarios and the issues encountered in a solar-powered cellular base station and proposed solutions as well. The also studied the current development in the field, citing the gains made in Asia and Africa. A case study of a rural location in Ghana was used to elaborate the need for developing solar to power a base station site. Some of the challenges identified by the study included economic challenges like high capital expenditure (CAPEX), geographical limitation like poor solar insolation in some locations. The study also proposed some network management and resource allocation like load management, base station on/off strategies, energy and spectrum sharing amongst base stations as solutions to some of the issues encountered in a solar-powered base station.

1.4 Literature review on Control of Hybrid Power System

One of the major challenges of RES is the unpredictable nature of the sources of generation. This often affects the quality and stability of power generated to meet the load demand. In an attempt to mitigate this challenges, sources of power with a stable energy output is most often integrated into the system to guarantee a stable power supply. An example of these sources include battery, storage capacitor, fuel cell and diesel generators to achieve a hybrid system.

Power quality is another challenge encountered with RES. There is a consistent variation in the voltage and frequency of generated power and a robust system must be able to integrate a control system that will be able to deal with this power quality issues, especially in a standalone application. There has been significant research into the control of this system by researchers and some of the works are reviewed below.

In [23], the control of power flow in a PV/Wind/Battery hybrid system was studied and a fuzzy logic controller implemented to mitigate the effect of fluctuation in voltage and frequency of generated power occasioned by the variation in the renewable sources of generation. The controller also maintains the battery state of charge within tolerable limits. The system is implemented in MATLAB/Simulink and simulations are carried out by varying the power generation and the load demand while setting the initial state of charge of the battery. The controller eliminates the effects of the changes in the supplied power while keeping the battery’s SOC within acceptable limits.

In a similar research carried out in [24], a small Wind/solar/Battery hybrid power system with energy management system (EMS) is studied. The individual converter controllers are integrated into the overall EMS saddled with maintaining the overall power balance in the system. The EMS operates in four modes depending on the power generation of the sources and the SOC of the battery. Rapid control prototyping was implemented in DSPACE 1104 controller board and verified experimentally under two conditions: constant load with varying RES and varying load with constant RES. The result shows the system was able to accommodate the different variations in the system.

A droop-based control strategy is employed in [25] to keep the voltage, frequency and load sharing between the RES and the battery storage stable while MPPT control is employed to control the active and reactive power in PV and wind sources of generation to extract maximum power from these sources. Simulations carried out shows that the system can operate within allowable voltage and frequency fluctuations level while supplying the load at different operating conditions. The only drawback to this work was lack of experiment to verify the result.

Admittance-based control algorithm is proposed in [26] too balance the load, and compensate for reactive power in a standalone photovoltaic hybrid three-phase system. A four-leg voltage sourced converter (VSC) is employed to achieve current compensation in the neutral line. An experiment is conducted to test the system under transient and steady-state conditions with linear nonlinear loads. The control system showed satisfactory response under the various test conditions.

In another research carried out in [27], the control of a bidirectional converter is studied to achieve DC bus regulation. A sliding mode controller is proposed to control the system to achieve the desired minimal voltage disturbance in the DC bus and good voltage regulation for optimal safe operation. A bus current is incorporated into the sliding surface to increase the controller response and minimize the settling time. Simulation and experimental result shows the proposed system has a better response and shows satisfactory regulation for various operating conditions.

In another research reported in [28], the control of a hybrid diesel generator/wind system with backup battery storage for water treatment plant in studied. A modified synchronous reference frame (SRF) control is applied to the diesel generator to operate it optimally. This is achieved by controlling the voltage source inverter. The controllers' showed rapid response time and both the simulation and experiment results showed satisfactory conditions under different modes of operation. The battery state of charge, the power generated by the wind turbine and the load determines the operating mode of the system.

A comprehensive review of the various control techniques in AC, DC, and hybrid AC-DC microgrid is carried out in [29]. The authors studied the hierarchical control architecture of microgrids with emphasis on the primary and secondary layer of control and concluded that the distinguishing factor amongst the various microgrids considered are the droop characteristics in the primary control and how the secondary and tertiary controls are applied to the various modes of operation of the system. According to the authors, the decentralized control technique is not reliable due to lack of interaction amongst the local controllers and the system's state cannot be ascertained in real time like the case of a centralized approach that depends on the central controller for all the communication task within the microgrid components. Distributed control approach will solve the reliability issues of both the centralized and decentralized approach with the drawback being the cost and complexity of implementation.

Communication is an integral part of any control process. For optimal system response and appropriate control action, the communication link between the various system components must be intact. In [30], a laboratory scale system to represent a microgrid is set up to achieve energy management and control. The various subsystem components are effectively controlled to achieve a stable operation under different generation and load conditions. The validation of this controller is carried out experimentally using Opal-RT OP5600 hardware, which act as the simulator for the rapid control prototyping of the microgrid system and OP8660 provides the data acquisition function which is needed for any control action. MATLAB/Simulink, integrated into the RT-LAB is used for real-time monitoring, test and control.

In [31], a low-cost SCADA system for a photovoltaic power system is studied. The current and voltage of both the PV and battery were monitored. The cost of the system was reported to be $62 and the experiment showed that SCADA can log data and can be monitored in real time. A low-cost SCADA system to monitor and control a single phase inverter was done in [32]. Several hardware and hardware were compared by the authors for both client and server. A system based on ESP12E was chosen as the best option for the client thingspeak based local server was selected for the server side. Some of the criteria for their selection included security, difficulty/ease of installation, usage and integrating new product to the system.

1.5 Objectives of the Thesis

From the review of the relevant literature, there has not been a study that has designed a hybrid power system for a telecommunication site in Nigeria taking note of the peculiarity of each site. Adequate sizing information based on the measured load profile on the site is also missing. Detailed design of each system component is also an identified gap. No previous work has also incorporated a low-cost data logging system to measure the generated renewable power and environmental data. A supervisory controller to regulate the energy balance in the system and maintain a nominal DC voltage for a BTS in the region is also missing. This thesis will attempt to bridge these gaps by designing a stand-alone hybrid power system based on the existing load profile of a particular BTS site in rural location in Nigeria and, incorporate a data logging system to measure relevant parameters and control the overall system to maintain a stable load voltage.

The objectives of this thesis are summarised below:

- To design an optimal-sized standalone hybrid power system using the existing load information, to replace the current diesel generator system being used in a rural telecommunication site in Nigeria.
- To carry out a complete analysis of the feasibility of the hybrid system over the project's lifespan of 15 years with regards to energy yield and economics.
- To analyse the savings in operational expenditure (OPEX) and the amount of green house gas emissions curbed by using this hybrid system over the conventional diesel generator that is being used currently.
- To build and simulate a dynamic model in MATLAB/Simulink based on the components from HOMER pro sizing result to study the transient behaviour of the system under varying environmental and load conditions.
- Design a low-cost data logger to measure relevant parameters in the hybrid power system and perform supervisory control of the whole system.

1.6 Thesis Organisation

A manuscript format of thesis presentation is adopted in preparing and presenting this thesis. A summary of each chapter and the thesis is presented as follows:

Chapter 2 presents the design and analysis of a stand-alone DC hybrid system that can serve the power needs of a rural base transceiver station in Nigeria. This was carried out to emphasis the need/effect of proper sizing on any renewable power system and how the variations of renewable energy sources can be mitigated. This work in this chapter helps to meet the first three objectives of the thesis. This work was published in 2020 IEEE Electric Power and Energy Conference (EPEC), Edmonton, AB, Canada. The paper has also been published in the IEEE Xplore Database as part of the IEEE EPEC 2020 conference proceedings (10.1109/EPEC48502.2020.9320006).

Chapter 3 presents the load analysis and design of a stand-alone power system for a secondary school in Nigeria. This research was carried out to further demonstrate the need to size properly. In this case, the load data was obtained using BEOpt. The dynamic response of the sized system was studied in MATLAB/Simulink to understand the transient behaviour of the system. This work was presented in the proceedings of the 28th Annual Newfoundland Electrical and Computer Engineering Conference (NECEC 2019), St. John's, NL, Canada. Objectives 1-4 was also demonstrated in this work though not directly related to the topic of the thesis.

Chapter 4 presents the dynamic modeling and simulation of the designed stand-alone DC hybrid microgrid for the base transceiver station sized in chapter 2. The dynamic and transient behaviour of the system is studied here to determine the stability of the DC bus voltage which is very important for a base transceiver site. The work in this chapter fulfils the fourth objective of this thesis and was published in European Journal of Electrical Engineering and Computer Science. Volume 5 No 2 (2021). DOI:https://doi.org/10.24018/ejece.2021.5.2.316.

Chapter 5 presents a low-cost open source IoT-based SCADA system based on ESP32 microcontroller and the Arduino Cloud IoT platform to monitor and control the hybrid power system. A prototype of the system was designed on a breadboard and the relevant sensors were used measure both electrical and environmental parameters of the system. The work fulfils the last objective of this thesis outlined in section 1.5. This work has been accepted for presentation at the

2021 IEEE 12th Annual Ubiquitous Computing, Electronics and Mobile Communication Conference (IEEE UEMCON), New York, USA.

Chapter 6 presents the conclusion and recommendations for future work to advance the presented study.

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Chapter 2

Design and Analysis of a Stand-alone DC Hybrid Microgrid for a Rural Base Transceiver Station in Nigeria*

Preface

A version of this article was peer-reviewed, accepted, and presented in the conference proceedings of the **2020 IEEE Electric Power and Energy Conference (EPEC), Edmonton, AB, Canada.** The paper has also been published in the IEEE Xplore Database as part of the **IEEE EPEC 2020 conference proceedings (10.1109/EPEC48502.2020.9320006).** I am the primary author on this research article and my thesis supervisor, Dr. M. Tariq Iqbal, is the co-author. As the primary author, I did most of the research work, including literature reviews, designs, hardware implementations, experimental settings, and data analysis in the article. I also wrote the initial manuscript and amended them based on feedback from my co-author and peer reviewers throughout the peer-review process. Dr. M. Tariq Iqbal, co-authored, oversaw the entire research project, read, and edited this paper and offered research ideas throughout the research and in the actualization of this article.

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Abstract

The proliferation of mobile base transceiver station sites in Nigeria comes with a growing need to address those sites' source of power. Sustainability and mitigating harmful environmental impact caused by the diesel-only method of power generation is of great concern. This article examines the optimal sizing of a small DC microgrid to power an outdoor base station site in Agbaja, a rural settlement in Kogi State, Nigeria. A DC system has better performance because multiple energy conversion experienced in the AC system is eliminated. HOMER pro is used to size the system based on the measured load and available renewable resources. The PV/Diesel/Battery configuration resulted in the least Net Present Cost (NPC), Cost of Energy (COE), and unmet energy. A comparison between this proposed system and the current system shows a reduction in operating expenditure (OPEX) by 75% with zero unmet energy.

Keywords – DC microgrid; HOMER; optimized system; Base Transceiver Stations; Renewable Energy

2.1 Introduction

The telecommunication sector in Nigeria has continued to experience a tremendous level of growth and more penetration in rural locations in the country. There is a growing demand for reliable energy that power the mobile base stations in an environmentally friendly way. In a 2018 report released by the Nigerian Communications Commission, an agency of government saddled with the responsibility of regulating the telecommunication sector in the country, there were 52,160 base transceiver stations (BTS) and colocation towers in the country most of which still depended on diesel generators for their power. This increases the operating expenditure (OPEX) and causes harm to the environment.

Nigeria's unstable grid generated electricity problem has been persistent for various reasons ranging from over-reliance on oil and gas-generated electricity and seasonal variations in water head experienced in hydro-powered generating stations [1, 2]. The other notable reason for this unstable grid has to do with grossly inadequate installed generation capacity [3]. The country only generates 14% of the total electrical energy demand [3]. Also, the transmission and distribution power facilities are in a deplorable state [4]. For these reasons, most individuals and businesses rely on diesel generators for power supply because the grid power supply is not guaranteed even in urban areas.

The solution which is viable and achievable is investing significantly in renewable distributed energy systems. This takes the pressure off the already dilapidated national grid and ensures that it is reliable and available. The advantage of such system is that it can be designed for a specific application and can be scaled up appropriately when needed to meet any growing energy needs that may arise in the future. The other advantage is the shorter time it takes to build a distributed energy generation station compared to the traditional power station that takes so many years to build.

Mobile operators in the country have been on a modernization drive for the past two years to replace all the less energy efficient BTS units and sectorial antennae with modern energy-efficient ones. Most of the new BTS units are outdoor, single cabinet units with a significant reduction in energy consumption. With these current realities, it is imperative to reconsider how these BTS units are powered, especially using renewable sources.

There has been significant research into the concept of powering base station sites with renewable energy sources in stand-alone applications and hybrid mode. In [5], a comparative analysis of a Solar-Powered base station for different generations of mobile communication technologies were examined. The result showed an OPEX saving between 32% for 3G Node B 4/4/4 and 66% for 2G BS 2/2/2. An off-grid hybrid power system for a specific remote mobile base station located in Oromia, Ethiopia, is considered in [6]. The study showed the optimal system configuration to be PV/Battery system with a net present cost (NPC) of $57,508 and the cost of electricity (COE) of $0.355/kWh. The study in [7] examined the potential of an optimized hybrid system in powering an off-grid macro base transceiver station in Ikwerre, a location in Rivers state of Nigeria. PV/hydro/diesel generator system with a battery for energy storage was the optimized system. In [8], a case study for the optimal sizing of a hybrid energy system to power a remote telecommunication tower was carried out for a site located in Doka-Shaaria nature reserve in Kaduna State, Nigeria. PV/diesel generator with battery storage proved to be the optimal configuration for the system with COE $0.420/kWh and 78% renewable fraction. The cost of energy for a hybrid system configuration was considered for different diesel generator schedules for a base transceiver station in 12 locations across Nigeria in [9]. The result obtained showed an optimal Levelized Cost of Energy (LCOE) that ranges from $0.156/kWh to $0.172/kWh depending on the BTS load. In all the previous work considered, as well an in [10-12], integrating renewable source(s) of energy to power a BTS site significantly reduces OPEX compared to powering it with diesel generator sets.

In all the literature considered, the load is sized as an AC load, whereas the telecommunication equipment uses DC electricity. This study's objective is to size a small, stand-alone DC hybrid microgrid based on the existing load of a known BTS site to replace the existing diesel generator system on the site and examine the cost-saving of deploying this proposed system on the site.

2.2 Site Description

The base station site in focus is in Agbaja, a small community located on a plateau in the North Central state of Kogi in Nigeria. The people are predominantly farmers with no grid power supply. They depend on diesel generators to supply their electrical appliances and wood for cooking. The site currently has a 13 kVA AC diesel generator and a string of 12 V, 150Ah battery. The load is predominantly DC. The generator is shutdown only during routine monthly maintenance. Fuel supply to this site is difficult because of the bad nature of the road and, being on a plateau adds more degree of difficulty. Agbaja is located on latitude 7° 59' N and longitude 6° 39' E and, like most of Nigeria, has much potential for renewable energy utilization for power generation. Figure 2.1 shows the physical and satellite image of the site.

Figure 2. 1: Physical and satellite image of the site.

2.3 Renewable Energy Potential in the Site.

Nigeria's proximity to the equator makes for high solar radiation. The country's weather condition is best described as hot and humid, with only two seasons, wet and dry. The direct normal irradiance (DNI) ranges from 3.0 kWh/m^2/day in the South to 7.5 kWh/m^2/day in the North with average sunshine of 6.5 hours [2]. Table 1 below shows the monthly average solar global irradiance for the site. This data is obtained from HOMER pro, which is linked to the National Aeronautics and Space Administration (NASA) database [13]. The average annual radiation for this site is 5.10 kWh/m^2/day. Figure 2.2 shows the average monthly wind speed in m/s for the site. The average wind speed is 2.91 m/s at anemometer height of 50m.

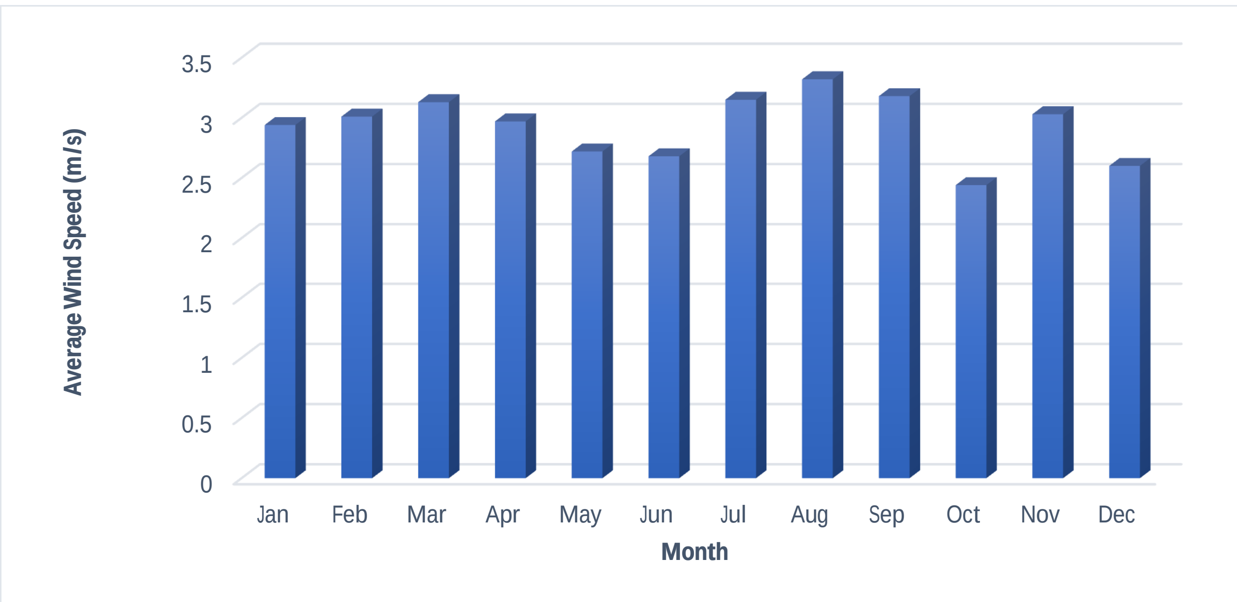

Figure 2. 2: Average monthly wind speed for the data

2.4 Site Electrical Load

For this site, the DC load was measured using the telemetry of the site connected directly on the rectifier. This load was measured every 15 mins for the entire year and there are 35,064 data points for the year. This is to eliminate the failure experienced in an undersized system and reduce the cost incurred for an oversized system. The plot of the load for the entire year is shown in figure 2.3. The instances where the load plot deviates from the trend where periods of failure on the site occasioned by generator set.

Table 2. 1: Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	**Clearness Index**	**Daily Radiation kWh/m^2/day**
Jan	0.631	5.77
Feb	0.598	5.84
Mar	0.553	5.71
Apr	0.517	5.42
May	0.499	5.13
Jun	0.466	4.70
Jul	0.427	4.34
Aug	0.399	4.13
Sep	0.420	4.33
Oct	0.487	4.80
Nov	0.585	5.40
Dec	0.628	5.59

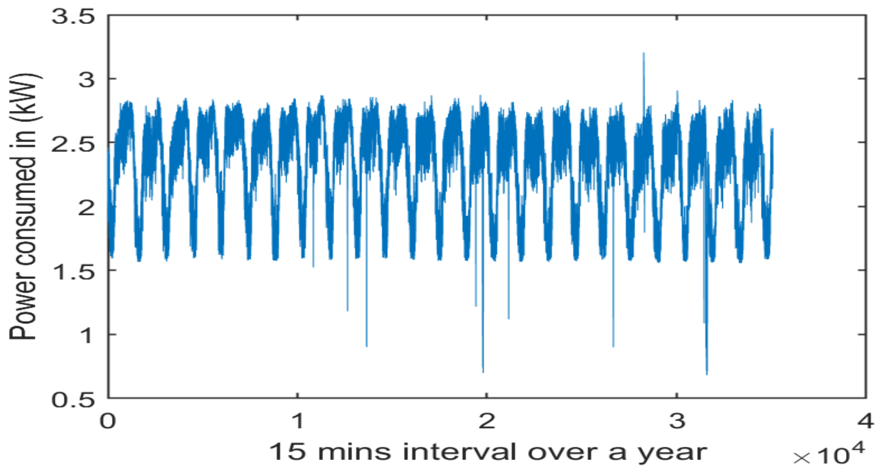

Figure 2.3: Measured load from the rectifier for 1 year.

2.5 Sizing the Proposed Hybrid System Components in HOMER pro

The Hybrid Optimization of Multiple Energy Resources (HOMER) software is used to size and optimize the system. Based on the resources available at the site, a PV/Wind/Diesel/Battery hybrid system is proposed. Since the site is an outdoor type and the load is predominantly DC, the system is designed as a DC microgrid. This configuration reduces the losses encountered in converting AC to DC. The diesel generator is also a DC generator to achieve seamless battery charging without using a rectifier like the AC counterpart. The components of the system and the cost based on the internet search are summarized in table 2.2 below, and the HOMER pro model of the proposed hybrid system is shown in figure 2.4. The cost of the system components is in USD.

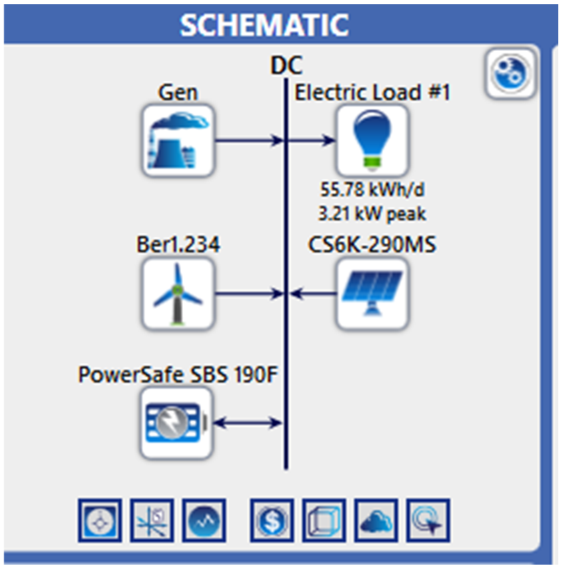

Figure 2. 4: Proposed HOMER schematic model for the Hybrid System.

Table 2. 2: Technical Specification of the proposed System Component

Solar Photovoltaic	
Model Number	CS6K – 290MS
Nominal Maximum Power (P_{Max})	290 Watts
Module Efficiency	17.72%
Derating factor	88%
Lifetime	25 years
Cost per kW	$1,000
Backup Battery	
Model	EnerSys PowerSafe SBS 190F
Rating	12 V, 190 Ah
Nominal capacity	2.57 kWh
Roundtrip Efficiency	97%
Throughput	2,747.70 kWh
Cost per unit	$400
Wind Turbine	
Model	Bergey BWCXL1
Rated Capacity	1 kW
Lifetime	20 years
Cut-in speed	2.5 m/s
Cost	$6,800
Diesel Generator	
Model	Polar Power 8080P – 40205
Rating (Continuous)	3.6 kW
Output DC Voltage	12 – 96 V
Engine's RPM	2900 rpm @ 5.5 kW
Efficiency	>85%
Cost	$4,400

2.6 Simulation Results and Discussion

The simulation is carried out using HOMER pro on an hourly basis for the entire year. The economic and technical data for the components summarized in table 2, the renewable resources at the site, and the measured load are used as input to HOMER. The result of the various system configurations is compared with regards to the Net Present Cost (NPC), the Cost of Energy (COE) and because of the critical nature of the load, the system capacity shortage. This simulation for the hybrid system is done based on the following constraints.

- The lifetime of the overall system is 15 years.
- Nominal discount and inflation rates are taken as 12% and 13%, respectively, consistent with the country's current value.
- Capacity shortage is zero to ensure reliability.
- Abrupt load variation is accounted for by incorporating a 10% reserve.
- The correct dispatch strategy, load following (LF), is adopted to harness the renewable resources available to charge the battery.

The optimal sizing result for each configuration is summarized as follows. DC bus voltage for all case is 48 V.

2.6.1 PV/Diesel/Battery Hybrid System.

This configuration uses 15 kW PV panel size, 3.6 kW diesel DC generator, and a 24 unit of the backup battery to meet the 100% of the load. The COE and the NPC are $0.223/kWh and $44,343, respectively. The operating cost is $1,723 for a year, with a renewable fraction of 89.4%. This system only uses 745 litres of diesel for the entire year. This reduces the amount of environmental pollution significantly.

2.6.2 PV/Wind/Diesel/Battery

The NPC of this system is $51,029, with $0.256/kWh as the COE. The components size is as follows: 14kW PV, 1 unit of the wind turbine, 3.6 kW diesel generator, and 24 units of the battery for backup. This system can also meet 100% of the load with a renewable fraction of 88.3%. The fuel consumption for the year is 828 litres.

2.6.3 PV/Diesel

This hybrid system uses 5 kW PV panel size and 3.6 kW generator size to meet 100% of the load. The NPC of this system is $65,473, with a COE of $0.329/kWh. The operating cost of this hybrid configuration $5,884 per year. This high operation cost is due to the 5,475 litres of diesel needed per year to run the generator. The level of emissions from this system is high because of the low renewable fraction of 22.7%.

2.6.4 Diesel/Battery

The NPC of this configuration is $67,212, and the COE of $0.337/kWh. The operating cost is $6,409 per year. The size of the diesel generator is 3.6 kW and 4 units of the backup battery. This system has a low initial cost but high operating because of the fuel cost. The total consumption is 6,072 litres for the year with very high harmful emissions.

2.6.5 Diesel only

The diesel-only configuration uses a 3.6 kW generator that runs for 24 hours a day throughout the year. The configuration has the least capital cost but the highest operating cost because of the diesel volume needed to run this system. Reliability is also an issue here because if the generator goes off, the entire site will be down, which is a scenario that must be avoided as much as possible. The NPC and COE is $67,829 and $0.340/kWh, respectively. Table 2.3 below summarizes all the critical parameters of the various system configuration.

Table 2. 3: Optimal configuration for different systems

	Size of components				Economic Parameters						
Configurations	**PV (kW)**	**WT (kW)**	**DG (kW)**	**Battery (Units)**	**Initial Cost ($)**	**O&M Cost ($)**	**NPC ($)**	**COE ($)**	**RF (%)**	**Diesel (L/yr.)**	**Gen Hr. (hr./yr.)**
PV/Diesel/Battery	15	-	3.6	24	27,480	1,723	44,343	0.223	89.4	745	1,181
PV/Wind/Diesel /Battery	14	1	3.6	24	33,280	1,813	51,029	0.256	88.3	828	1,324
PV/Diesel	5	-	3.6	-	7,880	5,884	65,473	0.329	22.7	5,475	8,760
Diesel/Battery	-	-	3.6	4	4,480	6,409	67,212	0.337	0	6,072	6,094
Diesel only	-	-	3.6	-	2,880	6,636	67,829	0.340	0	6,568	8,760

Based on the Net Present Cost (NPC), the Cost of Energy (COE), and the renewable fraction (RF), the PV/Diesel/Battery configuration is the best option. This system also has a battery autonomy of 18.6 hours, which is very crucial to powering a critical load of this nature during days of low solar radiation and diesel generator maintenance. Solar PV produces the bulk of the power needed to supply the load, and the diesel generator produces the deficit. The diesel generator only uses 745 litres of diesel in a year. This reduces OPEX significantly. The DC generator is made with a brushless permanent magnet alternator that outputs low voltage at very high frequency which is optimizes into DC current by employing a diode bridge. The output is then used to charge the battery bank which in turn supply the load.

2.7 Environmental Impact of Various Configurations

Base station sites have continued to contribute significantly to the increased carbon footprint of the telecommunication industry. For any significant progress to be made, renewable sources of power generation must be integrated into the generation mix to power them. Table 4 compares the amount of pollutants emitted between the generator alone configuration and the optimal hybrid system comprising PV/diesel/battery. The diesel-alone system emits more than 8 times the carbon dioxide emitted by the PV/diesel/battery system. Other harmful emissions are also reduced significantly in the hybrid configurations.

Table 2. 4: Emissions comparison between the winning and base configuration.

Emissions (kg/yr.)	**PV/diesel/battery**	**Diesel**
Carbon Dioxide (CO_2)	1,950	17,192
Carbon Monoxide (CO)	12.3	108
Unburned Hydrocarbons	0.536	0.657
Sulfur Dioxide (SO_2)	4.78	42.1
Nitrogen Oxides (NO_X)	11.5	102

2.8 Comparison between the Proposed Hybrid System and the Current System in use

A model of the existing system was simulated in HOMER pro to ascertain the advantage of the proposed system over the existing one. A 3.8 kW AC diesel generator with a rectifier size of 3.65 kW is enough to power the load from the result. The NPC, COE and O&M are $177,822, $0.892/kWh and $17,435/year. 6,328 litres of fuel is needed per year, and the 1 string battery is only capable of providing 3hrs autonomy. Compared to the proposed hybrid configuration, this system is 4 times more expensive, and the emissions are over 8 times higher.

2.9 Conclusion

The sizing of a hybrid power system to meet the current realities of a rural BTS site in Nigeria is considered. A 15 kW PV array, 3.6 kW DC diesel generator, and 24 units of 12 V, 190 Ah backup battery gave the optimal configuration. DC generator is chosen because of the higher fuel efficiency, and elimination of conversion losses, which are witnessed in the AC diesel generator. The current 13 kVA generator is oversized and hence, constantly wet stacking with increased maintenance and fuel cost. This proposed system will power the load with 89.4% renewable penetration and save the mobile operator over 75% of the current cost with less environmental impact.

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Chapter 3

Load Analysis and Design of a stand-alone Solar PV Power System for a Secondary School in Nigeria.

Preface

A version of this article was presented at the proceedings of the **28th Annual Newfoundland Electrical and Computer Engineering Conference (NECEC 2019), St. John's, NL, Canada.** I am the primary author on this research article and my thesis supervisor, Dr. M. Tariq Iqbal, is the co-author. As the primary author, I did most of the research work, including literature reviews, designs, hardware implementations, experimental settings, and data analysis in each of the articles. I also wrote the initial manuscript and amended them based on feedback from my co-author and peer reviewers throughout the peer-review process. Dr. M. Tariq Iqbal, co-authored, oversaw the entire research project, read, and edited this paper and offered research ideas throughout the research and in the actualization of this article.

Abstract

This paper presents the load analysis and design of stand-alone solar PV system for Uyo High School, Uyo, Akwa Ibom state in Nigeria. The solar potential of this location is 4.71 kWh/m^2 /day. The load analysis of the school was carried out in BEopt by varying the schedule to accommodate a building like a school. The system was designed for a load of 7.5 kW and the proposed system will satisfactorily meet the power needs of the school. The dynamic simulation was carried out in

MATLAB/Simulink and the system performance was evaluated. A storage battery system was incorporated into the system to provide backup and ensure continued supply to load during bad weather and periods of poor solar insolation. The research indicates that the designed system can meet the power need of the school satisfactorily.

3.1 Introduction

Energy has been one of the primary needs of man from time immemorial. The necessity to cook, keep oneself warm amongst others were some of the needs expressed by the caveman. The need for this same energy in the present day has reached unprecedented heights as this, directly and indirectly, measures the standard of living of any society and her level of industrialization [1]. Despite Nigeria's attempt in unbundling the monopoly of the nation's power company in 2005, which had hitherto been responsible for all the power supply chain management, vis-a-vis, generation, transmission, and distribution, it has not yielded the kind of result that was anticipated as the power situation in the country has not improve significantly [2]. According to Udoakah and David [3], Nigeria can satisfactorily meet all its energy needs if all the renewable energy options were adequately utilized. Wole-Osho et al. in [4] also attest to the potential of Nigeria in sustainably meeting her energy needs as he enumerates the country's vast potentials in Hydro, wind, biomass and solar.

Nigeria is located between latitudes 4°N and 14°N and longitudes 2°E and 15°E with a total area of 923,768 km2 [5]. Nigeria's proximity to the equator gives it a high potential for a full solar energy-driven economy all year round. The direct normal irradiance (DNI) ranges from 3.0 kWh/m2/day (1095 kWh/m2/yr.) in the south to 7.5 kWh/m2/day (2737.5 kWh/m2/yr.) in the north with average sunshine of 6.5 hours [6]. With this solar potential, one would expect the country to have made a significant investment in solar power generation to meet some of the energy challenges being faced in the country, but that is not the case. Presently, PV installation in Nigeria is still at its preliminary stages, with applications limited to street lighting, water pumping and small-scale household usage, its potential for large-scale electricity production in various locations especially northern Nigeria has been estimated with good annual yield [6]

The problem with Nigeria's power sector is not just in the generation; the transmission and distribution sectors are also in a terrible state [2]. There have been reported cases of power station generating below their capacity because the radial transmission system cannot accommodate the generated power [7]. The distribution lines are also old and in need of total overhauling. Since the cost implication of fixing these transmission and distribution networks is very high, the distribution companies have resorted to load shedding, and this has left the average customer in Nigeria having access to utility power for 4 to 5 hours in a day [7]. The other major challenge facing the consumers other than the unreliability of the grid is the problem of estimated billing by the distribution companies [8]. This has left the customers paying far more than the electricity they are consuming within the month. With the persistent power unavailability and estimated billing scheme, most power users have resorted to using diesel generators to power their homes and business premises. Besides the growing increase in the price of diesel, generating power this way is unsustainable and dangerous to the environment. Most schools, both secondary and tertiary institutions, are also being affected by this unreliable power supply, and this has had an adverse effect on both teaching and learning in these schools.

With regards to literature, Okoye et al [7] carried out an assessment of the solar resource availability and designed a stand-alone PV system for three commercial cities in Nigeria; Kano, Onitsha, and Lagos. They concluded that the cost of electricity for the PV system is lower than that of the diesel generator that is widely being used for power supply. In another relevant work, Udoakah et al. in [9] designed a 1KVA solar power system with automatic change-over for the Electrical Engineering laboratory at the University of Uyo to help students carry out their laboratory work even when the university's supply is gone. This system was able to solve the problems experienced by students during their laboratory sessions. Elsewhere, Okoye and Solyali [1] considered the optimal sizing of a stand-alone solar power system and applied this model to residential buildings in Nigeria. They used an integer programming optimization method to determine the optimal number of each component needed for the system stressing that accurate sizing is critical to achieving excellent economic viability of any stand-alone solar PV system. On applying this model in residential homes in Bursari, a local government in Yobe state, in the North-Eastern part of Nigeria, they concluded that each household would save $361 in one year when compared to the diesel generator that is being used in the area. Dumkhana and Idoniboyeobu in [10] carried out a solar PV and battery analysis was on the faculty of Engineering building in Rivers state University of Science and Technology Port Harcourt in the southern part of Nigeria, located on latitude 4.5°N and longitude 7.0°E. A 250KV solar PV system was analyzed using a PVSyst V5.5 software. The study considered the electrical load requirements for 8 hours a day, bearing in mind that, being an academic building, the significant demand for electricity will be within these 8 hours (8 am to 4 pm). He concluded that the PV system would reduce noise pollution as well as mitigate the harmful emissions that have resulted from the use of multiple diesel generators within the academic environment.

From the reviewed literature, there has not been any work that has explicitly considered any secondary school in the country for a complete off-grid PV system to power the loads. From the nature of most government-owned secondary schools, it will not make any economic sense for the schools to be connected to the grid as these schools, non-boarding ones, are only open for 6 hours (8 am to 2 pm) Mondays through Fridays. During these 6 hours that students are there for learning, the grid supply may not be available. This paper seeks to carry out a comprehensive load analysis and design a solar PV system that will take care of the entire electrical load in Uyo High School, Uyo, the capital city of Akwa Ibom State in the southern region of the country. The school is located on latitude 5° 1.3'N and longitude 7° 56.1'E.

3.2 Thermal Modelling of the School

Because of the unstable grid supply, getting the daily load profile of the school was difficult. Also, since the school is not in session all year round, the annual energy consumption cannot be explicitly determined. To solve these problems, the thermal modeling of the entire school was done in BEopt, taking into account the variations in the load during the entire day and the periods the school is not in session. Figure 3.1 shows the modeling of the school structure, and figure 3.2 shows the annual energy as estimated in BEopt as 23801 kWh/yr for the six units of the school building.

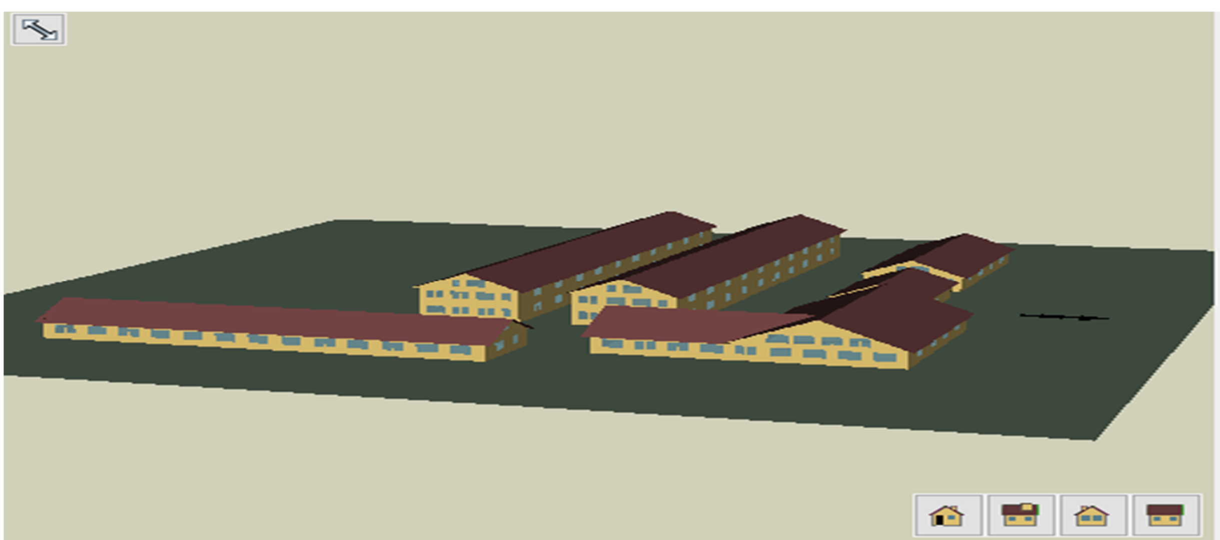


Figure 3. 1: Layout of the School building designed in BEopt.

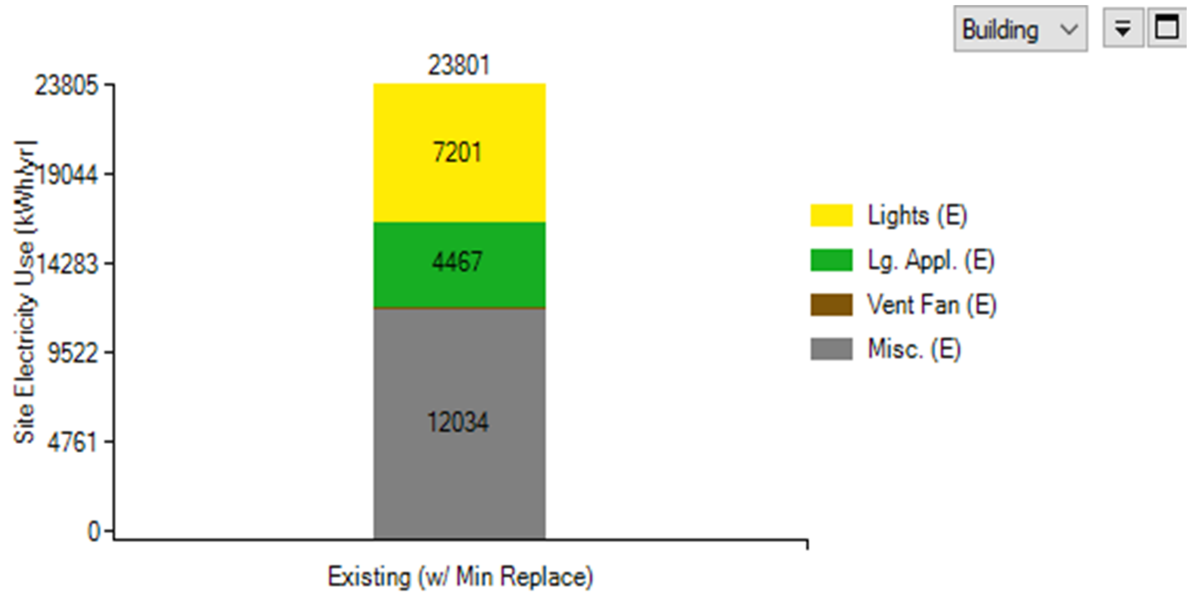


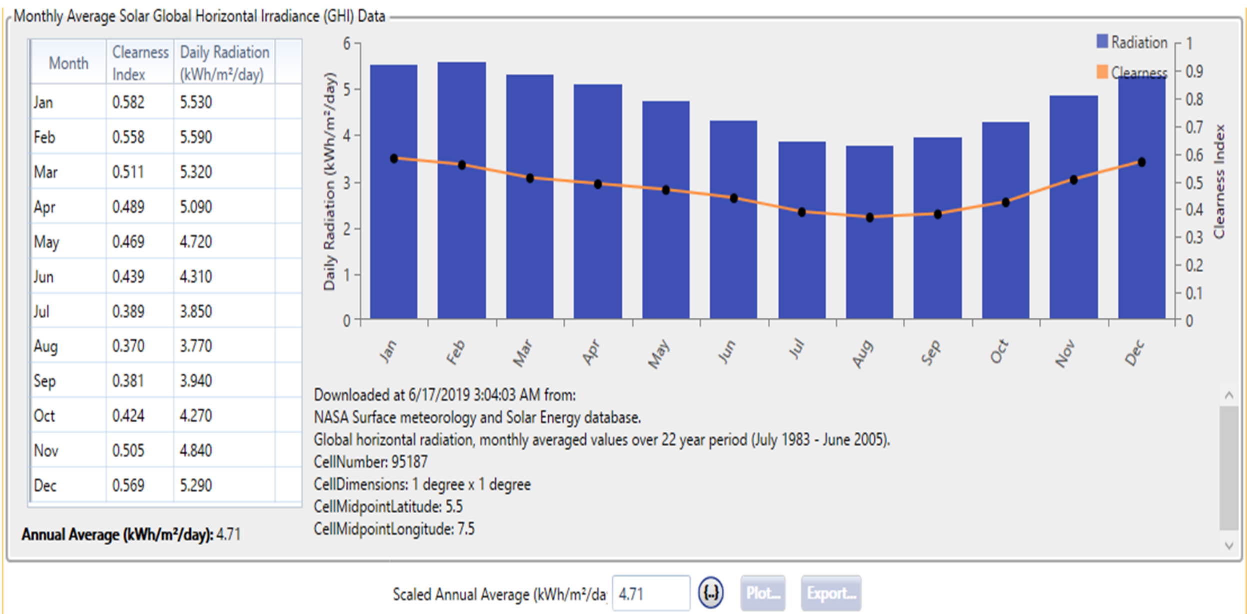
Figure 3. 2: Annual Electrical energy of the school, showing different loads.

There are six (6) separate buildings in the school which houses the principal staff offices, classrooms, library, and teaching staff rooms. The primary load in the school, as can be seen in fig. 2, is lighting, large appliances, ventilation fans, and miscellaneous load. Since Nigeria is a temperate country, the classrooms are built in such a way that opposite walls are practically made up of windows to allow for natural sunlight and ventilation during school hours. The lighting energy is for perimeter lighting during the night and lighting in offices when required. The bulk of the energy is on miscellaneous. These are energy used by the plug-in loads. The large appliances are for the few air conditioners in the computer laboratory. The active school session is for 6 hours (8 am – 2 pm) Mondays through Fridays. The peak load for the day is estimated at 8.83 kW, and the daily energy is 65.21 kWh/day.

3.3 Sizing and Optimization of System.

The system sizing and optimization was done with HOMER pro [11]**.** The average annual solar irradiance for the location is 4.71 kWh/m^2/day. The plot is shown in figure 3.3 HOMER simulated over 700 combinations of different solutions for the system. An optimized system was chosen by HOMER based on some parameters, which include net present cost (NPC), cost of energy (COE), excess energy generated, initial and operating cost, and battery autonomy. The optimized solution proposed by HOMER pro consists of 42.2 kW Canadian solar superpower CSK6-295MS panel each 295 W, 60 pieces 12V 205 Ah [12] Trojan lead acid battery, 360 V DC bus voltage hence, and battery autonomy of 40.6 hours to provide backup for periods of bad weather and cloudy days.

Figure 3. 3: Annual average solar energy potential of the selected school.



The optimized power converter size for the system is 9.78 kW, with a system peak load of 8.83 kW. Though the efficiency of CSK6-295MS panel is 18.02%, it made more economic sense when compared to some monocrystalline PV types that have an efficiency of 20% [13]**.** The battery storage is charged up during high solar insolation. Figure 3.4 shows the load profile for the school, and figure 3.5 shows the optimized result for the school. The net present cost (NPC) of the system is $98,471, with a Levelized cost of Energy of $0.320 per kWh. The bulk of these costs is accrued due to battery storage. If reliability is not the priority of the system, the storage capacity can be reduced to lower the cost of the system.

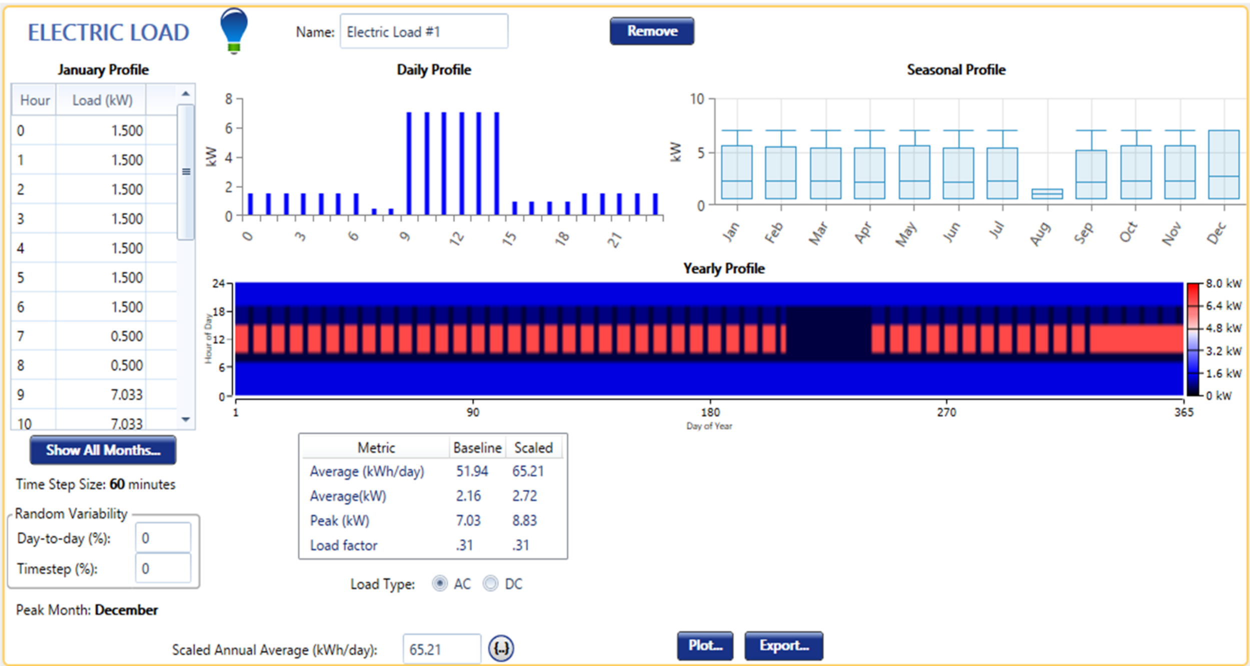


Figure 3. 4: Daily, Monthly and Annual load profile for the school from HOMER pro.

The electrical load for the school is primarily an AC load that is considerably constant every day. The system is 100% renewable and from the optimized result, can meet the energy demand of the school. The percentage of unmet electric load in a year is 0.0839%, which translates into 20 kWh/yr. The optimized schematic of the system in HOMER pro is shown in figure 3.6.

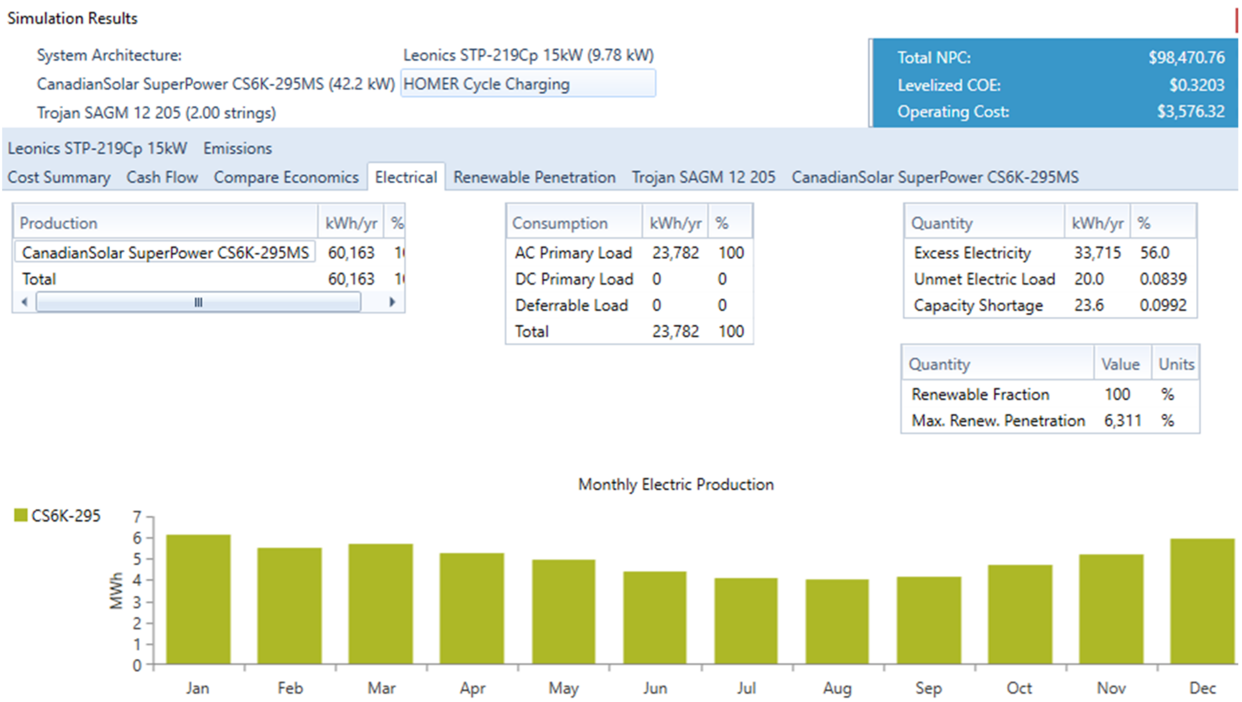


Figure 3. 5: HOMER pro Optimized result for the school.

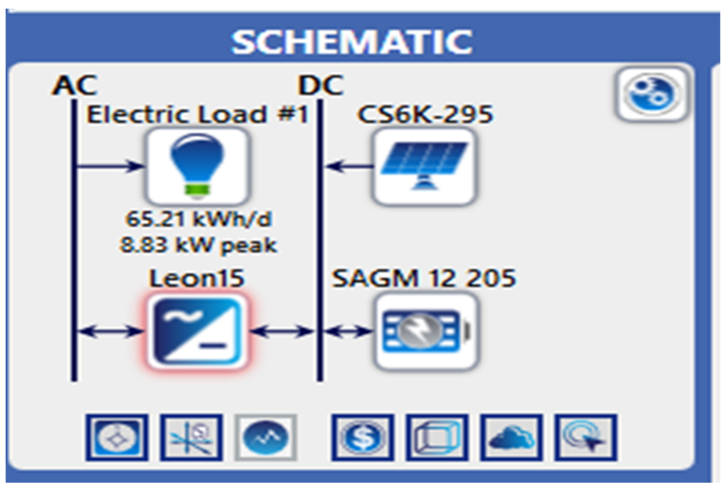


Figure 3. 6: Structure of the system showing the subblocks in HOMER pro.

3.4 Proposed System Design

The proposed system is made up of a roof-mounted solar PV, DC-DC boost converter, MPPT controller, battery bank, DC-AC converter, AC voltage controller, and electric load.

3.4.1 Solar Panel

Canadian solar CS6X 295W solar panel is used to simulate the system, and the configuration is 15 series-connected module per string and 10 parallel string to achieve the system power of (15*10*295W) 44.25 kW. A DC bus voltage of 360V is adopted for the system to reduce the cost of the copper conductor needed to carry a larger current for a lower voltage.

3.4.2 DC – DC Boost Converter

The DC-DC boost converter is to regulate the DC voltage that is coming out from the solar panels and output a fixed 360V needed to charge the battery bank and serve as the input to the DC-AC converter (inverter). The circuit diagram for the boost converter is shown in figure 3.7. The output voltage and current of the inverter are related to the input voltage and current by (1) and (2). It can be observed from the equations that both current and voltage is dependent on k, the duty cycle. The output voltage can be managed by fixing the duty cycle.

$$V_{OUT} = \frac{V_{IN}}{(1-k)} \quad (3.1)$$

$$I_{OUT} = (1 - k)\, I_{IN} \quad (3.2)$$

V_{OUT} and I_{OUT} is the output voltage and current respectively from the converter.

V_{IN} and I_{IN} is the input voltage and current respectively to the converter.

k is the duty cycle of the converter.

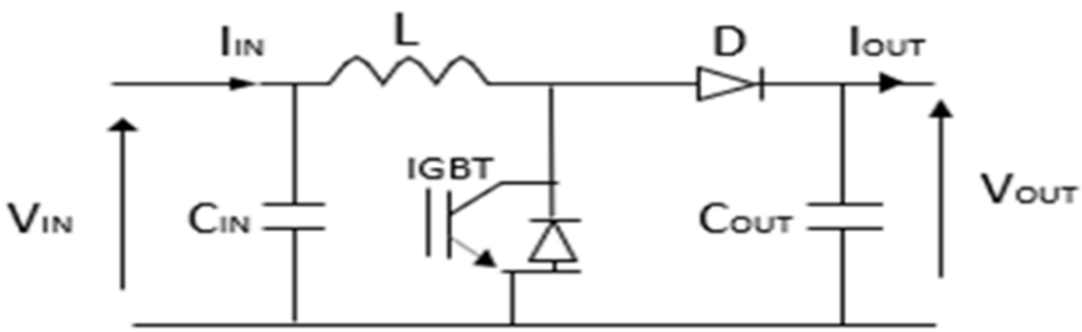


Figure 3. 7: DC-DC boost converter Circuit diagram

3.4.3 Maximum Power Point Tracking

The MPPT was applied to the boost converter following the PV system to maintain the power production of the PV system even in the event of variation in the environmental conditions. The tracking scheme used for the system is the perturbation and observation MPPT tracking Scheme. This MPPT system makes use of the output voltage and current from the PV system as input pulses to drive the pulse generator to control the boost converter duty cycle. This, in turn, then acts as feedback to control the voltage from the PV and eliminated ripples, thereby keeping the voltage value stable.

3.4.4 Battery Storage System

Trojan SAGM 12V 205 Ah was proposed in the HOMER sizing. The battery will provide autonomy of 40.6 hours. The parameters of the battery are as shown below:

Nominal Voltage: 12V

Nominal Capacity: 2.63 kWh

Maximum Capacity: 219 Ah

Maximum Charge Current: 41A

Maximum Discharge Current: 300A

The storage system is made up of 60 units of the battery, and the configuration is explained below;

The number of parallel strings:

$$N_p = \frac{Total\ Battery\ Size}{Rating\ of\ Battery} = \frac{438}{219} = 2\ Parallel\ banks$$

The number of batteries in series:

$$N_s = \frac{DC\ Bus\ Voltage}{Battery\ Norminal\ Voltage} = \frac{360}{12} = 30\ batteries$$

3.4.5 DC – AC Converter with Control

The voltage source inverter in this system is to convert the fixed DC Voltage into a single-phase AC voltage with variable magnitude and fixed frequency of 50Hz. The inverter design employed for this project is a full bridge, single-phase IGBT-based inverter [14]. It consists of four transistors, two of which are turned on per time for the positive cycle while the other two acts on the reverse cycle. The switches/gates are controlled by controlling the pulse rate. However, the inverter output voltage is easily affected by variations in the line and other system parameters. Therefore, the inverter output must be properly controlled to maintain a constant value [15]. For this project, the voltage control scheme was incorporated to maintain a steady DC voltage input to the inverter. The boost converter voltage is sensed and compared with a pre-set reference value; any error is then fed into the PI controller for correction. The output from the PI controller is then multiplied by a sinusoidal value to convert it to AC. This AC waveform is compared with a triangular waveform to generate a pulse for controlling inverter gates. Figure 3.8 shows the implemented control scheme for the single-phase inverter used in this system in block diagram form. [14,15]

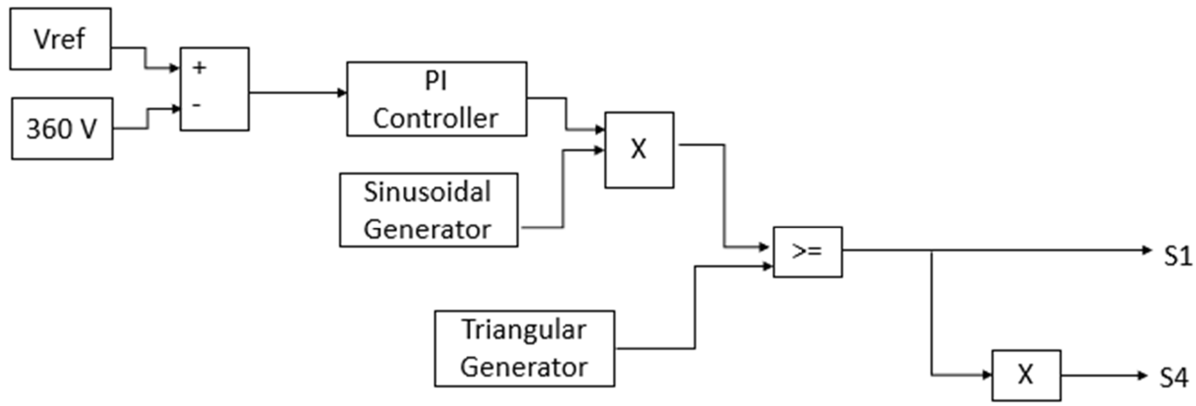


Figure 3. 8: Voltage Controller block for inverter.

3.4.6 Load

The load for the system is a purely resistive load. This is informed by the fact that the facility is a school, and the demand is resistive in nature.

3.5 Dynamic Simulation Results

The system was simulated in MATLAB/Simulink software to determine the overall system behavior and dynamics to change in irradiance, temperature, load, and general harmonics of the system. The simulation result is shown in figures 9-12.

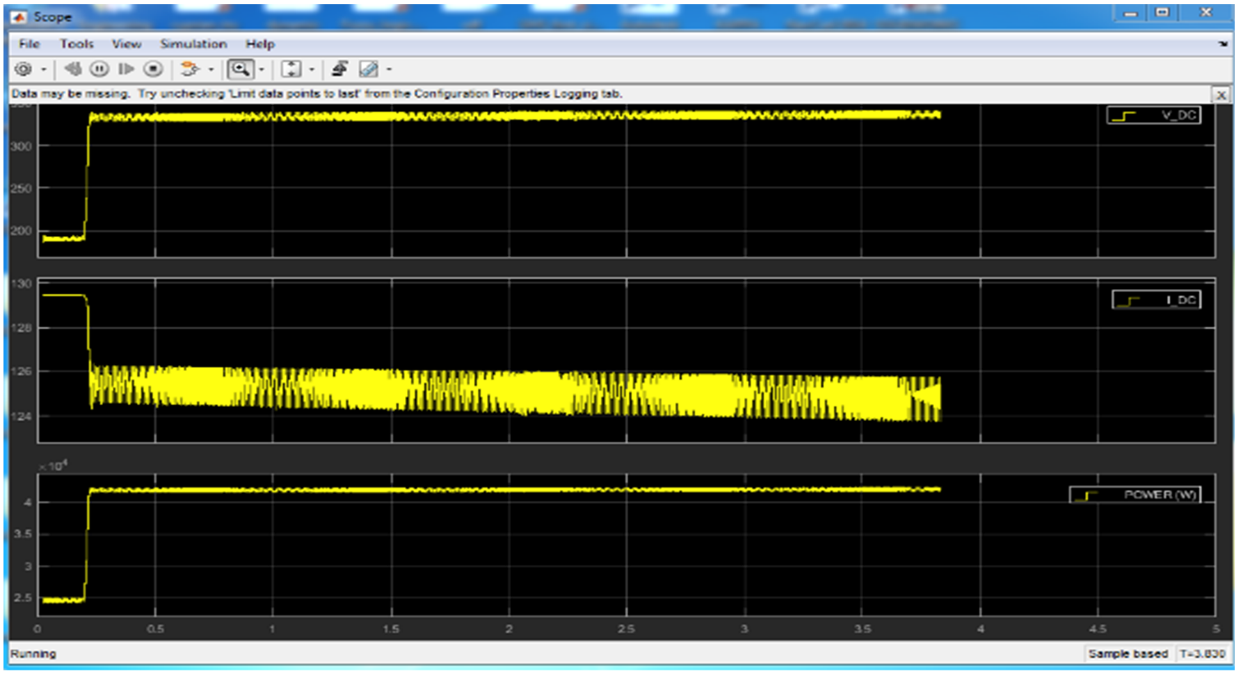


Figure 3. 9: Voltage, Current and Power output from the Solar PV.

The output current varies between 124 – 126A output current, and the power output is about 45 kW. The output voltage from the MPPT is seen in figure 3.10 with a more stable output of 360 V

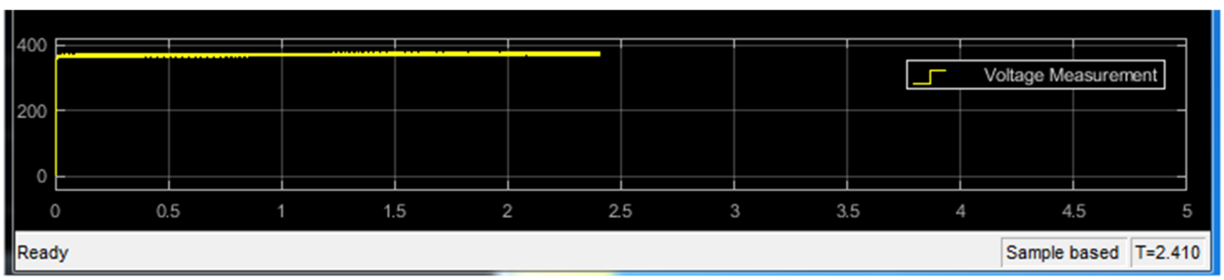


Figure 3. 10: Output voltage from the MPPT.

The output for the storage battery is shown in figure 3.11 with an initial state of charge set at 70%.

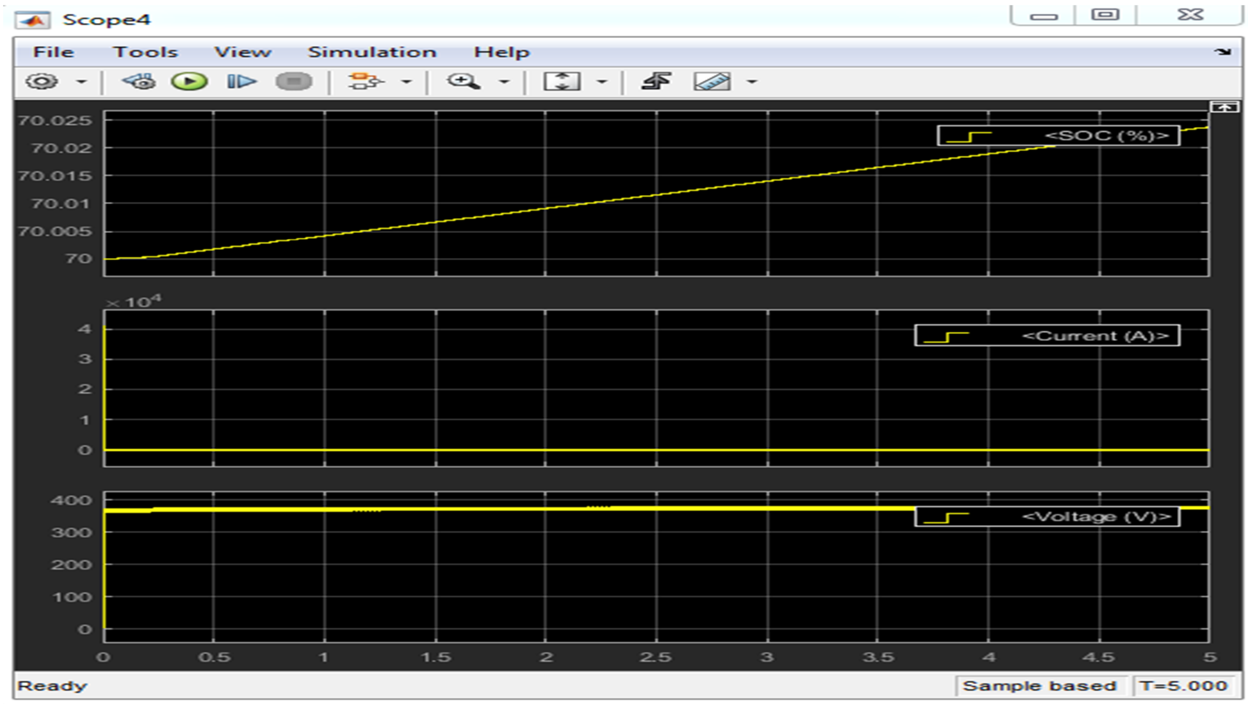


Figure 3. 11: SOC, Current, and Voltage of the battery.

The discharge current is zero because the battery is in the charging state. The output RMS voltage from the inverter is shown in figure 3.12. This power is fed into the distribution box and distributed to the load.

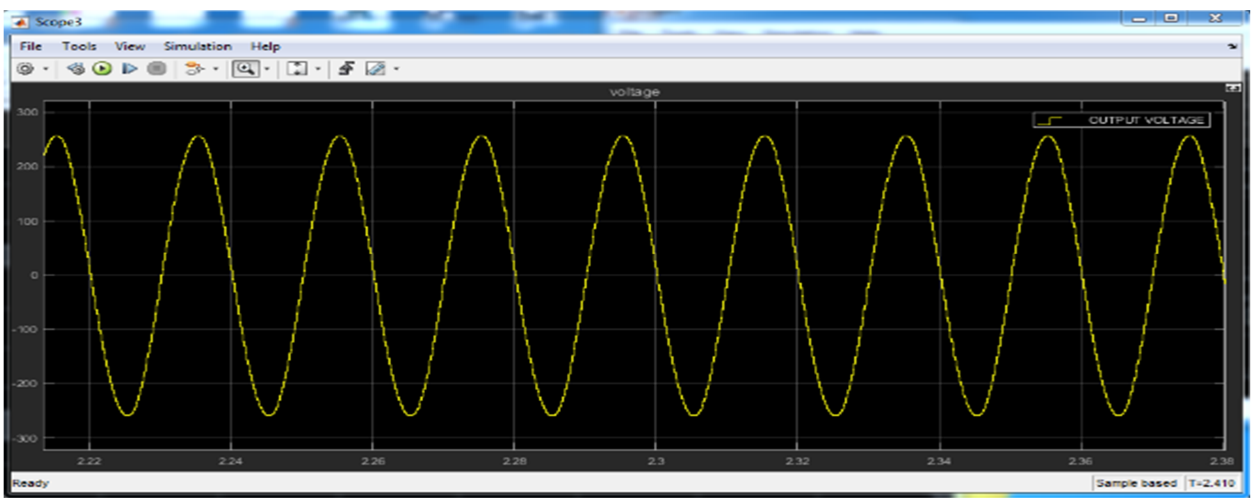


Figure 3. 12: Output voltage from the inverter.

3.6 Conclusion

For a country like Nigeria that is currently having issues with power supply, a distributed power system is highly needed to take the pressure off the existing national grid. For a public school like the one in the project, the power is in a very bad state, and the proposed stand-alone solar PV system will mitigate these power issues. This will deliver power in a timely manner and reliably. The system was simulated on a MATLAB/Simulink, and the dynamic behavior was studied. This showed acceptable output, and the simulated result met the load requirement for the school. If implemented, the power of Uyo High school can be met satisfactorily.

Acknowledgment

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Chapter 4

Dynamic Modeling and Simulation of a Stand-alone DC Hybrid Microgrid for a Base Transceiver Station in Nigeria†

Preface

A version of this article was published in the ***European Journal of Electrical Engineering and Computer Science*. 5, 2 (Apr. 2021), 41-49. DOI:https://doi.org/10.24018/ejece.2021.5.2.316.** I am the primary author on this research article and my thesis supervisor, Dr. M. Tariq Iqbal, is the co-author. As the primary author, I did most of the research work, including literature reviews, designs, hardware implementations, experimental settings, and data analysis in each of the articles. I also wrote the initial manuscript and amended them based on feedback from my co-author and peer reviewers throughout the peer-review process. Dr. M. Tariq Iqbal, co-authored, oversaw the entire research project, read, and edited this paper and offered research ideas throughout the research and in the actualization of this article.

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† This chapter is a version of " Dynamic Modeling and Simulation of a Stand-alone DC Hybrid Microgrid for a Base Transceiver Station in Nigeria", Oton, C. and Tariq Iqbal, M. *European Journal of Electrical Engineering and Computer Science*. 5, 2 (Apr. 2021), 41-49. DOI:https://doi.org/10.24018/ejece.2021.5.2.316.

Abstract

This work considers the dynamic modeling and simulation of a DC hybrid power system for a rural base transceiver station in Nigeria currently being powered by an AC diesel generator (DG). The transient behaviour of the system is studied under varying solar irradiation to ascertain the stability of the power supplied to the sensitive telecommunication equipment. Each component of the system is designed and simulated in a MATLAB/Simulink environment and connected to form the whole system. A permanent Magnet DC diesel generator is used as back-up power for the system. A detailed presentation of the solar array, buck converter, battery storage system, battery controller, diesel generator and the load are presented in this paper. The result shows a stable power output to the load at rated voltage of 48 V.

Index Terms—Base Transceiver station; DC microgrid; Dynamic simulation; MATLAB/Simulink.

4.1 Introduction

The quest for energy in rural areas and remote locations where conventional grid is unavailable has propelled the deployment of distributed energy resources to meet the energy needs of these locations in the form of micro and nano grids. These grids can be for a community, or it can be application specific. This arrangement mostly utilizes conventional diesel generator because of the low initial capital expenditure (CAPEX) but very high operating expenditure (OPEX). Example of the application/operation that relies heavily on power supply is the base transceiver station site.

Energy has continued to be a major challenge for developing and underdeveloped countries around the world while mobile communication industry has continued to experience tremendous growth in these countries. With this growth comes the need for more base station sites to be built, and some in very remote location with no electricity. With the growing concerns of the negative environmental impact of these conventional means of power generation, there is urgent need to switch to a renewable, environmentally friendly means of power generation. Also, with the current testing of 5G network in these countries, the need for more base station sites to be built is even greater as 5G network has a short wavelength and requires higher number of sites [1]. Powering these sites with diesel generators is simply not sustainable.

A thorough sizing work was previously done, and the result published in [2]. A rural base transceiver station site in Agbaja, in Kogi state of Nigeria was considered. The load data for the site was measured every 15 mins for one full year.

That data was used for the sizing the optimized system in HOMER pro. With this data, we are very sure that the entire scenario for the whole year is covered, and the loss of load probability is very low since data is very crucial to a reliable sizing result. A 10% variability index was also incorporated into the sizing design to handle any variability in the load. The PV/Diesel/Battery configuration gave the least Net Present Cost (NPC) and least Cost of Energy (COE). The system showed an operating expenditure that was 75% less than the current configuration in the site with zero unmet energy.

4.2 Literature Review

There has been a significant level of research into the concept of powering base transceiver station sites with renewable energy sources both in standalone applications and hybrid systems configurations. These researches have been championed by both the academics and industry expert who daily strive to reduce the carbon footprint of telecommunication networks. In [3], a comparative analysis of a Solar-Powered base station for different generations of mobile communication technologies was examined for different system architecture. The operational expenditure (OPEX) saving was between 32% for 3G Node B 4/4/4 and 66% for 2G BS 2/2/2. The disadvantage of a single renewable source of power generation like solar here is the lack of reliability of renewable sources generally. Since seasonal variation is a major challenge, a hybrid configuration is always recommended.

In [4], an off-grid hybrid power system for a specific remote mobile base station located in Oromia, Ethiopia is considered. The study only carried out HOMER pro modeling, simulation, and techno-economic study. A feasibility study between was done between the optimized system and the closest hybrid configuration. Similarly, in an attempt to reduce the operation cost, the adverse effect of carbon emission on the environment and ensuring sustainability of base station (BS) power generation source, a feasibility study of a Solar Photovoltaic PV/Battery hybrid system to power a specific mobile cellular BS site in Soshanguve in Pretoria, South Africa was conducted in [5]. The dynamic behaviour of the system was studied using MATLAB/Simulink with very little component analysis.

In similar studies done in [6-8], the authors considered optimal sizing of various hybrid systems configurations to power mobile base transceiver stations. Their studies focused on optimal sizing of the various systems with no form of simulation to study the transient behaviour of these systems. The techno-economic analysis of various hybrid power system configurations are also a very widely studied topic in mobile base transceiver stations compared to the conventional power (diesel generator and grid) system [5, 9, 10]. These studies focus on the economics of using the hybrid system as opposed to the conventional system. Nothing is done with regards to the simulation of these system.

There is very limited literature with regards to dynamic simulation of various hybrid system to power a base station site. This paper is an attempt to bridge this gap and provide a detailed study of the various components of the hybrid system to power an outdoor base transceiver station site. The rest of the paper is focused on system sizing, dynamic model of the system, analysis of system components, simulation results and discussion and a conclusion are drawn.

4.3 System Sizing

From the preliminary work published in [2], the optimal size of the system needed to power a base station site in a rural community in Nigeria consist of a 15 kW PV array, 3.6 kW DC diesel generator and 24 units of 12 V, 190 Ah back up battery. A DC diesel generator is adopted for its high current capacity at low voltage. This is particularly useful for battery charging and powering the base transceiver station load which is DC in nature. The HOMER pro schematic model of the hybrid system showing the daily energy requirement, the peak load and the various components is shown in Figure 4.1 and the electrical energy production summary with zero unmet energy and 89.4% renewable fraction is shown in Figure 4.2.

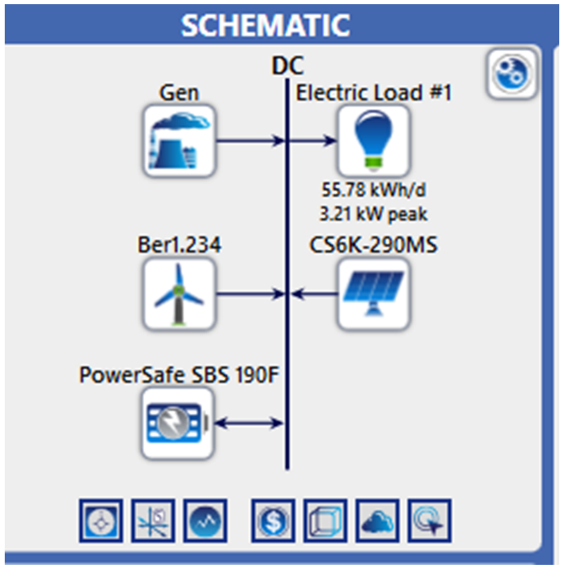


Figure 4. 1: HOMER pro schematic model of the hybrid system units.

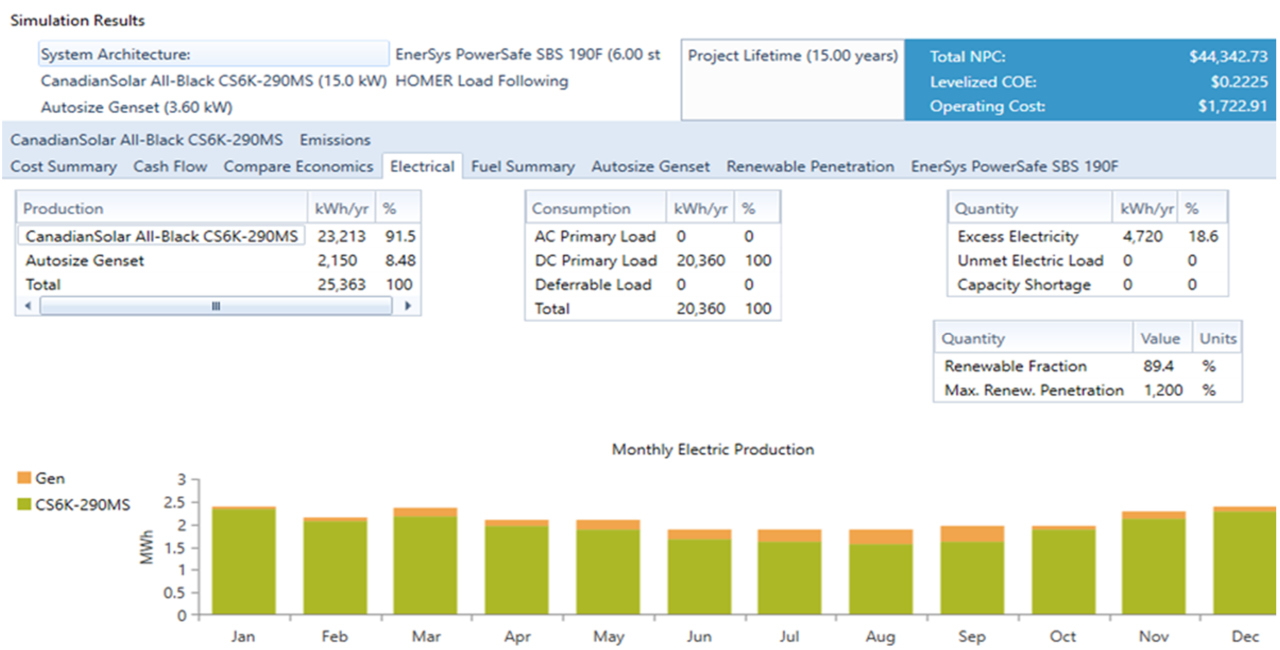


Figure 4. 2: Summary of electrical energy production in HOMER pro.

4.4 Dynamic Model of System

To study the transient behaviour of the system, dynamic modeling and simulation is necessary to access the system response under varying load and resources, the system reliability and representation of the performance and operation. Dynamic simulation is an integral aspect of any engineering design in this modern era. This process eliminates the possibility of failure that may occur from actual implementation of the system in the field and saves cost of the prototype.

For this paper, MATLAB/SIMULINK is employed to simulate and analyze the different components of the system individually and then these components are integrated to form the whole system. Simscape, environment in Simulink is particularly useful in dynamic system modeling by representing the various system using the dynamic equation that describe the system [11]. The PV modules, DC-DC converters, battery, DC diesel generator and battery charge controller is analyzed in this work. The various components of the system are simulated and connected to form the hybrid system model. The model is shown in Figure 4.3.

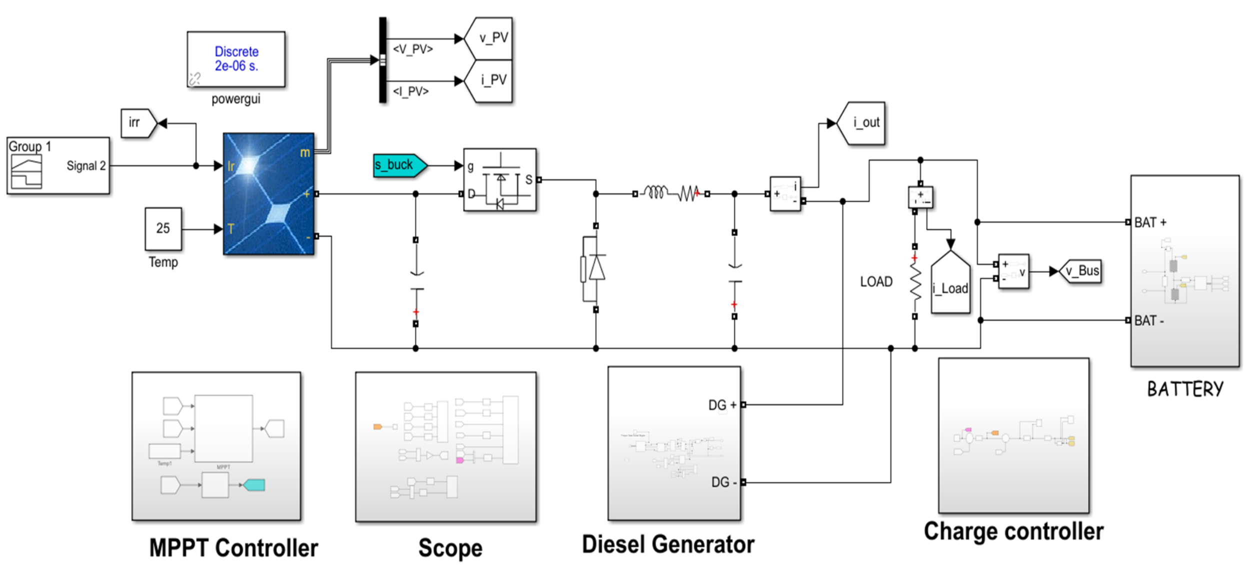


Figure 4. 3: Model of the hybrid system in Simulink.

4.5 Analysis of Different System Components

4.5.1 Solar Photovoltaic Array

Solar PV operates by converting sunlight directly to electricity in a process known as photovoltaic effect. This process occurs when a photon of light is strikes the cell, creating an electron-hole pair movement. This movement causes current to flow in an external circuit connected to the cell. Since the voltage of this cell is usually very small (in the range of 0.5 – 0.8V), the cells are connected in series to increase the voltage and parallel to increase the current and this in turn, forms a module. The aggregation of this modules forms a panel, and the panels are connected in series and parallel as well to form an array. A two-diode model of a PV cell has better accuracy than the single diode model [12]. A constant ideality factor is assumed in a single diode representation. This value changes with a change in voltage. A two-diode model best captures this effect. The two-diode model is shown in Figure 4.4 below. The equations that represent the various parameters of the circuit is summarized in (4.1) to (4.7) below [12].

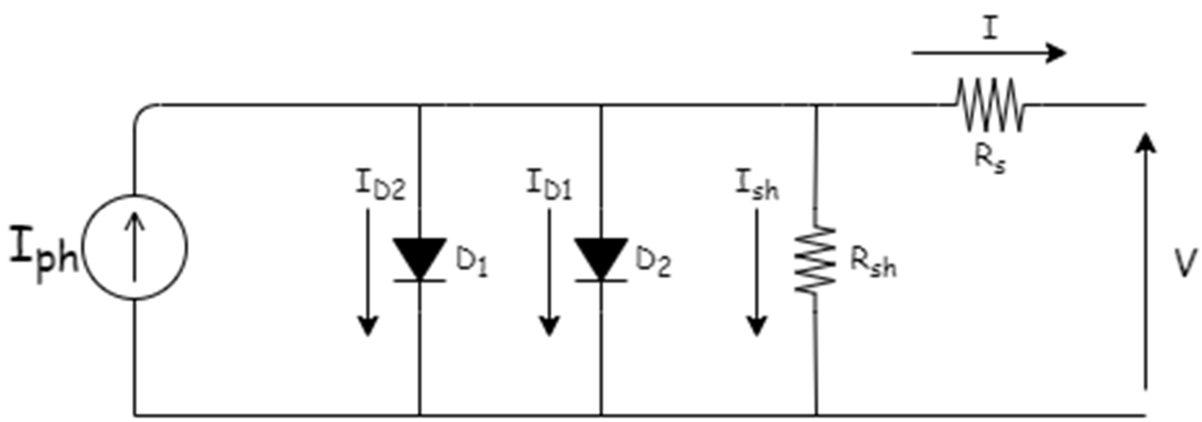


Figure 4. 4: Two-diode solar PV equivalent circuit model

$$I = N_p I_{ph} - N_p I_{D1} - N_p I_{D2} - I_{sh} \qquad (4.1)$$

$$I_{ph} = \left[I_{sc} + K_i\left(T - T_{ref}\right)\right]G/1000 \qquad (4.2)$$

$$I_{D1} = I_s\left[e^{\frac{q\left(\frac{V}{N_S}+\frac{IR_S}{N_P}\right)}{n1kT - 1}} \right] \qquad (4.3)$$

$$I_{D2} = I_s\left[e^{\frac{q\left(\frac{V}{N_S}+\frac{IR_S}{N_P}\right)}{n2kT - 1}} \right] \qquad (4.4)$$

$$I_{sh} = \frac{\frac{N_{pv}}{N_S} + IR_S}{R_{sh}} \qquad (4.5)$$

$$I_s = I_{rs}\left(\frac{T}{T_{ref}}\right)^3 e^{\frac{qE_g\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)}{kn}} \qquad (4.6)$$

$$I_{rs} = \frac{I_{sc}}{e^{\left(\frac{qV_{OC}}{N_S kT}-1\right)}} \qquad (4.7)$$

The current at the terminal of the PV cell is represented in (4.1). The current due to photon emission (photocurrent) is given in (4.2) and is expressed as a function of the solar irradiance and temperature. The current through diodes D1 and D2 is given (4.3) and (4.4) respectively. The shunt current and the series current are expressed in (4.5) and (4.6) respectively. The silicon contacts the metallic material and hence, creates a series resistance, R_s that reduces the current generated by the cell. Manufacturing defects accounts for the shunt resistance, R_{sh} which account for power losses in the cell by creating an alternate path for photocurrent current to flow. The reverse saturation current is given in (4.7). All the parameters used in the equations above are defined in table 4.1.

Table 4. 1: Photovoltaic Modeling Cell Parameters

Parameter	Description	Unit
I_{ph}	Photocurrent	A
G	Solar Irradiance	W/m^2
I	Output current	A
E_g	Band gap energy	$1.3\ eV$
I_{D1}	Current through diode 1	A
I_{D2}	Current through diode 2	A
R_s	Series resistance	Ω
R_{sh}	Shunt resistance	Ω
I_{rs}	Reverse Saturation current	A
I_s	Shunt current	A
I_{sc}	Short circuit current	A
I_{sh}	Shunt current	A
k	Boltzmann constant	$1.38\ x\ 10^{-23}\ J/K$
K_i	Temperature coefficient of current	$A/°C$
n_1	Ideality factor of diode 1	1
n_2	Ideality factor of diode 2	1
q	Electron charge	$1.6\ x\ 10^{-19}\ C$
T	Temperature of Solar cell	$°C$
T_{ref}	Temperature reference of cell	$°C$
V_{oc}	Open circuit Voltage	V
N_p	Number of parallel connected cell	N
N_s	Number of series connected cell	N

4.5.2 Maximum Power Point Tracking (MPPT)

Maximum power point tacking is implemented to continuously adjust the operating point of the solar PV array to the point of maximum power extraction by adjusting the impedance seen by the solar array continuously under varying irradiance, temperature and loading conditions. This is achieved by controlling array to operate at peak voltage. At this point, the power generated by the PV array is maximum for a given irradiance and temperature. Figure 4. 5. shows the schematic block diagram of most MPPT.

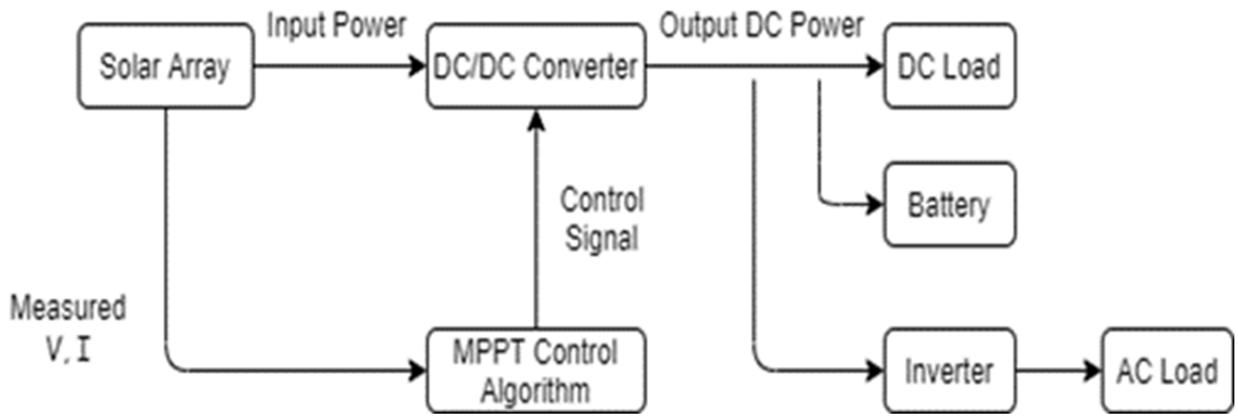


Figure 4. 5: MPPT schematic block.

The algorithm constantly monitors the operation point of the array by consistently measuring the output parameters (current and voltage) and using same as it input to adjust the duty cycle of the pulse width modulated (PWM) signal that controls the DC-DC converter switch [12].

For this work, the incremental conductance MPPT is utilized. This algorithm gives a higher degree of accuracy and efficiency than the perturb and observe method. It also yields a more stable result by ceasing to perturb the operating point resulting in one of the drawbacks of this method which is a higher response time [12]. The incremental conductance algorithm operates by comparing the incremental conductance, dI_{pv}/dV_{pv} with the instantaneous $I_{pv} - V_{pv}$ characteristics of the solar array. The flowchart of the Incremental Conductance algorithm is shown in Figure 4.6

At maximum power point (MPP), the change in power with respect to voltage is zero. This can be expressed as $\frac{dP_{pv}}{dV_{pv}} = 0$, since power is the product of voltage and current, the derivative can further be written as without the subscript as follows.

$$\frac{dP}{dV} = \frac{d(V.I)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} \tag{4.8}$$

$$\frac{dP}{dV} = I + V\frac{dI}{dV} \tag{4.9}$$

$$\frac{dI}{dV} = -\frac{I}{V} \text{ at MPP} \tag{4.10}$$

$$\frac{dI}{dV} > -\frac{I}{V} \text{ at the left side of the MPP} \tag{4.11}$$

$$\frac{dI}{dV} < -\frac{I}{V} \text{ at the right side of the MPP} \tag{4.12}$$

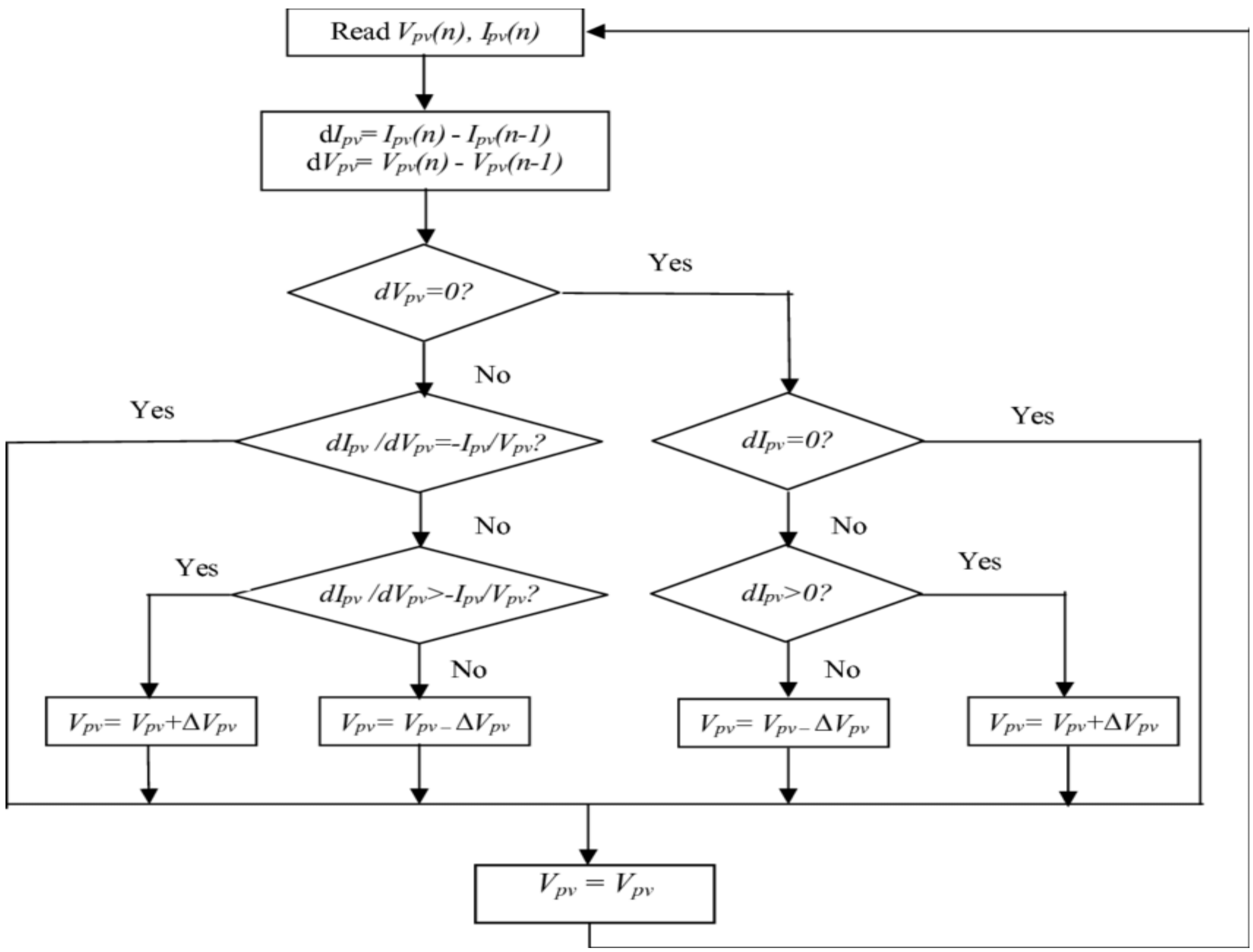


Figure 4. 6: Incremental Conductance algorithm flowchart.

4.5.3 Buck Converter

DC-DC converters are used to convert from one voltage level to another to suit a particular purpose within the circuit. They are high-frequency power conversion circuits that operates by periodically opening and closing a switch [13]. The output voltage of a buck converter is lower than or equal to the input voltage, it is otherwise known as a step-down converter. These converters can operate either in Continuous Conduction Mode (CCM), where the inductor current remains positive throughout the switching period, or in discontinuous Conduction Mode (DCM), where the inductor current remains 0 for some time in the switching period. For this work, our converters will operate in CCM. Figure 4.7 shows the buck converter circuit.

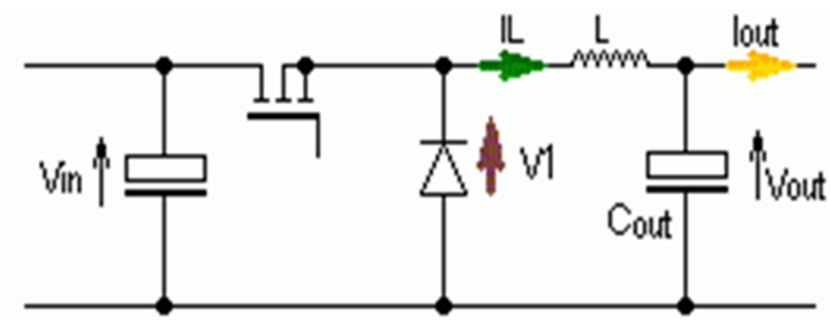


Figure 4. 7: Buck Converter Circuit.

The output voltage of the buck converter is related to the input voltage by (4.13) below.

$$V_{out} = V_{in} * D \qquad (4.13)$$

The output voltage is V_{out} and the input voltage is V_{in} while the duty ratio is D. The duty ratio represents the fraction of the commutation period during which, the switch of the converter is on. Its value ranges from 0 to 1. The minimum inductor value for which the inductor current reaches zero is given in (4.14) [13].

$$L_{min} = \frac{(1-D)R}{2f} \qquad (4.14)$$

L_{min} is the minimum inductance required for continuous operation, D is the duty cycle calculated at minimum input voltage, R is the maximum load resistance and f is the switching frequency. Any value of inductor lower than this minimum or critical value will cause the buck converter to operate in DCM which is undesirable. The buck converter design parameters for this work are summarized in Table 4.2.

Table 4. 2: Buck Converter Design parameters

Input	V_{in_min} = 48.0V	V_{in_max} = 128.0V	V_{in} = 128.0V
	V_{out} = 48.0V	I_{out} = 314.17A	f = 5.0kHz
Result	L = 53.60uH	ΔI_L for V_{in_max} = 125.67A	

V_{in_min} and V_{in_max} are the minimum and maximum input voltages, output voltage is V_{out} and output current I_{out} and f is the switching frequency. V_{in} is the voltage used as input to sample the behaviour of the converter. The inductor value is L and the inductor current variation at maximum input voltage is given $\Delta I_L = 0.4 I_{out}$ for our design. The voltage and current responses of the buck converter is shown in Figure 4.8 with the output voltage given as 48 V and the PV's input voltage at MPP given as 128 V.

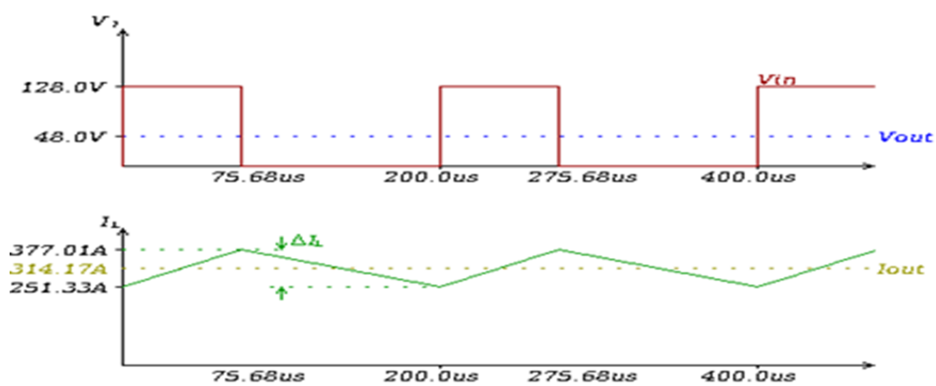


Figure 4. 8: Output Voltage and Current responses of the Buck Converter at MPP Voltage.

4.5.4 Battery Storage System

Energy storage is critical to the operation of a standalone microgrid that utilizes renewable energy. This is because renewable resources are variable in nature and fluctuates during different times of the day and year. Energy storage is what smoothens out this fluctuations and maintain output voltage stability [13]. Lead acid Battery serves as the storage in this study because of its high energy density when compared to other alternatives like supercapacitors. The response time for a supercapacitor on the other hand is quicker because the energy is not stored in a chemical form like in the battery. In DC microgrid, the response time is not as critical when compared to AC microgrid because of the absence of frequency regulation [13, 14]. Simulink models a battery as a non-linear voltage source where the output voltage depends on the current and the changing state of the battery (SOC). The SOC is a non-linear function of current and time [15]. Figure 4.9. shows the model of the battery in Simulink. This model has internal resistance connected in series with a controlled voltage source.

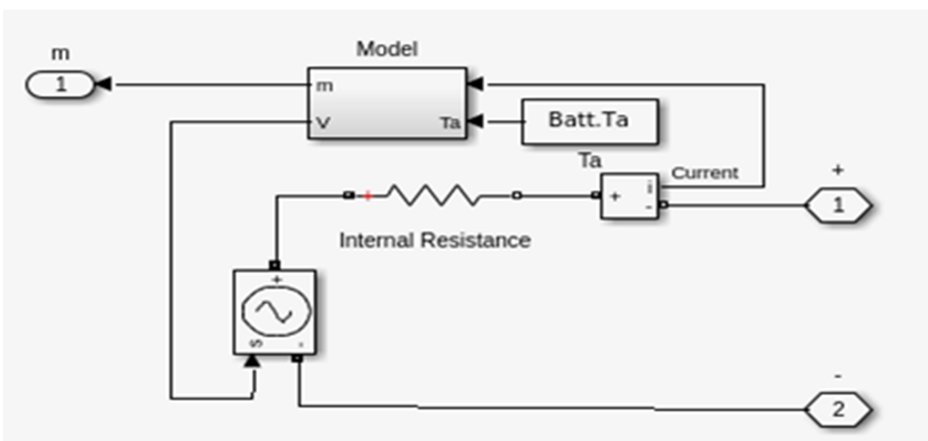


Figure 4. 9: Masked Battery model in Simulink.

The charging, discharging and the SOC of the battery can be modeled as follows [13, 16]

$$E_{charge} = E_0 - \frac{KQi^*}{i_t + 0.1Q} - \frac{KQi_t}{Q - i_t} + Laplace^{-1}\left(\frac{A}{s/_{Bi_t} + 1} \cdot \frac{1}{s}\right) \tag{4.15}$$

$$E_{discharge} = E_0 - \frac{KQi^*}{Q - i_t} - \frac{KQi_t}{Q - i_t} + Laplace^{-1}\left(\frac{A}{s/_{Bi_t} + 1} \cdot 0\right) \tag{4.16}$$

$$SOC = 100 * \left(1 + \frac{\int i_t dt}{Q}\right) \tag{4.17}$$

Where E_0 is constant voltage V, Q is the maximum battery capacity in Ah, K is the polarization constant in Ah^{-1}, i_t is extracted battery capacity Ah, i^* is the low frequency current dynamics in A, B is exponential capacity $(Ah)^{-1}$ and A is the exponential voltage in V.

4.5.5 Battery Charge Controller

The charge controller is designed to operate by comparing the actual bus voltage, *V_Bus* to the reference voltage *V_Ref* which is 48V. The error which is the difference between *V_Bus* and *V_Ref* is fed into a PI controller. The output of the PI controller gives the battery reference current *IB_Ref* and this is compared with the actual battery current *I_Bat* forming the inner current loop. The deviation is adjusted by a PI controller and fed to the IGBT switch through a PWM signal. Boost switch is activated for an increase in *V_Bus* and buck switch for a decrease in *V_Bus*. as shown in Figure 4.10.

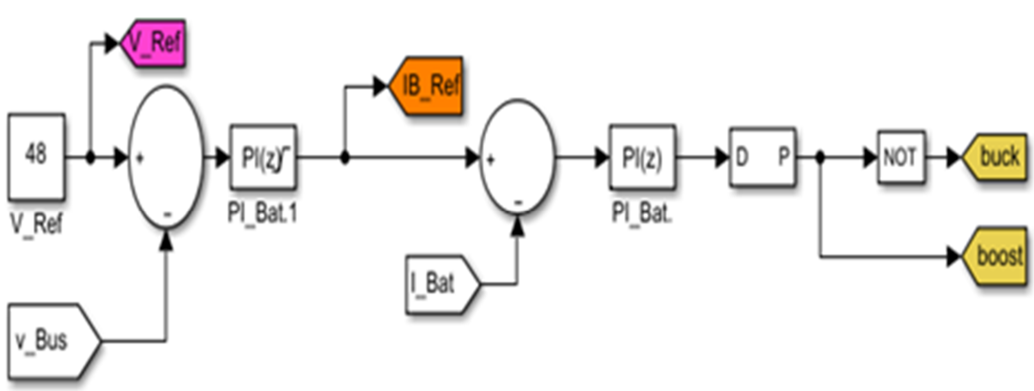


Figure 4. 10: Charge controller topology for the Battery.

4.5.6 Diesel Generator

Diesel generator (DG) is employed as a backup power supply when the battery state of charge (SOC) goes below the minimum safe operating value. The DG is in operation when the solar power is not available, and the backup battery has discharged to it minimum operating SOC of 45%. A permanent magnet synchronous generator (PMSG) employed for this project for its high efficiency, its current production at low voltages and minimal losses. Rectification of the AC generated by the PMSG is done internally using a diode bridge and a smoothening capacitor. The power is then used to charge the battery and supply the load instantly or later. The model of the PMSG in the d-q coordinate (rotor reference frame) where all quantities in the rotor reference are referred to the stator is given by [17, 18].

$$\frac{di_d}{dt} = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}p\omega_m i_q \tag{4.18}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}v_q - \frac{R}{L_q}i_q + \frac{L_d}{L_q}p\omega_m i_d - \frac{\lambda p\omega_m}{L_q} \tag{4.19}$$

$$T_e = \frac{3}{2}p\left[\lambda i_q + (L_d - L_q)i_d i_q\right] \tag{4.20}$$

The subscript d and q are the physical quantities that has been transformed into the d-q rotating frame. Table 4.3 defines the parameters of the PMSG.

Table 4. 3: PMSG Parameters

L_q, L_d	*q*-axis and *d*-axis inductances of the generator (H)
R	Resistance of the stator windings (Ω)
i_q, i_d	*q*-axis and *d*-axis currents (A)
v_q, v_d	*q*-axis and *d*-axis voltages (V)
ω_m	Angular velocity of the rotor (rad/s)
λ	Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases
p	Number of pole pairs
T_e	Electromagnetic torque (N.m)

4.5.7 Load

The load for the system was selected as a resistive load since telecoms load is DC in nature. The simulation is carried out for a peak power demand of 3.2 kW and this translate to a resistor value of 0.72 Ω on a bus voltage of 48 V. Peak value is considered to ensure the simulated system can withstand the highest load requirement.

4.6 Simulation Results and Discussion

This model is simulated for 5 seconds to study the transient behaviour of the system. The parameters of the system like output voltage, current of PV, battery SOC, bus voltage and other relevant parameters of interest are observed using scopes. Figure 4.11 shows the graph of PV's output voltage, current, buck converter output current and DC bus voltage. The output PV voltage is at MPPT (128 V) for variable irradiance values other than zero. This demonstrates the effectiveness of the MPPT algorithm. The current changes to reflect the irradiance the PV is exposed to. The buck converter is designed to give output voltage of 48 V.

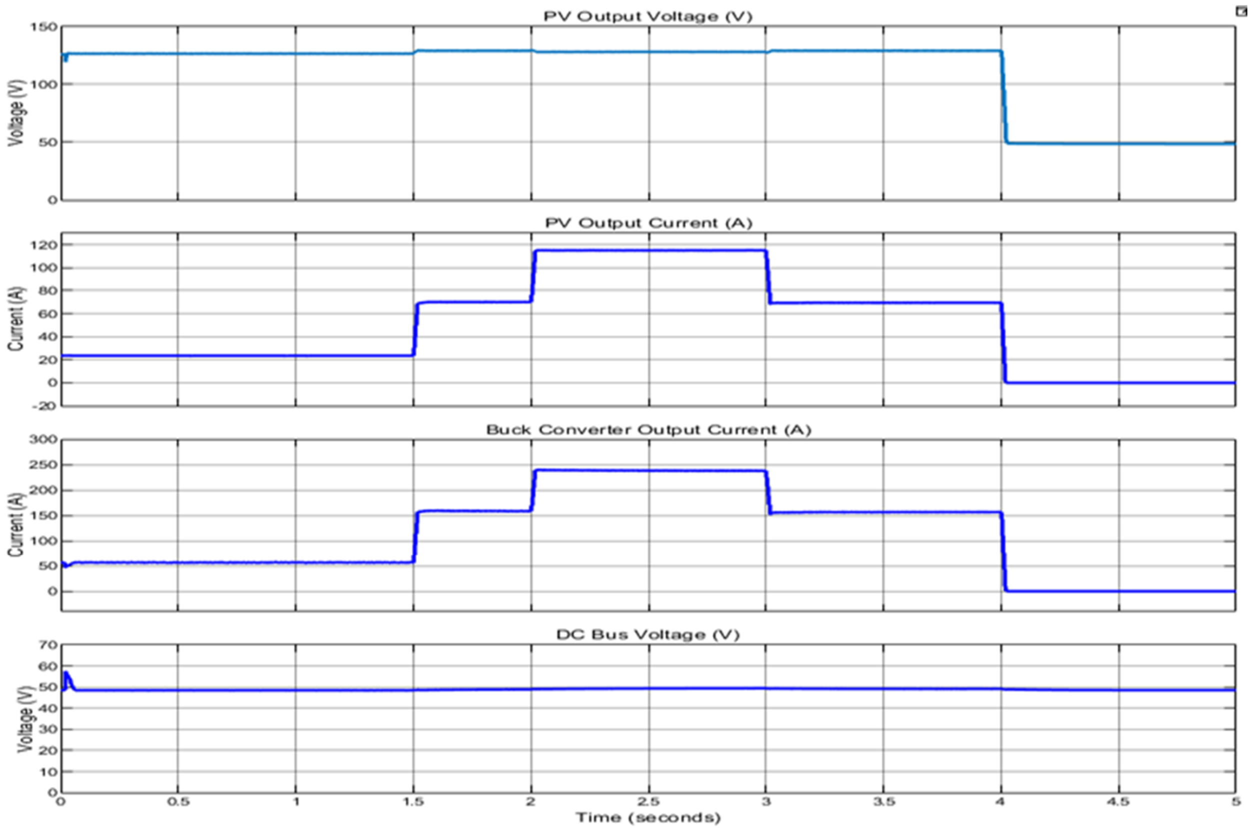
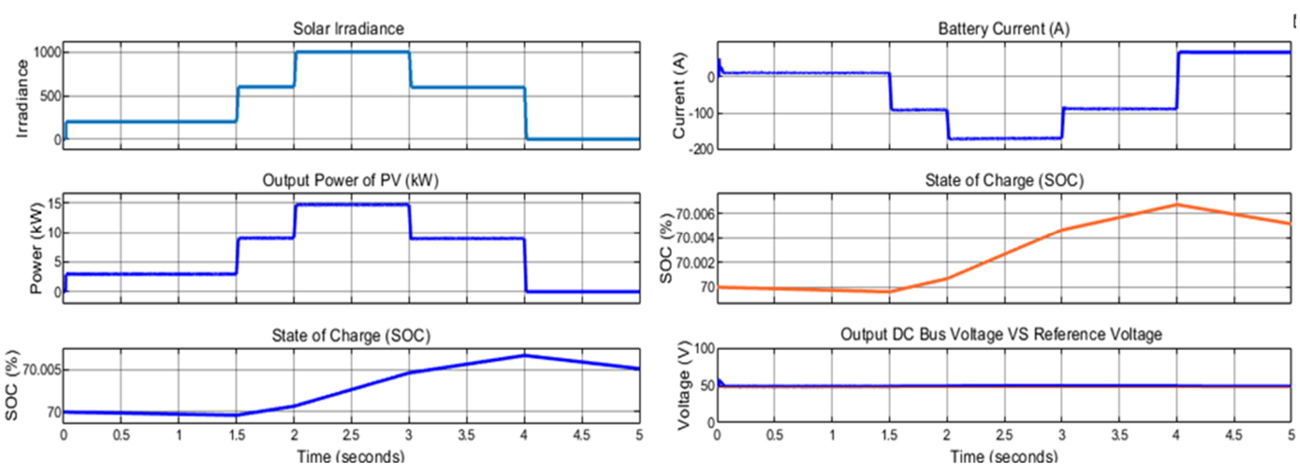


Figure 4. 11: PV voltage, Current, buck converter current and DC bus voltage.



(a) Solar Irradiance, PV output power and SOC of battery. (b) Battery current, SOC and DC bus voltage.

Figure 4. 12: Solar Irradiance, PV output power SOC of battery, current, DC bus voltage.

Figure 4.12 (a) shows the solar irradiance, PV output power and battery state of charge (SOC). Between 0 – 1.5 s, an irradiance of 200 W/m^2 is applied to the solar array, a power of 2.8 kW is generated, this power is not enough for the load, the battery is discharged from an initial 70% SOC to support the load. Between 1.5 s – 2 s, an irradiance of 600 W/m^2 is enough to supply the load and the remaining power is used to charge the battery. Between 2 s – 3 s, maximum irradiance of 1000 W/m^2 is applied to the PV and the output power of the PV is 15 kW which correspond to the power at MPPT. Between 4 s – 5 s, there is no irradiance applied to the PV and hence, no power generated from the PV. The load is supplied entirely by the battery, hence the reduction in the SOC of battery.

Figure 4.12 (b) shows the battery current, battery SOC and the output DC bus voltage following the reference bus voltage. When the battery is discharging (between 0 – 1.5 s and 4 s – 5 s), the battery current is positive. When the battery charging (1.5 s – 4 s), the current is negative. The battery regulates the effect of the varying irradiance and maintains a constant output bus voltage by either charging or discharging depending on the solar resource available to the solar array.

The simulated system can supply a stable power output despite the variability of the solar resource. Figure 4.13 shows the load current, and the power delivered to the load at a constant voltage. The current drawn by the load is constant at 66.7 A at a bus voltage of 48 V.

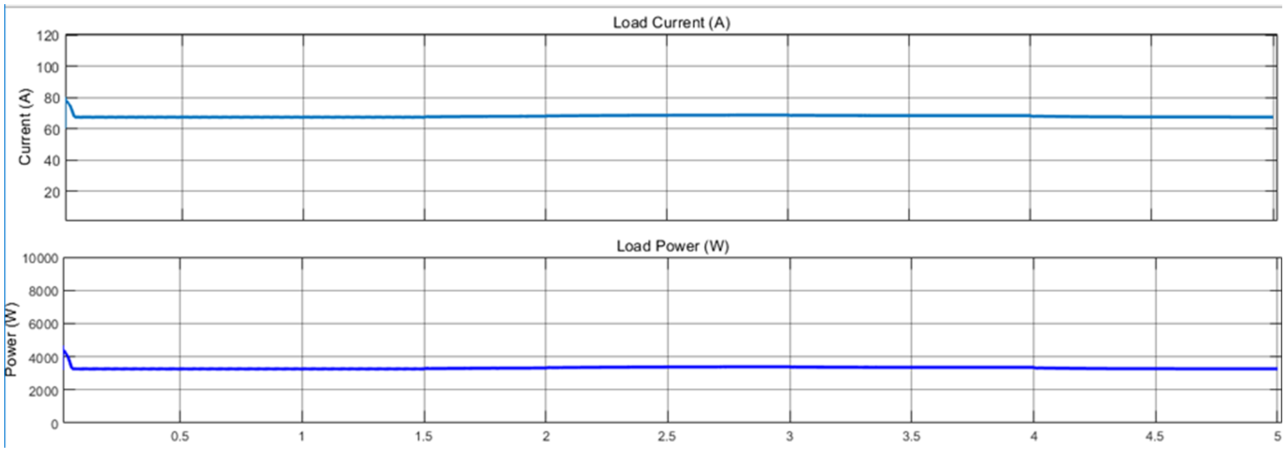


Figure 4. 13: Load current and load power.

When the solar array is not producing power and the state of charge of the battery is less than 45%, the diesel generator is activated to supply the load. This generator is sized to power the load primarily while relying mostly on solar power to charge the battery because of load following dispatch strategy employed in HOMER pro during sizing. This dispatch strategy prioritizes battery charging using renewable resource, in this case solar power.

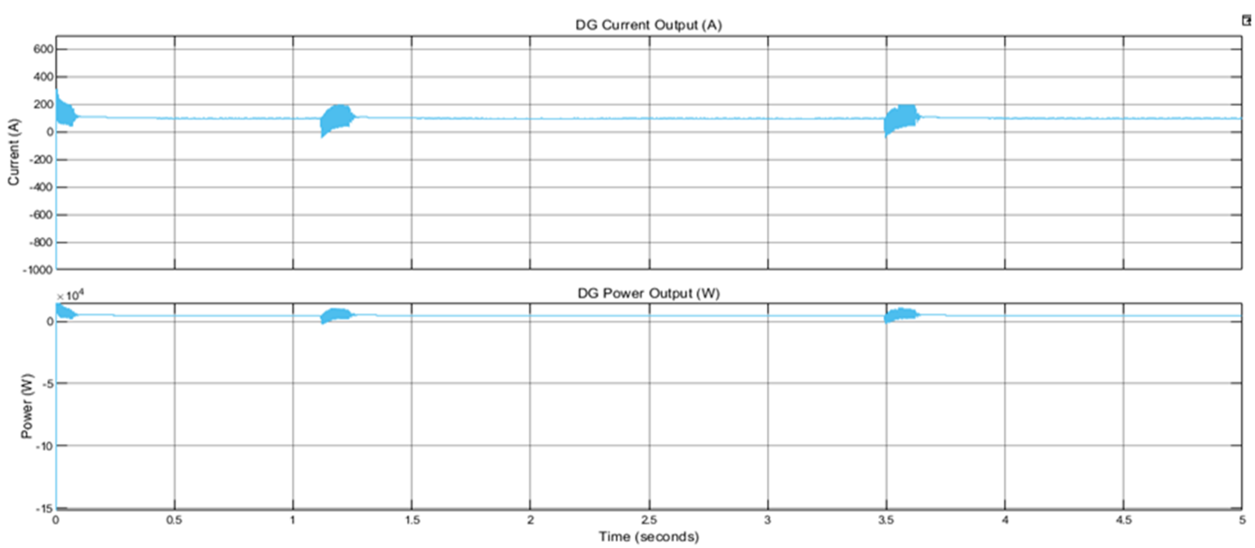


Figure 4. 14: Rectified diesel generator output current and power.

Figure 4.14 shows the rectified current output of the diesel generator at a constant voltage of 48 V and the power with minor ripples caused by the harmonics in the PMSG output. The battery is absorbing the excess power from the diesel generator after supplying the load, hence the negative battery current, meaning the battery is charging as seen in Figure 4.15.

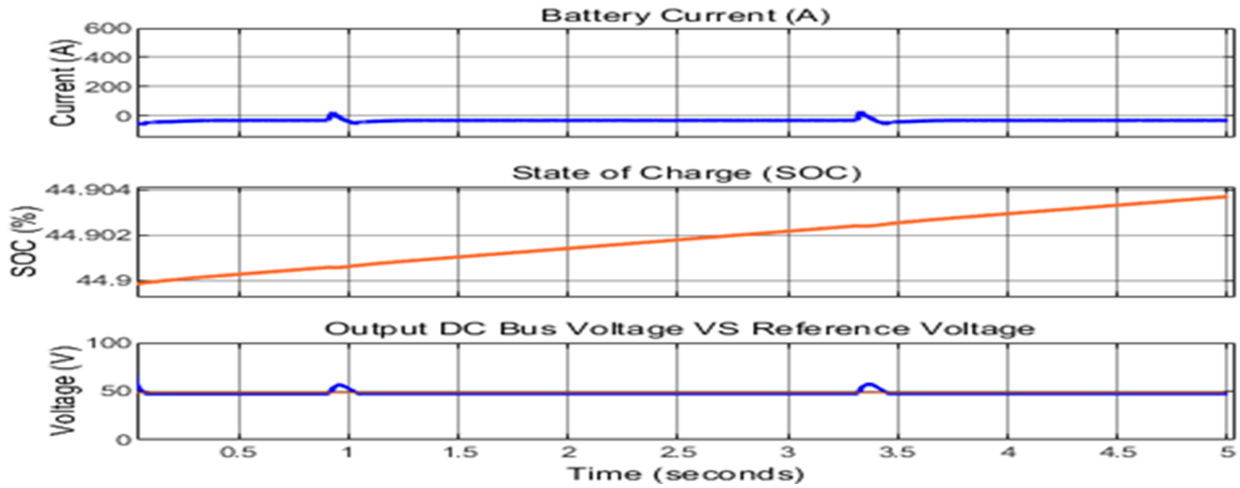


Figure 4. 15: Battery charging current, SOC and output DC voltage due to diesel generator.

The power supplied to the load due to the diesel generator is seen in Figure 4.16. The current absorbed by the load is 66.7 A similar to when the PV supplied the load.

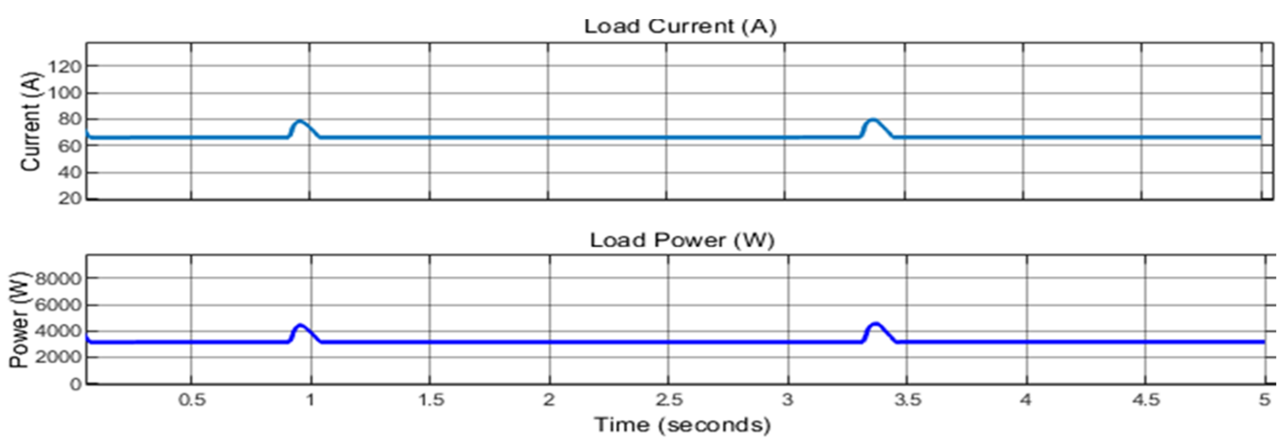


Figure 4. 16: Output current and power due to diesel generator.

4.7 Conclusion

The modeling and simulation of a DC hybrid power system for powering a base transceiver station was studied in this paper. The system was simulated under varying solar irradiance and the result obtained was observed using scopes. The MPPT algorithm worked to keep the voltage at its MPP for varying irradiance values and maximum power was extracted from the PV. The dc-dc buck converter steps down the voltage to the required level with higher output current. The result also showed that the battery storage system absorbed excess energy during periods of high energy production and gave out energy during periods of low/no energy production. The diesel generator was able to inject a predetermined constant power to the system to supply the load and charge the battery during periods of no solar irradiance and low SOC of battery. The SOC for which the battery is cut-off and generator kick in is 45%. The studied system showed a satisfactory response and can provide a stable power to the load. For future studies, a low-cost, open source IoT-based supervisory control and data acquisition system (SCADA) will be implemented to log historical data for the system and provide control for the system remotely.

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Chapter 5

Low-Cost Open Source IoT-Based SCADA System for a BTS Site Using ESP32 and Arduino IoT Cloud

Preface

A version of this article was peer-reviewed, accepted, and will be presented in the conference proceedings of the **2021 IEEE 12th Annual Ubiquitous Computing, Electronics and Mobile Communication Conference (IEEE UEMCON) New York, USA** scheduled for **1-4th December 2021.** The paper will also be published in the IEEE Xplore Database as part of the **IEEE UEMCON 2021 conference proceedings.** I am the primary author on this research article and my thesis supervisor, Dr. M. Tariq Iqbal, is the co-author. As the primary author, I did most of the research work, including literature reviews, designs, hardware implementations, experimental settings, and data analysis in the article. I also wrote the initial manuscript and amended them based on feedback from my co-author and peer reviewers throughout the peer-review process. Dr. M. Tariq Iqbal, co-authored, oversaw the entire research project, read, and edited this paper and offered research ideas throughout the research and in the actualization of this article.

Abstract

A low-cost open source IoT-based SCADA system for a rural BTS site using ESP32 and Arduino IoT Cloud is presented in this work. Current, voltage, temperature, and humidity sensors are programmed to measure relevant parameters of interest, and the measured Data is processed and

parsed to the Arduino IoT Cloud via a Wi-Fi network communication channel. A widget-based dashboard is created on the Arduino IoT Cloud to monitor and control the system. A mobile application is also deployed to aid remote monitoring and control as well. LEDs are used to implement a high temperature and low voltage control logic. A prototype is used to demonstrate this as an illustration of what is obtainable in a Base Transceiver Station (BTS), where the voltage must be within a specific value (48 V) and the temperature within an acceptable value too.

Keywords—SCADA, ESP32, Arduino IoT Cloud, sensors, Internet of Things.

5.1 Introduction

Supervisory Control and Data Acquisition (SCADA) is a system with a primary objective of controlling and monitoring devices in the field, mostly located in very remote and obscure places. Deploying a SCADA system on any process/plant also ensures full automation of that process/plant. Various conditions and parameters of the system can be accurately measured, monitored, and controlled optimally and in real-time. The efficiency of the process/plant is greatly improved because of the real-time nature of the data collection, processing, and carrying out the control action when necessary. Since these are achieved automatically, the chance of failure is minimized as human errors which had hitherto been prevalent are eliminated.

For a mobile telecommunication site located in a very remote area, a reliable SCADA system cannot be overemphasized as a human operator cannot be stationed at the site continuously for monitoring. With an effective SCADA system, the frequency of visits by the operators is reduced significantly, thereby reducing the overall operation cost of the site.

SCADA leverages the coalescence of hardware components like sensors and actuators and software programs like the Human Machine Interface (HMI) to perform its four primary functions:

data acquisition, networked data communication, data presentation, and monitoring and control [1, 2]. To carry out these functions effectively, SCADA relies on various elements. These elements are Field Instrument Devices (FIDs) like sensors and actuators, Remote Terminal Units (RTUs) like microcontrollers and microprocessors, Master Terminal Units (MTUs) in this case, the Arduino IoT Cloud and the communication network in the case a Wi-Fi network provided by my home router. This work is based on the fourth generation of SCADA architecture which is the Internet of Things (IoT) configuration. IoT SCADA have several advantages, including remote assess/control, real-time monitoring and alarming, data sharing, data manipulation and visualization, system optimization, trend analysis, flexibility, and increased productivity. In [3, 4], our previous work on designing, sizing, and dynamic modeling of a DC hybrid power system for a remote telecommunication facility in Nigeria was examined. This work presents the SCADA aspect of the work using a prototype.

5.2 Literature Review

Monitoring, control, and instrumentation is a very crucial aspect of mobile base station sites operation. Several parameters are simultaneously monitored for effective and optimal operation with limited downtime. The significant parameters of interest are the voltage and temperature, which have a direct impact on the site. The voltage must stay within a stipulated range of value, and for a temperate region like, Nigeria, the temperature must be monitored and controlled for continuous operation of the site. The SCADA system currently operational on the site is proprietary with all the associated disadvantages and costs.

Several studies have been presented using a Web-based SCADA system. In [5], the authors presented a Web-SCADA system to monitor and control a Wind-PV power system using the IntegraXor software to create and view the graphical interface and ATMEGA8535 microcontrollers interfaced with several sensors to measure relevant data. The IntegraXor software is complicated to understand. In [6], a Web-based, low-cost SCADA system was applied to control a renewable energy system microgrid. Arduino boards were used to measure relevant electrical and environmental data using appropriate sensors. The measured data was sent to a local database hosted on a Raspberry Pi. A wireless radio frequency transceiver created the communication link between the microcontroller and the Raspberry Pi. The system is very complex to build, demanding the knowledge of HTML, MySQL, and lots of C++ codes. These can be very hard to implement.

In [7], a SCADA system to monitor the electrical parameters of a stand-alone solar photovoltaic system is presented. This work focuses on the electrical parameters of the solar system and battery efficiency. No environmental parameter is considered, and there is no room for remote control of the system. The authors in [2] developed IoT based open source SCADA system for a PV system to monitor solar panel current, voltage, and backup battery voltage. It uses Arduino Uno as the remote terminal unit for receiving the measured sensor data, and a Raspberry Pi is used as the communication channel to parse the measured data to Emoncms platform for storage, monitoring, and control.

In all the work reviewed, there are minor limitations that this paper seeks to address. Implementing this work on the Arduino IoT Cloud platform offers a significant level of simplicity as the code is not written from scratch. Significant code is pre-written by just declaring the variables.

5.3 System Description and Experimental Design

The simplified version of the studied DC hybrid system for a rural BTS site is illustrated in Figure 5.1. Some parameters of interest for monitoring purposes are highlighted, albeit not exhaustive of what is typically monitored and controlled on the site. The connected components have local controllers that can receive a control signal remotely and carry out the control action via an actuator. The power management system implements the supervisory control.

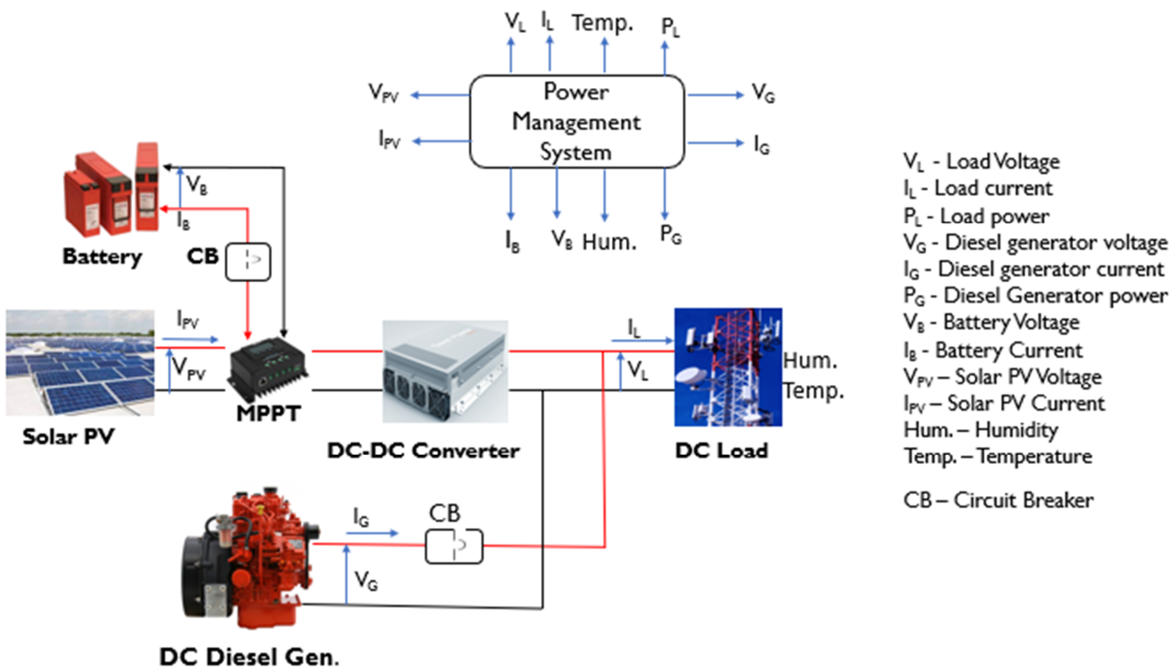

Figure 5. 1: Hybrid power system showing connected devices.

The system proposes an open source, low-cost supervisory control, and data acquisition system using the recently upgraded Arduino IoT cloud platform to monitor and control the prototype of our hybrid system. Current, voltage, temperature, and humidity sensors are connected to the ESP32 microcontroller to read the voltage, current, temperature, and humidity and trigger the relevant LED when the voltage goes below a pre-set value and temperature goes above a stipulated value, as will be explained further in the course of this work. These data can be monitored and controlled from the Arduino cloud dashboards and anywhere using mobile applications. The schematic diagram of the proposed IoT SCADA is shown in figure 5.2.

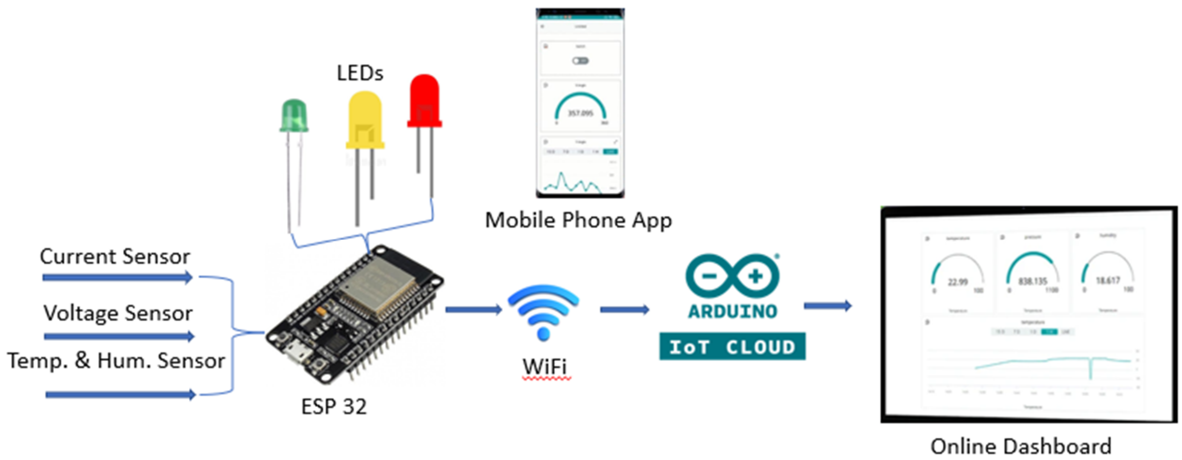

Figure 5. 2: Schematic of the Proposed IoT SCADA system.

5.4 Implementation Methodology

As a proof of concept, a circuit is designed and implemented on a breadboard with three sensors; voltage, current, and temperature and humidity sensors connected to the microcontroller (ESP32) to read the sensor values. The yellow LED is used as the load for which the current flowing through is measured, while the green and the red LED implements the under-voltage logic and over-temperature control logic, respectively. The Wi-Fi compatibility of the microcontroller is leveraged to create the connection with the Arduino IoT Cloud. Dashboards are created in the Cloud to monitor and control the various variables of interest. A mobile application can also be used to control and monitor the variables from anywhere in the world. The connected sensors are the FIDs, and the microcontroller is the RTU. The Arduino IoT Cloud represents the MTU, while the Wi-Fi router at home creates the communication link. The three sensors are the DHT11 temperature and humidity sensor, MH electronics voltage sensor, and ACS 712 Hall-Effect current sensor. The features and properties of these sensors are further discussed and examined below.

5.4.1 DHT11 Digital Temperature and Humidity Sensor

This sensor ensures excellent reliability and accuracy by employing an innovative digital signal acquisition technique and temperature and humidity sensing technologies to read the digital signal output. The sensor links to a high-performance 8-bit microcontroller and combines a resistive-type humidity measurement component and a Negative Temperature Coefficient (NTC) measuring component, providing excellent quality, fast response, anti-interference ability, and cost-effectiveness. It has a temperature range of 0 to 50°C, a humidity range of 20% to 90%, 1°C temperature, and 1% humidity precision, respectively. DHT11 comes in two alternative pin layouts, with either four or three pins. The three-pin configuration is used in this work. Vcc is the power supply, Ground is the circuit ground, Data is the serial data output reading the temperature and humidity. The operating voltage of the sensor is between 3 - 5.5 V. A 10kΩ pull-up resistor is used to connect the output pin to the Vcc of the microcontroller. For this work, we are connecting the data pin to GPIO 33 of the ESP32 microcontroller. Figure 5.3 shows the connection of the sensor to the ESP32 microcontroller.

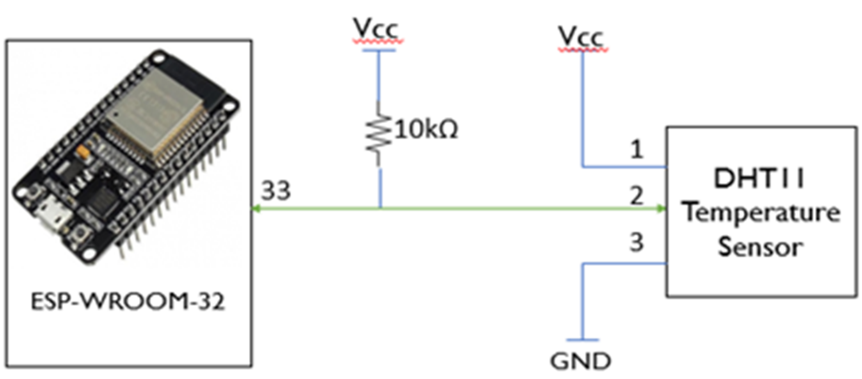

Figure 5. 3: The connection between ESP32 and DHT11.

5.4.2 Voltage Sensor Module

This sensor operates by using the voltage divider principle to measure the voltage. It has an embedded series connection of 7.5 kΩ and 30 kΩ resistors to achieve a voltage divider of 5 to 1 for the measurement. The range of operational voltage for the sensor is between 3.3 – 5.0 V, and using a 12-bit ADC can measure voltage in the range of 0 – 25 V DC. Voltage sensors are usually connected in parallel to the voltage source (a 9V AC/DC adapter or a battery) to measure its voltage. ESP32 operates on a 3.3 V input voltage. The sensor is connected directly to measure the voltage as follows: The voltage sensor's pin S is connected to analog pin 32 on the ESP32, and pin – is connected to the ESP32's GND pin, with the sensor's GND and VCC pins connected across positive and negative terminals of the 9 V /5 V buck converter as shown in Figure 5.4. The converter is used as the breadboard power supply to provide the needed 5 V needed for the circuit.

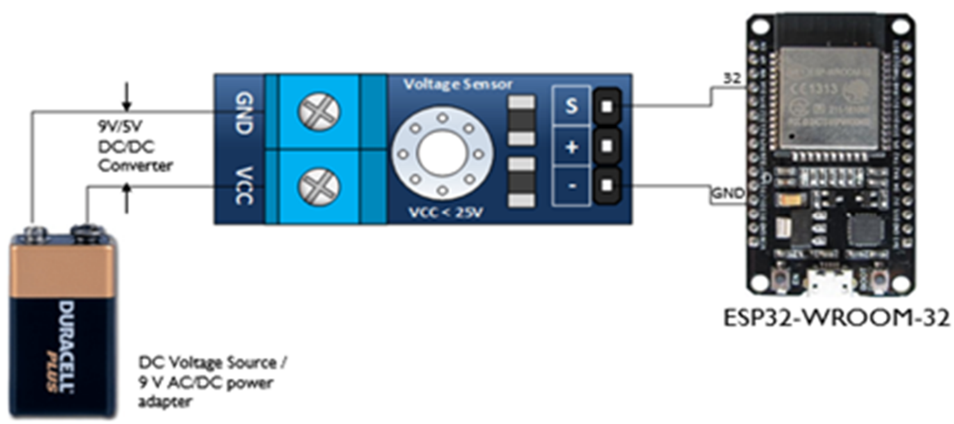

Figure 5. 4: Interfacing diagram of the voltage sensor with ESP32.

5.4.3 ACS712 Hall-Effect Current Sensor

As the name implies, this sensor works on the principle of Hall-Effect, a phenomenon where a current-carrying conductor placed in a magnetic field generates a voltage perpendicular to both the current and the magnetic field. This generated voltage is used to measure the current. It is a fully integrated, economical, and relatively high precision sensor that employs a non-inversive method of current measurement by measuring the magnetic field created in the wire. ACS712 Hall-Effect sensor can measure both DC and AC by using a low-resistance current conductor. The sensed circuit and the sensing circuit are electrically isolated.

It requires a 5 V DC to power it and comes in three versions of 5A, 20A, and 30A and gives a 2.5 V DC output when no current is detected. Its sensitivity/scale factor ranges from 66 mV/A for 5A, 100 mV/A for 20A, and 185 mV/A for the 30A module. Because the current sensor's signal voltage is 5 V, it is not compatible with direct connection to the ESP32 microcontroller's ADC pins that operate between 0 - 3.3 V. As a result, a pull-down resistors arrangement is implemented to match the current sensor's 5 V signal demand to the ESP32 3.3 V ADC signal capacity, ensuring the accuracy of the measured values [8]. Figure 5.5 shows the connection of ACS712 sensor with a step-down resistor configuration to provide the necessary voltage input to the ESP32. Current sensors are always connected in series with the load or source on which the current is measured.

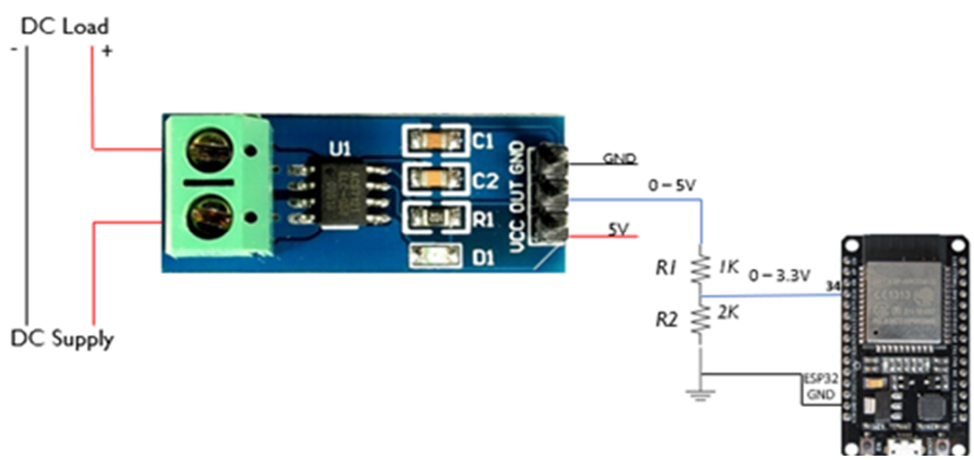

Figure 5. 5: ACS712 connection to ESP32 microcontroller.

The voltage divider equation uses a 1 kΩ and 2 kΩ resistor combination and is expressed as shown in equation (5.1)

$$V_{ESP} = \frac{R_2}{R_1 + R_2} \times V_{CC} \tag{5.1}$$

V_{ESP} is the ESP32 voltage, and V_{CC} is the sensor input voltage.

5.4.4 ESP32 – WROOM – 32 Module (RTU)

This is a powerful microcontroller that supports Wi-Fi, Bluetooth, and Bluetooth Low Energy (BLE) used in diverse applications. Wi-Fi's connecting radius is wider than Bluetooth, which senses the module and connects it to a smartphone with low-energy beacons. The microprocessor uses a dual-core, individually controlled CPU that clocks at an adjustable frequency between 80 MHz to 240 MHz. A co-processor can be employed to save power during low power demanding tasks. It has an infinitesimal sleep mode current (5 µA), making it suitable for battery-powered applications. The Wi-Fi capability of the microcontroller is leveraged to implement the connection to the Arduino IoT Cloud. The Arduino Integrated Development Environment (IDE) in the Cloud is used to write the sketches. The measured data from the sensors are acquired by the board, displayed on the Arduino cloud serial monitor, and sent to the dashboard for monitoring.

5.4.5: Wi-Fi Router (Communication Link)

Actiontec R3000 FibreOP router is used to create the communication channel between ESP32 (RTU) and the Arduino IoT Cloud MTU). The data transfer rate of this router is 1 Gbps over ethernet and up to 2.3 Gbps over Wi-Fi in dual-band, dual-concurrent 2.4G, 802.11n, and 5G, 802.11ac. Since ESP32 can implement the TCP/IP IEEE 802.11 b/g/n, it is seamlessly connected to the router using the network SSID and password. The router is configured to provide the needed Wi-Fi connection for the implementation of the project. The router's credentials (SSID and the password) provide the needed security against unauthorized access to the system. The login credential of the Arduino IoT Cloud is another layer of security.

5.4.6 Arduino IoT Cloud Platform

The Arduino community has recently released Arduino IoT Cloud, an IoT platform. The Arduino IoT Cloud features an end-to-end solution that makes creating networked projects simple for creators, IoT enthusiasts, and professionals from inception to delivery. HTTP REST API, MQTT, command-line tools, JavaScript, and WebSocket, are some of the interaction methods supported by the platform. Multiple devices can be linked together, and data can be exchanged in real-time. A simple user interface allows to monitor data from anywhere and execute control when necessary. This platform works with specific Arduino microcontrollers or a third-party board that is compatible with the platform. The third-party boards are ESP32 and ESP8266 microcontroller boards. All cloud-compatible boards come with a cryptographic co-processor with secure hardware-based key storage for enhanced security key storage. The steps involved in creating a project on the Arduino IoT Cloud and all the associated steps, components, and terms are listed below [9, 10]

- **Creating Arduino IoT Cloud Account and Cloud Plan:** Like with every other platform, the first step is to sign up using a functional email address and select a plan.

- **Creating a “Thing”:** A "Thing" is the foundation of all Arduino IoT Cloud projects. The term "Thing" refers to a cloud-based virtual item. It stores variables and information about linked devices and networks safely. An online "Thing" editor can generate a Thing for each project you make in the Cloud. A blend of variables, a device, network information, and a sketch will make up an item [9].

- **Connecting Devices to a Network:** Microcontrollers that link to the Cloud are known as devices. Some Arduino microcontrollers and a few third-party boards like the ESP32 used in this work can also suffice. The network is the Wi-Fi credentials, SSID, and password. The ESP32 used in this work, like other third-party microcontrollers, requires a "secret key" which the Arduino IoT Cloud editor will create when the device (microcontroller) is added along with the network credentials.

- **Creating and Declaring Cloud Variables:** Variables are locations where data are stored. It has a name, holds a value, and are of a particular type. These variables, once declared, are available to the attached microcontroller and the dashboard as well. Its can either be Read and Write or Read Only to. For variables that need to be controlled, we use the Read and Write option, while we use the Read-Only option for variables we are interested in just monitoring.

- **Creating Sketches and Dashboard:** Sketches are the C++ programs written to the microcontroller to execute a defined command. One prominent feature in Arduino IoT Cloud is that when creating a "Thing", a significant portion of the sketch is written automatically when the variables are declared. Sketches are written and edited directly in the Thing editor or using the Arduino Web editor. A dashboard is employed for monitoring and controlling the IoT Cloud Thing. Several widgets are used to build the dashboard and declared variables are linked to the appropriate widget and labeled accordingly. The dashboard can be monitored on the web browser and/or a mobile application on any Android or IOS device to carry out remote monitoring and control.

- **Installing Arduino Create Agent:** Arduino create agent is installed on the PC used for this work. This agent links the PC's USB port on which the microcontroller is connected and the Arduino IoT Cloud. This is necessary because the encryption built into the web browser prevents a website from connecting directly to a PC resource which is essential to our 'Thing' and web editor to work [9].

5.5 Hardware Prototype Design

The proposed system prototype to demonstrate monitoring and control of a small hybrid power system is designed on a breadboard. The system consists of 9 V AC/DC adapter or (battery), DC/DC converter, current sensor, voltage sensor, temperature and humidity sensor, LEDs (red, green, and yellow), ESP32-WROOM-32 microcontroller, and some pull-down resistors. The 9V is stepped down to approximately 5.5 V by the DC/DC converter. The yellow LED represents the load. A current sensor is connected to analog Pin 34 of ESP32 in series with the yellow LED to measure the current flowing through the LED. The voltage sensor is connected to analog Pin 32 of ESP32 across the output of the DC/DC converter to measure its output voltage (input voltage to the system). The temperature and humidity sensor is connected to analog pin 33 of the ESP32 microcontroller to read the environmental temperature and humidity. The red and green LEDs, with the appropriate "If statements" in the code are used to implement a control logic. They are connected to analog pins 18 and 19 on ESP 32 microcontroller, respectively. When the temperature is greater than 23°C, the red LED comes on. If the measured voltage is less than 4.5 V, the green LED comes on. This control logic is synonymous with what is obtainable in the field, where an air conditioner or an extraction fan regulates the temperature in the shelter or cabin of a BTS site, and the green LED represents the starting relay of a diesel generator that comes ON when voltage drops below a certain threshold (~ 46 V). The ESP32 can be connected either through the USB port or using Over-the-Air (OTA) to upload sketches wirelessly from the Cloud to the board. The prototype is shown in figure 5.6, and the flowchart for the SCADA system in figure 5.7.

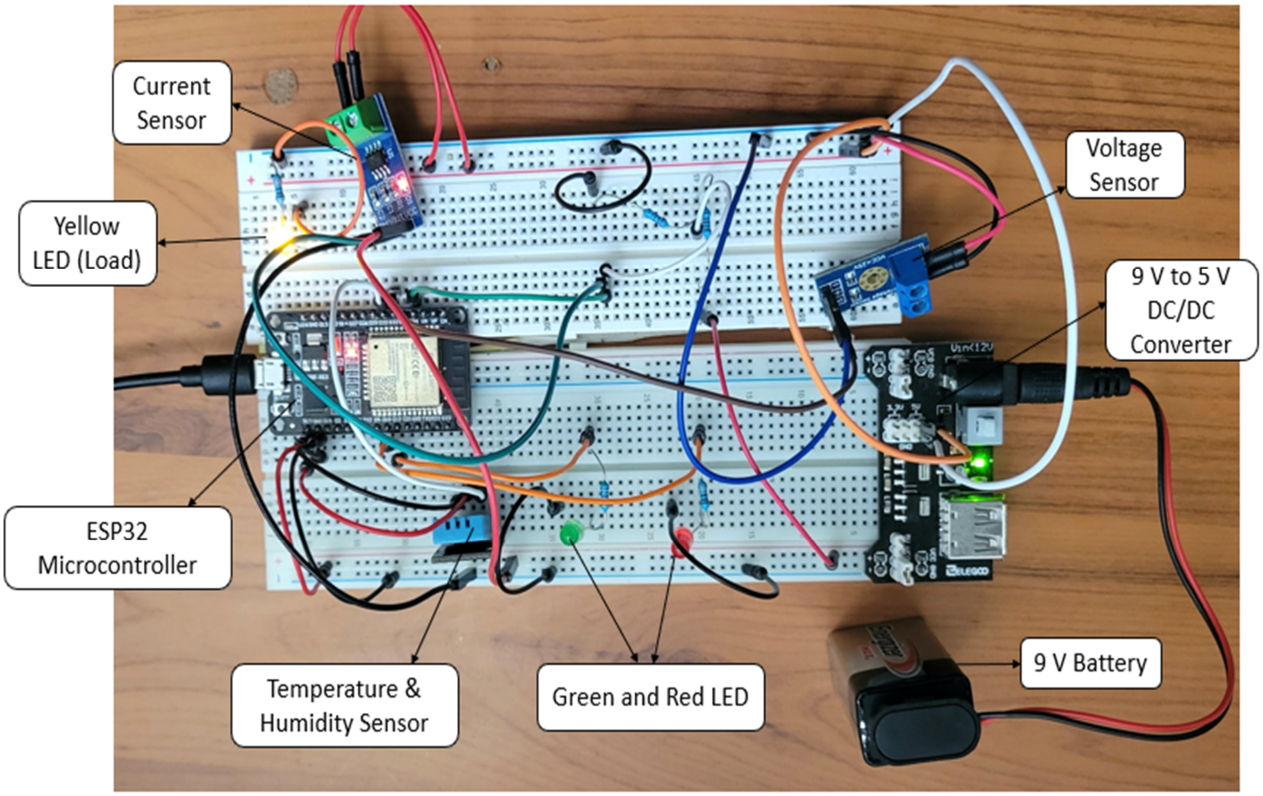

Figure 5. 6: Experimental circuit setup for the IoT SCADA system prototype.

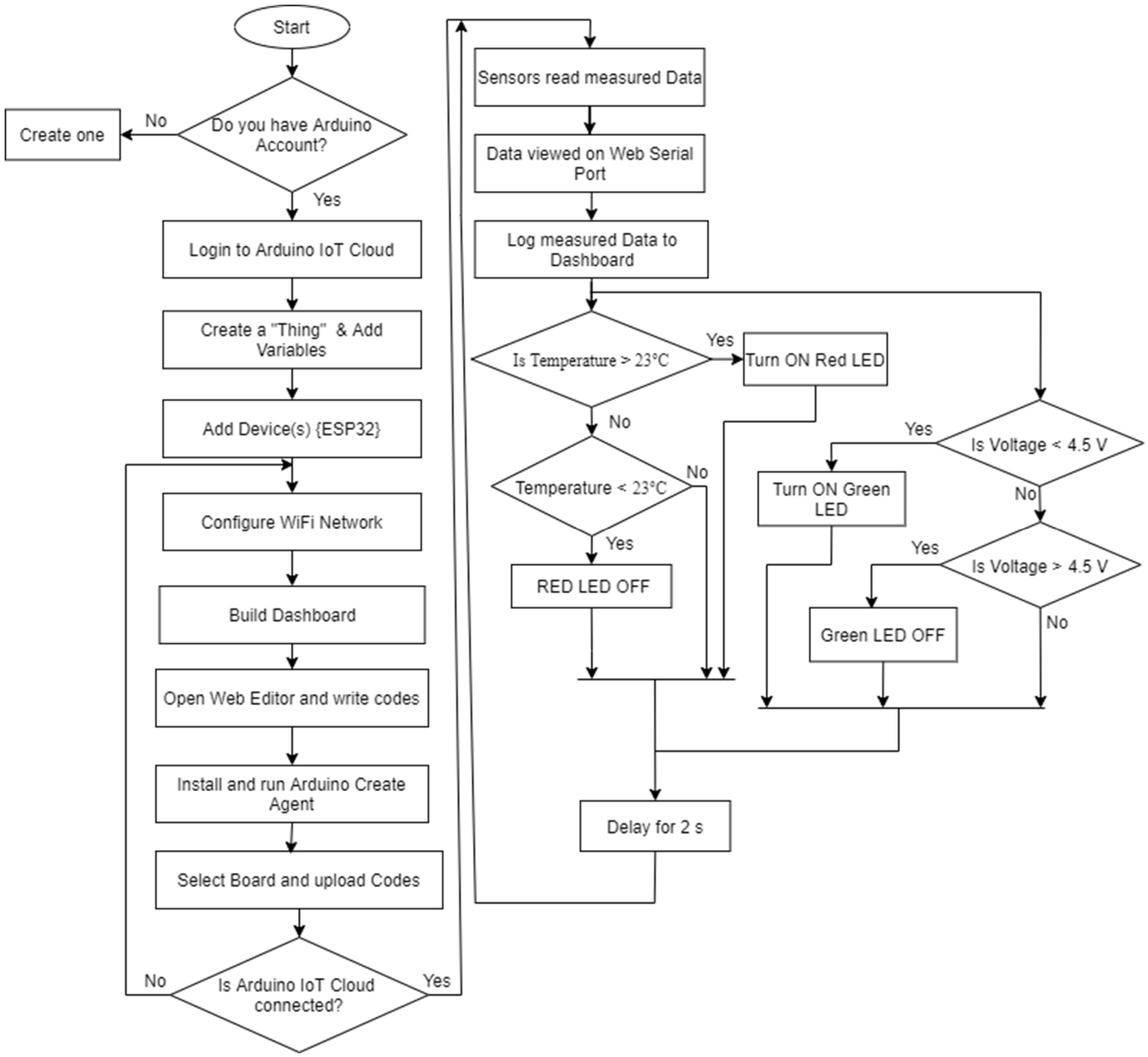

Figure 5. 7: Flowchart of the IoT SCADA system solution.

5.6 Testing and Results

The prototype circuit is shown above, and the current, voltage, temperature and humidity were logged every 2 seconds over a period using charts. Instantaneous temperature and humidity were also monitored using a gauge. Gauges are very conspicuous to see the instantaneous values being measured compared to tracing it on a chart. The current measured is that flowing through the load LED (Yellow), and the unit is in milliamp. The voltage measured is the output voltage of the

DC/DC converter in Volt. The temperature and humidity are that of the surrounding. Arduino IoT remote mobile application is also installed on my mobile phone where remote monitoring and control can also be carried out from anywhere around the world with the requirement of internet connection and access to the Arduino IoT account login details. The login details ensure only authorized persons have access to the system to monitor and execute any control action. Figure 5.8. shows the dashboard of the different parameters. The D represents the days, while H represents the hour. Live is the instantaneous value recorded by the sensors at the very time.

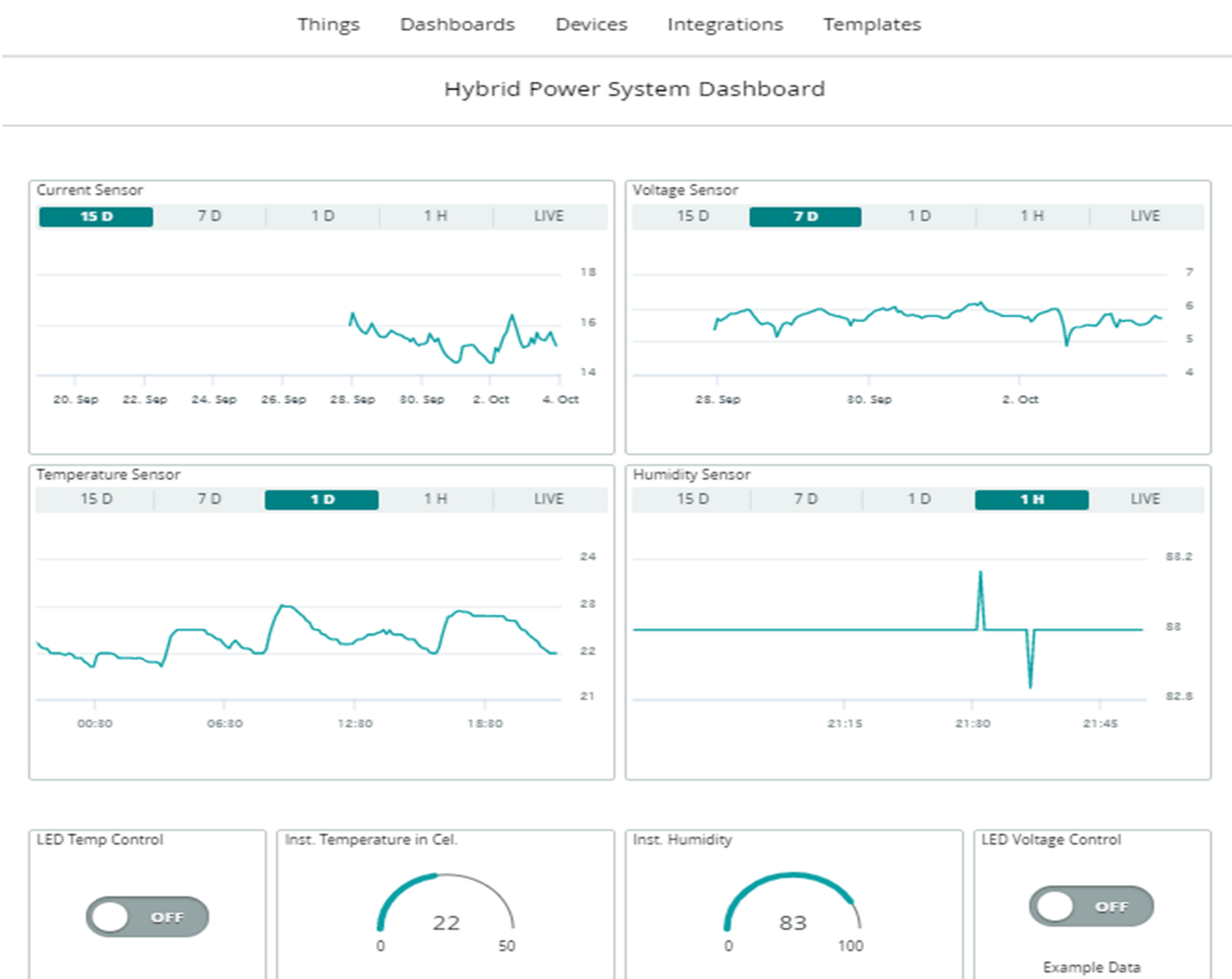

Figure 5. 8: Dashboard showing the measured parameters at different times.

The historical data stored depends on the Arduino plan chosen. The more expensive plans have a higher data storage capacity compared to the free plan and the less expensive plan.

To demonstrate the control capability of the system, the surrounding temperature is increased to 24°C. Once a higher temperature is recorded beyond our predefined value of 23°C, the red LED comes ON. The LED goes OFF once the temperature goes below the pre-set value. The voltage control can be carried out in the same manner as the temperature. When the voltage drops to 4.5 V, the green LED turns ON and stays ON until the voltage increases above the predefined value.

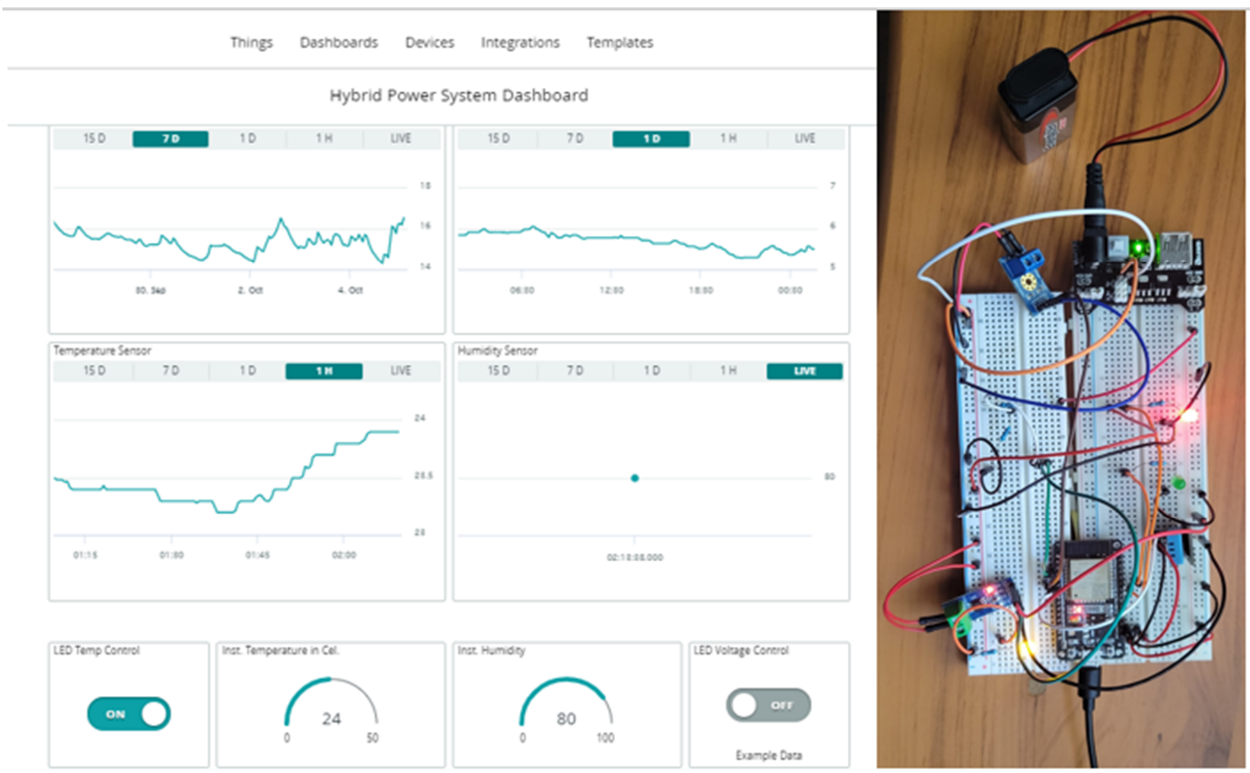

Figure 5. 9: Temperature control of the system.

5.7 Discussion

The system is based on the Internet of Things (IoT) configuration. The prototype acts as the plant/process while the sensors are the Field Instrument Devices (FIDs), the ESP32 microcontroller is the Remote Terminal Unit (RTU), Arduino IoT Cloud acts as the Master Terminal Unit (MTU) for creating the necessary Human Machine Interaction (HMI) while the communication channel is the Wi-Fi. The components used for the execution of this project are all low-cost, readily available, and open source. The cost of each component is summarized in table 5.1. In the field, a microcontroller with an option for SIM card like the Arduino MKR boards can be used to provide the necessary internet connection.

Table 5. 1: List of components and cost

S/N	Component(s)	Quantity	Price (USD)
1	ESP32 WROOM-32	1	13.85
2	9 V AC/DC power adapter	1	10.34
3	Breadboard Power Module	1	6.40
4	Current Sensor	1	4.76
5	Voltage Sensor	1	4.80
6	Temperature/Humidity Sensor	1	5.20
7	Arduino IoT Cloud plan (Entry) per month	N/A	2.99
8	Miscellaneous (Resistors, Breadboard, LEDs, wires, USB	N/A	40.00
	Total		**88.34 USD**

The dashboard provides the interface to monitor the measured Data both on the PC and mobile device(s). Supervisory control can also be carried out both on the PC dashboard or with the mobile device from anywhere with an internet connection and login details. This provides some form of security from unauthorized personnel.

5.8 Conclusion

The place of monitoring and control in a critical infrastructure like the base transceiver station cannot be over-emphasized. An IoT-based, open source SCADA system is proposed to remedy the limitations of the proprietary SCADA currently in operation. A prototype circuit was used to demonstrate this concept. Three (3) sensors were connected to read the analog values of current, voltage, temperature, and humidity. These data are sent over the Wi-Fi to the Arduino IoT Cloud for monitoring and control through the created dashboard. There is also a mobile application for remote monitoring from anywhere around the world. The cost, though being a prototype, is negligible compared to the proprietary option, and the power consumption is very low as well.

5.9 Future Work

The study has been conducted on a prototype circuit. In the future, the authors would like to demonstrate this system on a physical rural telecommunication site to determine the accuracy to which this system can monitor and control the sites' parameters and compare its cost to the proprietary SCADA in use. A database can be incorporated to read the data into a spreadsheet. Also, automatic email and text messages can be sent to relevant authorized personnel to be abreast of the events happening on the site.

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Chapter 6

Conclusions and Future Works

6.1 Conclusion

Energy cost accounts for 10-15% of the operating cost of a base transceiver station. The energy demand of the telecommunication industry is between 2-3% of the global total energy demand. Associated with this is the cost, which has consistently been on the rise the world over. For a developing country like Nigeria with an unstable grid power supply, this cost continues to increase exponentially. With the increase in the cost of fuel, haulage, maintenance cost, and in rural areas, lack of access roads, there is no cost reduction in sight if a drastic measure to address the nature of the power supply is not made. The introduction of the 5G network into the market will further increase the cost of energy for these sites.

The new 5G services are currently being tested in Nigeria and are expected to bring an enormous energy burden because of the exponential increase in traffic associated with the 5G standard. Although the 5G radios are more efficient per gigabyte than the 4G standards currently in use, the anticipated 5G standard would utilize a new spectrum band with a shorter penetrating distance. With many mobile sites, the energy efficiencies associated with the 5G radios are outweighed. According to industry estimates, each 5G site will require two to three times the power of a 4G-equivalent site. 5G network services are delivered at the edge; hence, data centres will increase accordingly. This will also result in a significant increase in the energy consumption associated with mobile services.

Relying on a generator set to supply these sites, as is currently the case, increases the operational cost and the carbon footprint with a devastating environmental effect. Attracting investors to the sector could also be challenging as most investors will not want to invest in the current state to portray a good environmentally friendly reputation. These were the concerns that necessitated this study.

A rural site in the North Central state of Kogi in Nigeria was used as a case study. This site is typical of all rural BTS sites in the country. It is an outdoor site with a 13 kVA diesel generator running on the site. This generator is only shut down during planned maintenance. About 2,500 litres of diesel is burnt on the site monthly. The logged load data on the site for a year was obtained and used for sizing a hybrid power system on HOMER pro to replace the existing diesel genset. With the data, we could guarantee the accuracy of the proposed system designed especially sizing.

One of the key features identified by this study is that the current diesel generator is oversized. This is the case for other rural sites as well and running gensets at low load results in poor cylinder compression, low efficiency, high soot generation due to the presence of unburnt fuel, and this result in the overall increase in the maintenance cost and lower service life of the gensets.

From the measured load data, the power consumed was 2.4 kW at peak periods for the site. This load was measured every 15 minutes for the entire year with 35,064 data points generated. This was fed into HOMER pro for the system sizing. The optimized system was a 15 kW PV array, 3.6 kW DC diesel generator, and 24 units of 12 V, 190 Ah backup battery. A DC diesel generator was considered to reduce the conversion losses associated with the conventional generators since the site is an outdoor site with no need for air conditioning. Studies have also shown that a DC generators have a higher fuel efficiency than conventional gensets. The cost of this proposed system is 75% less than what is currently being spent within the same period in consideration with

89.4% renewable component resulting in better environmental impact as the diesel generator only utilizes 745 litres of diesel per year.

The dynamic behaviour of the system was also studied at varying solar irradiance. The different components showed an appropriate response from the MPPT extracting maximum power at the specified point to dc-dc buck converter stepping down the power to the required 48 V. A control algorithm was embedded in the design based on the state of charge (SOC) of the battery. The generator kicks in to maintain a stable voltage when the renewable source and backup battery cannot meet the load requirement.

The Supervisory Control and Data Acquisition System (SCADA) in the field is currently proprietary, with the associated procurement and maintenance cost. With the proposed Hybrid System, the need for an effective, low-cost open source SCADA system was studied here, and the result, howbeit on a prototype system, showed a satisfactory response both for data acquisition and supervisory control. Remote control is also possible using a mobile application, and the system uses the fourth generation IoT-based SCADA architecture using ESP32 and Arduino IoT Cloud.

The research contributions of this study can be summarized as follows:

- Accurate sizing of the hybrid system based on actual field data.
- Cost comparison between existing system and the proposed DC hybrid system.
- Dynamic modeling and simulation of the system to study the transient behaviour.
- Implementing a low-cost IoT-based SCADA system for the designed hybrid system.

6.2 Future Work

The study presented in this thesis opens new frontiers in designing and controlling a Hybrid Power System for rural base transceiver stations in rural parts of Nigeria and sub-Saharan West Africa, where power supply is still a challenge. Based on this study's knowledge gaps, there are several recommendations, and the scope can be further explored. These are listed below:

- This study was done based on actual load data measurement from the site. Having this implemented on the site to study the actual dynamics of the system will be a priority.
- The backup battery can be upgraded from the lead-acid battery to a lithium-ion battery to improve the discharge rate for which lead-acid ideally cannot be discharged above 0.1C.
- Designing a solar/wind/diesel/fuel cell system with a more renewable penetration for the site
- Carry out similar studies for other locations and compare all the parameters to conclude what can be adopted as the standard for a rural telecommunication site in Nigeria.
- Accurately compare the carbon emission of this studied system with the current one on site.
- Incorporate Email and text messages to the IoT platform when any supervisory control is carried out anywhere in the world.
- Investigate the integration of low power systems like LoRa to replace the Wi-Fi used as a communication channel for the IoT SCADA.

6.3 List of Publications

1. C. Oton and M. T. Iqbal, "Design and Analysis of a Stand-alone DC Hybrid Microgrid for a Rural Base Transceiver Station in Nigeria," *2020 IEEE Electric Power and Energy Conference (EPEC), 2020*, pp. 1-6, doi: 10.1109/EPEC48502.2020.9320006.

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