Design And Simulation Of A Microgrid System For A University Campus In Nigeria

by

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Abstract

The thesis presents the design and simulation of a microgrid system for a university community in Nigeria. Firstly, the system sizing and design was done in Homer Pro software where the microgrid system obtained consist of the grid system, 3,726 solar panel of 0.5kW, diesel generator of 1.5MVA and inverter of 500kW installed in an area of 17,696m2 at a cost of ₦295 with a simple payback of 3 years and 5 months at a reduced cost of electricity bill by 88.0% and a reduce CO_2 emissions. Due to the high PV size of 1,863kW required by this design, other software such as OpenSolar, PVWatt and REopt was used to design the same system to optimise the PV size. The resulting system design consist of a PV size of 675.2 kW comprising of 96 cell modules each of 500W, with 25 connected in series and 54 in parallel. Also, a utility grid system and a diesel generator set in case of emergency. The system was then simulated in MATLAB/Simulink environment to determine the dynamics of the university microgrid system. Simulated results indicate that the system has acceptable dynamics with changes in the electric load, but the dynamic simulation was extremely slow. To solve these challenges, the reduced order model of the microgrid system was design in MATLAB/Simulink environment to speed up the simulation time. Simulated results indicates that the reduced order model obtained is more than 4 times faster than the original microgrid system of the campus community. Lastly, the monitoring system of the campus microgrid system was designed. Analysis shows that to monitor the dc part of the network, 54 number dc current sensor and a dc voltage sensor would be required and for

the ac portion, 9 number ac current sensor and 6 number ac voltage sensor would be required. These sensors are connected to a data logger that is directly connected to a computer system with internet for remote monitoring and control of the microgrid system. Complete details of system design, sizing, dynamic simulation, reduced order model and monitoring are presented and explained in this thesis.

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List of Abbreviation and Symbols

A	Ampere
AC	Alternating Current
AFFSMC	Adaptive Fractional Fuzzy Sliding Mode Control
Ah	Ampere Hour
BESS	Battery Energy Shortage System
CHP	Combine Heat and Power
COE	Cost of Energy
CS	Capacity Shortage
CT	Current Transformer
DC	Direct Current
DER	Distributed Energy Sources
DG	Distributed Generators
ECN	Electricity Cooperation of Nigeria
EDSU	Edo State University
EMS	Energy Management System
EMU	Energy Monitoring System

FC	Fuel Cell
GA	Genetic Algorithm
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
GPSRA	Electric Power Sector Reform Act
GRNN	General Regression Neutral Network
GS	Grid Sales
GTD	Generation Transmission and Distribution
HOMER	Hybrid Optimization of Multiple Energy Resources
HRES	Hybrid Renewable Energy System
Hz	Hertz
IIDG	Inverter Interfaced Distributed Generators
kV	Kilo Volt
kVA	Kilo Volt Ampere
kW	Kilo Watt
kW	Kilo Watt
kWh	Kilo Watt Hour

LECO	Levelized Cost of Energy
LV	Low Voltage
MG	Microgrid
MPPT	Maximum Power Point Tracking
MTG	Microturbine generating system
MVA	Mega Volt Ampere
MW	Mega Watt
MWh	Mega Watt Hour
NDA	Niger Dam Authority
NELMCO	National Electricity Liability Management Company
NEPA	National Electric Power Authority
NERC	Nigerian Electricity Regulatory Commission
NG	Natural Gas
NPC	Net Present Cost
PCC	Point of Common Coupling
PCS	Power Conditioning System
PHCN	Power Holding Company Of Nigeria

PIC	Pacific Island Country
PMG	Polygeneration Microgrid
PMS	Power Management Strategy
PQ	Power Quality
PSO	Particle Swarm Optimization
PV	Photovoltaic
PVDPS	Photovoltaic Diesel Power System
RBFNSM	Radial Basis Function Network Sliding Mode
RES	Renewable Energy Sources
SC	Super Capacitor
SEAPI	Sustainable Energy Industry Association of Pacific Island
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
SVC	Static Var Compensator
T & D	Transmission and Distribution
TNPC	Total Net Present Cost
UPS	Uninterrupted Power Supply

V	Volt
VSI	Voltage Source Inverter
W	Watt
WHR	Waste Heat Recovery

Chapter 1

Introduction and Literature Review

1.1. Introduction

Microgrid are decentralized group of electricity sources and loads that normally operates, connected to and synchronous with the traditional wide area synchronous grid (microgrid), but can disconnect from the interconnected grid and function autonomously in "island mode" as technical or economic conditions dictate. A microgrid has self-sufficient energy system that serves a discrete geographic footprint, such as a business centre, or neighbourhood, college campus and hospital complex.

The United States Department of Energy Microgrid Exchange Group defines a microgrid as a group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both connected or island-mode. An EU research project describes a microgrid as comprising Low-Voltage (LV) distribution systems with distributed energy resources (DERs) (microturbines, fuel cells, photovoltaics (PV), etc.), storage devices (batteries, flywheels) energy storage system and flexible loads. Such systems can operate either connected or disconnected from the main grid. The operation of micro sources in the network can provide benefits to the overall system performance, if managed and coordinated efficiently.

Electropedia defines a microgrid as a group of interconnected loads and distributed energy resources with defined electrical boundaries, which form a local electric power system at distribution voltage levels, meaning both low and medium voltage up to 35 kV. This cluster of associated consumer and producer nodes acts as a single controllable entity and can operate in either grid-connected or island mode.

1.2. Microgrid based on characteristics

Microgrid can also be defined based on their characteristics as follows:

1.2.1. A microgrid is local

This is a form of local energy generated and supplied to nearby customers. This distinguishes microgrids from the kind of large, centralized grids that have provided most of our electricity for the last century. Central grids push electricity from power plants over long distances via transmission and distribution lines. Delivering power from afar is inefficient because some of the electricity – as much as eight to fifteen percent – dissipates in transit. A microgrid overcomes this inefficiency by generating power close to those it serves; the generators are near or within the building, or in the case of solar panels, on the roof.

1.2.2. A microgrid is independent

Microgrid can disconnect from the central grid and operate independently. This islanding capability allows them to supply power to their customers when a storm or other calamity causes an outage on the power grid. In the US, the central grid is especially prone to outages because of its sheer size and interconnectedness – more than 5.7 million miles of transmission and distribution lines. As we learned painfully during what's known as the Northeast Blackout of 2003, a single tree falling on a power line can knock out power in several states, even across international boundaries into Canada. By islanding, a microgrid escapes such cascading grid failures. While microgrids can run independently, most of the time they do not (unless they are in a remote area where there is no central grid or an unreliable one). Instead, microgrids typically remain connected to the central grid. If the central grid is operating normally, the two function in a kind of symbiotic relationship.

1.2.3. A microgrid is intelligent

Microgrid especially advanced systems are intelligent. This intelligence emanates from what's known as the microgrid controller, the central brain of the system, which manages the generators, batteries, and nearby building energy systems with a high degree of sophistication. The controller orchestrates multiple resources to meet the energy goals established by the microgrid's customers. They may be trying to achieve lowest prices, cleanest energy, greatest electric reliability, or some other outcome. The controller achieves these goals by increasing or decreasing use of any of the microgrid's resources –

or combinations of those resources. A software-based system, the controller can manage energy supply in many ways. But here's one example. An advanced controller can track real-time changes in the power prices on the central grid. (Wholesale electricity prices fluctuate constantly based on electricity supply and demand.) If energy prices are inexpensive at any point, it may choose to buy power from the central grid to serve its customers, rather than use energy from, say, its own solar panels. The microgrid's solar panels could instead charge its battery systems. Later in the day, when grid power becomes expensive, the microgrid may discharge its batteries rather than use grid power.

Microgrids are one or more kinds of distributed energy (solar panels, wind turbines, combined heat & power, generators) that produce its power. Interconnected to nearby buildings, the microgrid provides electricity and possibly heat and cooling for its customers, delivered via sophisticated software and control systems. In addition, many newer microgrids contain energy storage, typically from batteries. Some also now have electric vehicle charging stations. Microgrids have been around for decades, but until recently were used largely by college campuses and the military. So, the total number of microgrids is relatively small but growing. The pace of installation has picked up and is expected to grow dramatically as distributed energy prices drop and worries heighten about electric reliability, due to severe storms, cyberattacks and other threats.

1.3. Types of microgrids

Three types of microgrids exist: remote, grid-connected, and networked microgrid.

1.3.1. Remote Microgrids

These refers to the off grid-microgrids which are physically isolated from the utility grid and always operate in island mode due to the lack of available and affordable transmission or distribution (T&D) infrastructure nearby. Renewables, such as wind and solar, typically provide a more economic and environmentally sustainable distributed energy resources (DER) solution for these microgrid to operator. Additionally, many remote microgrids are considering battery energy storage systems for backup power in lieu of conventional generators.

1.3.2. Grid-connected Microgrids

These microgrids have a physical connection to the utility grid through a switching mechanism at the point of common coupling (PCC), but they also can disconnect into island mode and reconnect back to the main grid as required. In this case, the microgrid is effectively integrated with the utility service provider to provide grid services (e.g., frequency and voltage regulation, real and reactive power support, demand response, etc.) to help address potential capacity, power quality and reliability and voltage issues on the utility grid. In islanded mode, local voltage and frequency controls are required within the microgrid and can be provided by energy storage (e.g., battery, flywheel) or a synchronous generator (e.g., natural gas, fuel cell diesel). Due to its ability to perform multiple functions for grid services and emergency backup power, battery energy storage systems have been gaining popularity for microgrids that need to operate in both grid-connected and island modes. When serving a relatively small geographic area, grid-connected microgrids demonstrate economic viability for educational campuses, medical complexes, public safety, military bases, agricultural farms, commercial buildings, and industrial facilities.

1.3.3. Networked Microgrids

These type of microgrids consist of several separate distributed energy resources (DERs) and/or microgrids connected to the same utility grid circuit segment and serve a wide geographic area. Networked microgrids are typically managed and optimized by a supervisory control system to operate and coordinate each grid-connected or island mode at different tiers of hierarchy along the utility grid circuit segment. Community microgrids, smart cities and new utility adaptive protection schemes (e.g., closed-loop self-healing) are examples of networked microgrids.

1.4. Topologies of microgrids

Architectures are needed to manage the flow of energy from different types of sources into the electrical grid. Thus, the microgrid can be classified into three topologies:

1.4.1. AC microgrid

Power sources with AC output are interfaced to AC bus through AC/AC converter which will transform the AC variable frequency and voltage to AC waveform with another frequency at another voltage. Whilst power sources with DC output use DC/AC converters for the connection to the AC bus.

1.4.2. DC microgrid

In DC microgrid topology, power sources with DC output are connected to DC bus directly or by DC/DC converters. On the other hand, power sources with AC output are connected to the DC bus through AC/DC converter.

1.4.3. Hybrid microgrid

The hybrid microgrid has topology for both power source AC and DC output. In addition, AC and DC buses are connected to each other through a bidirectional converter, allowing power to flow in both directions between the two buses.

1.5. Basic components in microgrids

1.5.1. Local generation

Microgrid have various types of generation sources that feed electricity, heating, and cooling to the user. These sources are divided into two major groups – thermal energy sources (e.g., natural gas or biogas generators or micro combined heat and power) and renewable generation sources (e.g., wind turbines and solar).

1.5.2. Consumption/Load

In a microgrid, consumption simply refers to elements that consume electricity, heat, and cooling, which range from single devices to the lighting and heating systems of buildings, commercial centres, etc. In the case of controllable loads, electricity consumption can be modified according to the demands of the network.

1.5.3. Energy storage

In microgrid, energy storage can perform multiple functions, such as ensuring power quality, including frequency and voltage regulation, smoothing the output of renewable energy sources, providing backup power for the system, and playing a crucial role in cost optimization. It includes all chemical, electrical, pressure, gravitational, flywheel, and heat storage technologies. When multiple energy storages with various capacities are available in a microgrid, it is preferred to coordinate their charging and discharging such that a smaller energy storage does not discharge faster than those with larger capacities. Likewise, it is preferred a smaller one does not get fully charged before those with larger capacities. This can be achieved under a coordinated control of energy storages based on their state of charge.

1.5.4. Switchgears, inverters, and other equipment

Finally, microgrids include other critical components such as electrical cables, circuit breakers, transformers and more. These components are the bones, muscles, and blood vessels of a microgrid. They connect generation resources to consumers and allow the microgrid's control system to effect changes to the state of the microgrid.

1.6. Point of common coupling (PCC)

This is the point in the electric circuit where a microgrid is connected to a main grid. Microgrids that do not have a PCC are called isolated microgrids which are usually present in remote sites (e.g., remote communities or remote industrial sites) where an interconnection with the main grid is not feasible due to either technical or economic constraints.

1.7. Literature Review

In this thesis, focus is on some reported works done in the field, assumptions, presumptions, and their resolutions.

1.7.1. Renewable energy system

Kotb, K. M. et al. (2020), currently stated that the global gives a unique awareness of sustainable development by exploiting renewables to provide the people with affordable and clean energy and preserve the climate. Their paper proposes a methodical and explicit framework of four phases, to design an autonomous hybrid renewable energy system in a community area in Egypt: preliminarily assessment, design optimization analysis, findings evaluation, and power-quality assessment. In the first three phases which was performed by HOMER Pro software, five hybridization scenarios were evaluated and compared regarding their life-cycle cost, carbon outflows, and reliability to distinguish the extraordinary scenario to supply the addressed community area. Contrary to most studies that suffice only the first three phases, the fourth phase is proposed to perform a power-quality valuation based on a power management strategy (PMS). The results reveal that the optimal configuration consists of a photovoltaic generator, wind-driven generator, diesel-genset, battery-bank, and a power converter as shown in Figure 1.1 with the minimum net present cost of 351,223 $ and energy cost of 0.2262 $/kWh among all configurations. The optimal system has a negligible capacity shortage of

0.0955% and produces the least number of emitted gases by 50.43 tones/year due to the high renewable fraction (57%). Moreover, the optimal proposed system can recover the invested money after only 3.4 years [1].

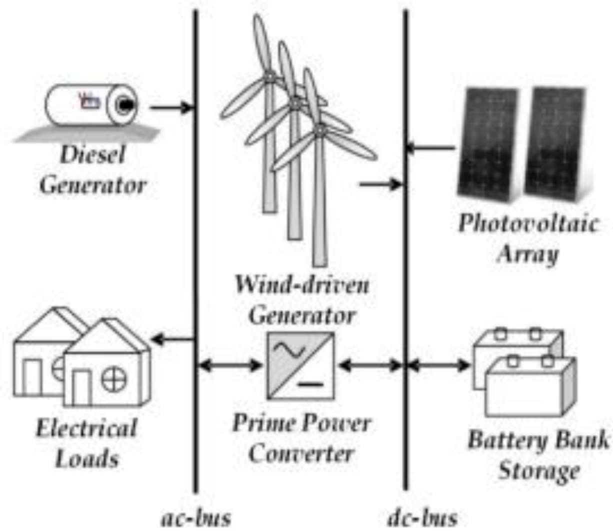

Fig. 1.1: Microgrid hybrid power system with renewable sources and a diesel generator

Ryan G, and Longe O. M. (2020), stated that the increasing demand for electricity and the inability of the current generation systems to meet the demand, urges for more renewable electrical energy systems in South Africa. The Rand West Municipality was a community that has a slow-paced rural electrification and was subject to multiple power cuts weekly thereby affecting the households, farms, and businesses in the area. It was therefore taken as a case study for the investigation of a Renewable Energy Sources (RES) microgrid. Simulation, optimization, and sensitivity analyses were conducted to determine the feasibility and optimal RES mix for the location using the Hybrid Optimization Model for Electric Renewable (HOMER) software. The simulations yielded an optimal microgrid system consisting of a combination of Solar Photovoltaic (PV) panels, Solar Concentrated Photovoltaic system, Battery Energy Storage System, and a Diesel Generator with a Cost of Energy (COE) of $0.068/kWh, compared to the grid COE of $0.12/kWh for this area [2].

Ahmad, Furkan, and Mohammad Saad Alam (2018), present details of governmental initiatives in terms of acts, policies, mission, scheme & incentives since 2000, worldwide investment in the Indian power sector to promote the Renewable Energy Sources (RESs) and the feasibility of solar and wind-based electrical energy throughout Indian terrestrial. This work further presents a comprehensive framework for the deployment of microgrids in the Indian scenario. To validate the presented framework, 9 microgrid at different locations were considered deploying Homer as simulating and optimizing tool by incorporating environmental constraint and grid availability parameter [3].

Ishraque M. F. et al. (2021), stated in their research paper that system design and performance evaluation were conducted on a solar battery-based hybrid renewable energy system (HRES) with diesel backup for a school in a remote area located in the northern part of the country, where conventional power grid connectivity was not available. From field survey, a load demand of 10.468 kWh/day for a normal working day and a peak demand of 3.3 kW were considered in their work for the proposed site. For simulation purpose hybrid optimization model for electric renewable, very well-known software was used. The solar radiation data required for the work were collected from NASA Surface meteorology and Solar Energy database. Analysing the load requirements and metrological data a solar-battery diesel generator-based HRES was proposed for the school. From the analysis and simulation, the Net Present Cost (NPC) for the proposed system was found USD 6191 with a Cost of Energy (COE) of $0.125/kWh. Further, a comparative study was done, and the proposed system can reduce the COE and Green House Gas (GHG) emission of about 29.85% and 69% respectively than the conventional power plants [4].

Evbogbai M. J. E. and Ogbikaya S. (2019), in their work stated that the solar energy is available for everybody, hence if harnessed, can sustain the electrical energy need for meaningful development in Nigeria. Although the initial cost implication may be high, but on the long run, it is more economical because of its renewable nature, less maintenance cost, and its environmental friendliness. Hence, for sustainable development to take place in Nigeria, the government, corporate bodies, and individuals should focus on photovoltaic power generation as one of the most viable options that could drive the civilization for ever [5].

1.7.2. Hybrid power system

Majdi Nasab, N. et al. (2021), this paper evaluates the feasibility of using a hybrid system consisting of wind and tidal turbines connected to a microgrid for power supply to coastal communities that are isolated from a main supply grid. The case study was Stewart Island, where the cost of electricity, provided by a central diesel power station, was higher than the grid network in New Zealand. Local residents believe that reducing the consumption of diesel and having a renewable source of electricity generation were two of the island’s highest priorities. In their findings, merging a tidal energy source (predictable) with wind (unpredictable) and diesel (back-up), through a microgrid, may be a way to increase reliability and decrease the cost of generation. Several off-grid configurations were simulated using HOMER and WRPLOT software. Using two wind and four tidal turbines, plus one diesel generator for back-up, was the best design in terms of lower greenhouse gas emissions, higher renewable fraction, and reduced net present cost [6].

Dash R. L. et al (2018), presents an economical expediency of grid connected hybrid (PV/Wind turbine) power system for remote village in Khurdha District, Odisha (20.1301°N,85.4788° E) in India. Their work was an approach towards the betterment of rural areas providing a cleaner ecofriendly environment by using renewable energy resources to meet the load requirements. Analysis was carried out by investigating the potentials of wind and solar energy and collecting data from different sources. Hybrid Optimization Model for Electric Renewable (HOMER) Pro software was used to analyse the available data and economic feasibility of the proposed hybrid power system. In this research, two types of models named off-grid and on grid were designed and optimized for comparison purposes. Also, sensitivity analysis was performed for each model to determine the effect of variations in grid energy cost on its total cost. Their simulation results indicate that the proposed grid connected hybrid (PV/Wind turbine) power system was most suitable and cost competitive for the mentioned region [7].

Arribas L. et al (2021), stated that during the last decades, there has been great interest in the research community with respect to PV-Wind systems, but figures show that, in practice, only PV-Diesel Power Systems (PVDPS) were being implemented.

There were some barriers for the inclusion of wind generation in hybrid microgrids and some of them were economic barriers while others were technical barriers. Their work focused on some of the identified technical barriers and presents a methodology to facilitate the inclusion of wind generation system in the design process in an affordable manner. An example of the application of this methodology and its results was shown through a case study. The case study was an existing PVDPS where there was an interest to incorporate wind generation to cope with a foreseen increase in the demand [8].

Ahmad, Jameel, et al (2018), focuses on the techno-economic feasibility of a grid-tied hybrid microgrid system for local inhabitants of Kallar Kahar near Chakwal city of Punjab province in Pakistan and investigates the potential for electricity generation through hybrid wind, photovoltaic and biomass system. The comprehensive resource assessment of wind, biomass and solar energy was carried out for grid integration. Homer Pro software was used to model a hybrid microgrid system. Optimization results and sensitivity analysis was carried out to ensure the robustness and cost-effectiveness of the proposed hybrid microgrid system. The total load was optimally shared among generated power through wind, photovoltaic and biomass resources and surplus power was supplied to the national grid in case of low local demand of the load. Their research results of techno-economic feasibility study show that hybrid power system can generate more than 50MW. The cost of energy based on peak load demand profiles were considered for both residential and commercial sectors. The cost of hybrid system for peak load of 73.6MW was 180.2 million USD and levelized cost of energy was 0.05744 $/kWh [9].

Brunaccini, G., et al (2019), in their work, a combined approach with Fuel Cell (FC) and Fuzzy Logic (FL) was investigated to determine a good compromise between equipment installation, control logic, and availability of the service (downtime probability), even accounting for weather forecast, energy price and storage system exploitation (depth of discharge). In their simulation, a landline station located in Italy is analysed by simulating different functions and power equipment to assess the benefits achievable. Their research also reveals that despite reaching a revenue from the electrical energy exchange through the grid, the actual economic balance of the system was affected by the natural gas cost. For this reason, the correct cost evaluation suggests implementing such hybrid scheme with a single FC generator powering different ICT stations in a circumscribed area; this allows increasing the natural gas conversion efficiency, reducing the initial investment cost to acquire the generator, and reducing the tariff (as per big users) of natural gas supply. Lastly, modifying the battery control logic in a UPS function with fuzzy control, allowed a further reduction of the battery capacity (from 7 kWh down to 3.8 kWh), with only slightly reduction of the energy revenue due to the reduced promptness of the system to exploit time slots with low energy price to purchase energy from grid [10].

1.7.3. Micro-Grid Technology

Srinivasa Murthy, S., et al (2020), analysis a stand-alone Polygeneration Microgrids (PMG), which caters for electrical, thermal and hydrogen loads. The stand-alone PMG consisting of solar PV field, FC, solid state hydrogen storage and electrolyzer was modelled using commercial software HOMER. An hourly simulation was conducted to analyse its annual performance. A case study was carried out for a typical Indian village of about 50 households needing electrical energy of 100 kWh/day. It was found that, for the given load profile having 7.69 kW peak power demand and 100 kWh/day of electricity requirement, a PV system size of about 45 kW was needed to meet the load demand during daytime and for production of hydrogen for the fuel cell. The optimized component sizes of the microgrid are PV – 45 kW, Electrolyzer – 25 kW, FC – 8 kW, AC/DC Converter – 8 kW and Hydrogen Storage – 5 kg. Significant thermal output at about 60 °C was an added benefit [11].

Prakash S. S. et al. (2017), a methodology of designing a localized hybrid Microgrid for a rural area in the Pacific Island Countries (PICs) was presented in their paper. Nasau village was the chosen location for this design since necessary information of the village was provided by a local renewable energy sources (RES) installer. Typical loads found in rural villages were used to estimate the energy demand. This was accomplished using the bottom-up modelling strategy. Energy demand was then classified into three categories: typical village household, typical residential and commercial shop. Total energy demand of the village was then estimated from the product of each classification with respective quantities present in the village. This estimated energy in conjunction with input parameters were used in HOMER for the final simulation. The system configuration satisfies the design parameters and Sustainable Energy Industry Association of the Pacific Island (SEAPI) guidelines. It was observed that the proposed microgrid design was feasible after comparing the supply behaviour of the sources (PV, Battery Energy Storage System (BESS) and diesel generator) with the load profile [12].

Ramazan B. et al (2014), present an overall description and typical distributed generation technology of a microgrid. It also adds a comprehensive study on energy storage devices, microgrid loads, interfaced distributed energy resources (DER), power electronic interface modules and the interconnection of multiple microgrids. Details of stability, control and communication strategies were also provided in their study. This article describes the existing control techniques of microgrids that were installed all over the world and has tabulated the comparison of various control methods with pros and cons. Moreover, it aids the researcher in envisioning an actual situation using a microgrid today and provides insight into the possible evolvement of future grids. In conclusion, the study emphasizes the remarkable findings and potential research areas that could enrich future microgrid facilities [13].

Yuqi Wang (2018) summarized the origin, development and characteristics of microgrid technology in his paper. This paper introduces the protection technology and control technology in the microgrid technology. His analysis reveals that the protection technology of microgrid is different from the traditional large power grid protection technology. As for microgrid protection, the followings need to be considered: the direction of the power flow in the microgrid is bidirectional and the magnitude of short-circuit current is quite different in the two cases of grid connected operation and island operation [14].

Sedaghati, R. & Shakarami, M. R. (2019), proposes a new control and power management strategy for a grid-connected microgrid, which includes a hybrid renewable energy sources (HRES) system and a three-phase load. The HRES system consists of a PV, a battery storage system (BSS), a super-capacitor (SC) and a solid oxide fuel cell (SOFC). The dynamic model of each of these units was described. The PV is the main energy source, while the SC and the BSS due to their various power densities are considered to provide a steady and transient load demand, respectively. For increasing the reliability of the system, SOFC source was selected to keep the BSS completely charged. All these units with different DC-DC converters are connected in parallel to a common DC bus. Then, a three-phase voltage source inverter (VSI) is employed to convert the DC voltage to AC. To maintain the power balance and appropriate load-sharing, an adaptive fractional fuzzy sliding mode control (AFFSMC) strategy for VSI-based HRES system was presented. The controller can track the pre-defined instruction precisely and quickly in the microgrid. For stable performance of the control strategy under load variation, a fractional order-based sliding surface was considered. Moreover, fractional adaptive rules-based fuzzy sets were employed to accurately estimate the uncertain parameters in the microgrid. The simulation results demonstrate the effectiveness and capability of an AFFSMC strategy under various faults and different loading conditions [15].

Wang, Yongli et al. (2018), in their work, an intelligent park micro-grid consisting of photovoltaic power generation, combined cooling heating and power system, energy storage system and response load was modeled to study the optimal scheduling strategy of these units by considering the price-based demand response. To achieve their goal, an optimization model for the economic operation of micro-grid was established, and the model presented mainly aims to minimize the operating cost of micro grid system and make full use of clean energy under the premise of considering distributed power generation and demand response. This operation optimization problem was solved by the Genetic Algorithm (GA) and the best solution on the best operating strategy was determined by the clean energy resources and demand response program. Finally, a micro-grid project in China was used to carry out optimization simulation to verify the accuracy and reliability of the established model. It was found that the operation optimization model of micro-grid with demand response can effectively reduce the operation cost of and improve the utilization rate of renewable energy sources [16].

Ou, Ting-Chia, and Chih-Ming Hong (2014), this paper examines the dynamic operation and control strategies for a microgrid hybrid wind-PV-FC based power supply system. The system consists of the PV power, wind power, FC power, SVC (static var compensator) and an intelligent power controller. A simulation model for this hybrid energy system was developed using MATLAB/Simulink. An SVC was used to supply reactive power and regulate the voltage of the hybrid system. A GRNN (General Regression Neural Network) with an Improved PSO (Particle Swarm Optimization) algorithm, which has a non-linear characteristic, was applied to analyse the performance of the PV generation system. A high-performance on-line training RBFNSM (radial basis function network-sliding mode) algorithm was designed to derive the optimal turbine speed to extract maximum power from the wind. A fast and stable response for real power control was achieved by the intelligent controller which consists of an RBFNSM and a GRNN for MPPT (maximum power point tracking) control [17].

Nsengimana, C. et al. (2020), studies focused on the economic power generation model mainly based on solar resources to minimize the electricity cost and provide income for the excess energy produced. This study covers on-grid power system with PV, battery and converter shown in Figure 1.2, off-grid power system with generator, PV, battery and converter shown in Figure 1.3 and off-grid power system with PV, battery and converter shown in Figure 1.4.

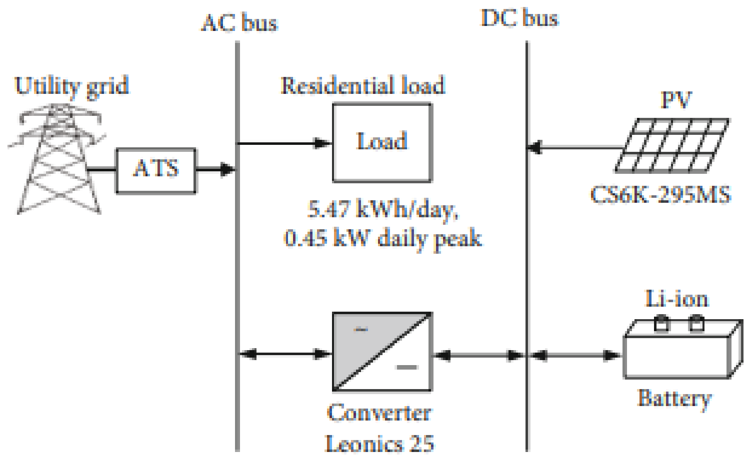

Fig. 1.2: On-grid power system with PV, battery and converter

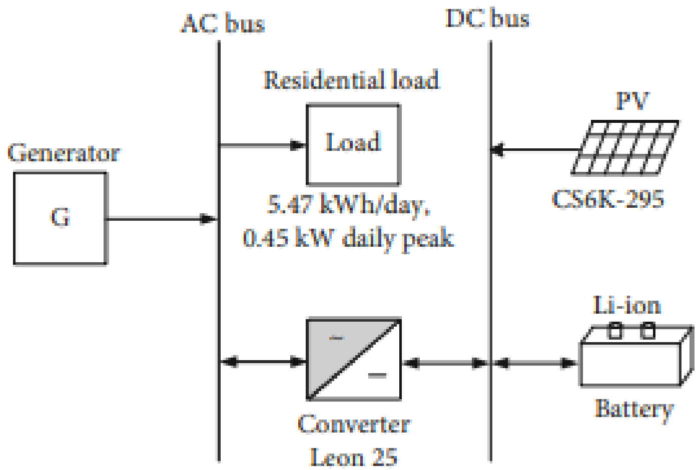

Fig. 1.3: Off-grid power system with generator, PV, battery and converter

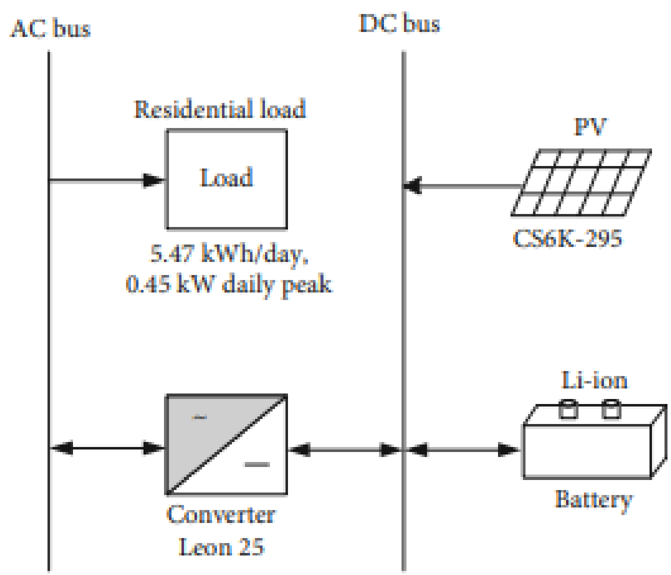

Fig. 1.4: Off-grid power system with PV, battery and converter

Moreover, the study resulted in a low-cost (four times cheaper), reliable, and affordable grid-connected PV and battery microgrid model for a residential home with a minimum daily load of 5.467 kWh as shown in Figure 1.2. The simulation results based on economic comparison analysis found the levelized cost of energy (LCOE) and net present cost (NPC) for each power-generated model by using HOMER Pro software. Their results shows that the LCOE for electricity production by each of the Grid connected-PV-Battery system, Diesel GenSet-PV-Batteries, and PV-Batteries systems was 0.0645 US$/1 kWh, 1.38 US$/1 kWh and 1.82 US$/1 kWh, respectively, compared with 0.2621 US$/1 kWh, the current residential electricity price (2020) for Rwanda [18].

Boussetta, M. et al. (2019), presents an implementation of real-time energy management systems (EMS) to maximize the efficiency of the electricity distribution in a microgrid. In this case, the grid serves a load with an off-grid hybrid renewable energy system made of photovoltaic modules, a battery energy storage system, a diesel generator, and a wind turbine. Furthermore, a proper power flow control was developed using LabVIEW software and embedded in a suitable platform for the real-time management of the hybrid energy system. The developed EMS was tested and validated through a small-scale application which accurately represents the case study of an isolated mosque located in a remote area of Morocco. [19].

Vera G. et al (2019), this paper presents a literature review of energy management in microgrid systems using renewable energies, along with a comparative analysis of the different optimization objectives, constraints, solution approaches, and simulation tools applied to both the interconnected and isolated microgrids. To manage the intermittent nature of renewable energy, energy storage technology was an attractive option due to increased technological maturity, energy density, and capability of providing grid services such as frequency response. Finally, future directions on predictive modeling mainly for energy storage systems were also proposed [20].

Waqar A. et al. (2017), in considering developing country like Pakistan, discovered that the capacity shortage (CS) of electricity was a critical problem. The frequent natural gas (NG) outages compel consumers to use electricity to fulfil the thermal loads, which ends up as an increase in electrical load. In this case, the authors have proposed the concept of a combined heat & power (CHP) plant to be a better option for supplying both electrical and thermal loads simultaneously. A CHP plant-based microgrid comprising a PV array, diesel generators and batteries (operating in grid-connected as well as islanded modes) was simulated using the HOMER Pro software. Different configurations of distributed generators (DGs) with/without batteries were evaluated considering multiple objectives. The multiple objectives include the minimization of the total net present cost (TNPC), cost of generated energy (COE) and the annual greenhouse gas (GHG) emissions, as well as the maximization of annual waste heat recovery (WHR) of thermal units and annual grid sales (GS). These objectives were subject to the constraints of power balance, battery operation within state of charge (SOC) limits, generator operation within capacity limits and zero capacity shortage. The simulations were performed on six cities including Islamabad, Lahore, Karachi, Peshawar, Quetta and Gilgit. The simulation results were analysed to find the most optimal city for the CHP plant integrated microgrid. The multi-objective analysis shows that a single city does not meet all the objectives in a single configuration. However, Gilgit and Quetta were the two cities which satisfy more than one objective in a single configuration. [21].

Shoeb, M. and Shafiullah, G. (2018), in their research stated that due to high investment and maintenance costs, the government of Bangladesh was unable to provide sufficient support for grid extension and supplying electricity to remote or rural areas. The deficit in electricity introduces a crisis in powering irrigation systems, which negatively influences the country's dominant income-generating sector, agriculture. Islanded microgrids with solar photovoltaic (PV) cells was one of the most attractive solutions for providing power to rural areas due to their cost-effectiveness, reliability, and environment-friendly attributes. Therefore, a techno-economic feasibility study was undertaken to investigate the prospects of renewable energy-based islanded microgrids to support rural electrification to power both households and irrigation systems. Three case studies based on the operation time of irrigation pumps during the day were developed using the HOMER Pro Microgrid Analysis Tool to identify the optimised configurations for the proposed system. The optimised configurations were then assessed considering the performance matrices of the cost of electricity (COE), net present cost (NPC), greenhouse gas (GHG) emissions and renewable energy fraction (RF). From the analyses, it was perceived that the operation of irrigation pumps at different times of a day was a significant influence, and the optimum method considering techno-economical evaluation was to run the irrigation pumps during the daytime by solar PV. It was evident that the proposed islanded microgrid has significant potentialities in powering irrigation systems as well as rural electrification with low energy generation costs, a contribution to the reduction of global warming and to ameliorating the energy crisis in Bangladesh to achieve a sustainable future [22].

Yoshida Y. and Farzaneh H (2020), this paper aims at the optimal designing of a stand-alone microgrid (PV/wind/battery/diesel) system, which can be utilized to meet the demand load requirements of a small residential area in Kasuga City, Fukuoka. The simulation part was developed to estimate the electrical power generated by each component, considering the variation of the weather parameters, such as wind, solar irradiation, and ambient temperature. The optimal system design was then based on the Particle Swarm Optimization (PSO) method to find the optimal configuration of the proposed system, using the least-cost perspective approach [23].

Shirzadi, Navid, et al (2020), this research aims at developing a configuration-sizing approach to enhance the cost efficiency and sourcing reliability of renewable energies integrated in microgrids. To achieve this goal, various technologies were considered, such as solar PV, wind turbines, converters, and batteries for system configuration with minimization of net present cost (NPC) as the objective. Grid connection scenarios with up to 100% renewable contribution were analysed. Their results show that the integration of renewable technologies with some grid backup could reduce the levelized cost of energy (LCOE) to about half of the price of the electricity that the university purchases from the grid. Also, different kinds of solar tracker systems were studied. The outcome shows that by using a vertical axis solar tracker, the LCOE of the system could be reduced by more than 50 percent. This research can help the decision-maker to opt for the best scenarios for generating reliable and cost-efficient electricity [24].

Agua O. F. B. et al (2020), in their work, a comparative study on decentralized and clustered hybrid renewable energy system microgrids in the Polillo group of islands in the Philippines, using HOMER Pro, was performed. Microgrids comprising solar photovoltaics, lithium-ion battery energy storage, and diesel generators were designed on each island. Clustered systems encompassing multiple islands in the island group were simulated by also considering the least-cost interconnection paths. The techno-economics of each decentralized or clustered system and the four-island system were evaluated based on the levelized cost of electricity (LCOE). Reliability was assessed using the change in LCOE upon the failure of a component and during weather disturbances. Transitioning from diesel-only systems to hybrid systems reduces generation costs by an average of 42.01% and increases the renewable energy share to 80%. Interconnecting the hybrid systems results in an average increase of 2.34% in generation costs due to the cost of submarine cables but improves system reliability and reduces the optimum solar photovoltaic and lithium-ion storage installations by 6.66% and 8.71%, respectively. Their research serves as a framework for the interconnection pre-feasibility analysis of other small off-grid islands [25].

Canziani F. et al (2021), their article analyses data obtained from the operation of a 9-kW hybrid microgrid in the fishermen's cove of Laguna Grande, Paracas, in the Ica region of Perú, which has been running for 5 years. This microgrid was equipped with data acquisition systems that measure and register wind speed, solar radiation, temperatures, and all the relevant electric parameters. Battery dynamics considerations were used to determine the depth of discharge in a real-time operative situation. The collected data were used to optimize the design using the specialized software HOMER, incorporating state-of-the-art technology and costs as a possible system upgrade. Their work aims to contribute to better understanding the behaviour of hybrid rural microgrids using data collected under field conditions, analysing their reliability, costs, and corresponding sensitivity to battery size as well as solar and wind installed power, as a complement to most studies based on simulations [26].

K. Ravichandrudu et al (2013), this work analyses micro-grid operation of a system based on renewable power generation units. The system behaviour and technical issues involved with three operational modes in micro-grid scheme were identified and discussed. The investigation was performed based on simulation results using MATLAB/Simulink software package. Simulation results indicate that dump load and suitable storage system along with proper control scheme were additionally required for the operation of the study system in a micro-grid scheme. A control coordinator and monitoring system was also required to monitor micro-grid system state and decide the necessary control action for an operational mode. The required control schemes development for the proposed micro-grid system is currently under investigation by the authors [27].

1.8. Historical Overview of the Nigerian Power System and challenges

The amount of electricity generated is one of the major indicators to determine whether an economy is growing or not. Therefore, no modern economy toys with its electricity industry since power is the underbelly of wealth creation activities. The low level of economic development in Nigeria can, therefore, be traced to the state of the country's power sector. Attempts at electricity generation started in Nigeria in 1896. The first private electricity company, NESCO, which is still in existence, started operations in 1929. These pioneering efforts were followed with the formation of an electricity distribution company- Electricity Corporation of Nigeria (ECN) in 1951 and the Niger Dam Authority (NDA) in 1962.

At about that time, various works departments, communities and municipalities across the country were making efforts at generating electricity and distributing electricity in their localities. The Federal Government in 1972 considered it appropriate to merge the Niger Dam Authority and the Electricity Corporation of Nigeria to form the defunct National Electric Power Authority otherwise known as NEPA, which was in existence until 2005. The decision to make concerted efforts at electricity generation initially paid off with increasing numbers of cities, towns, villages connected to the national grid, especially in the early 1970s to mid-1980s. As a matter of policy, all local government council headquarters are expected to be connected to the national grid. This is without corresponding policy to expand electricity infrastructure to accommodate new structures in government. Besides, the three tiers of government continued with electrification projects, connecting more of their towns and villages to the national grid without recourse to the system capacity.

The excessive pressure on the system notwithstanding, the Federal Government, which later had the sole authority for electricity generation, transmission and distribution continued to fail to meet its financial obligations. The utility company, NEPA, became a tool to meet social and political objectives of people in government. These resulted in neglect and insufficient investments in day to day running of infrastructure. Throughout the 1990s there was no expansion in power generation facilities despite expansion in population and government institutions and structures. As of 1999 the installed capacity of 5,906 megawatts could hardly deliver 1,750 megawatts of electricity to a population of 120 million people. By the year 2000, and with the advent of democracy, the operating capacity had further declined to 1,500 megawatts or 25.3 per cent of installed capacity. At this rate, total collapse of the system was imminent. Something drastic needed to be done. The Federal Government currently estimate that the power sector would require about N1.5trillion investment over the next few years to ensure that adequate electricity is generated, transmitted, and distributed.

It was in the realization of this that the Federal Government, at the advent of the democratic dispensation in 1999, started the process of reversing the decay in the power sector with the inauguration of the Electric Power Sector Implementation Committee. That effort brought about the Electric Power Sector Reform Act (EPSRA) in 2005. Its Major objective was to ensure private sector participation. This brought about the formation of the Nigerian Electricity Regulatory Commission NERC. It also led to the transition of the erstwhile NEPA to the Power Holding Company of Nigeria (PHCN) and the formation of such other structures like the National Electricity Liability Management Company (NELMCO) to wind down the government utility. Other developments that have followed the enactment of that Act include the breaking down of the erstwhile NEPA strategic business units into 18 different companies. The Federal Government during this period repaired some of the broken-down power station and constructed new ones. These efforts brought about increase in the amount of electricity distribution to over 3,500 megawatts. This is, no doubt, a major improvement. It is, however, a far cry from what is required to provide power for a population of 213 million people (based on Worldometer elaboration of the latest United Nations data).

1.9. Justification of Study

Iwuamadi O. C. and Dike D. O. (2012), despite its long history, electricity generation has been very slow and had deteriorated over the years in Nigeria. This is rarely expected given the country's enormous endowment in natural resources that facilitate and enhance electricity production. While the generation, transmission, and distribution (GTD) deteriorated, the demand for electricity exponentially increases continuously. This has led to the electricity company been incapable of providing minimum acceptable international standards of electricity service reliability, accessibility, and availability for the past three decades [28].

Omorogiuwa E. and Ike S. (2014) said that Nigeria power system is faced usually with problems of insufficient generation and transmission lines, resulting in the overloading, and stressing of the network beyond their thermal limit because of the increasing load demand [29].

This has led to consistent blackout nationwide. The epileptic nature of electricity generation in Nigeria associated with the existing 330kV network has become unbearable to most Nigerians, especially in the big cities. It has posed a constant threat to the growth of the country’s economy. The existing 330KV network has series of drawback ranging from inadequate generation, weak and fragile transmission lines that is not robust enough to wheel out the generated power in the network. The high load demand on the network makes the network prone to voltage instability which causes voltage limit violation in some of the buses that may lead to voltage collapse in the entire network. Voltage collapse is characterized by an initial slow progressive decline in the voltage magnitude of the power system buses and a final rapid decline in the voltage magnitude. The voltage problems associated with the network are caused by long distance power transmission (i.e., load centres far away from generating stations) and overloading of the transmission line (i.e., transmission lines carrying load beyond their available transfer capacity).

The high load demand on the existing 330KV network resulting to system insecurity and several voltage collapses on the network has made it necessary for a microgrid system in Nigeria. This research is focused on the design and simulation of a microgrid system for a university campus in Nigeria taking Edo State University Uzairue, Auchi, Edo State, Nigeria as a case study.

1.10. Research Objectives

The following are the research objectives of this work:

i. To do a literature review on microgrid system.

ii. To determine the load profile (kWh) of the university community selected.

iii. System design and sizing of the campus microgrid would be done with the aid of Homer Pro and other software such as OpenSolar, PVWatts and REopt to obtain the optimal PV size of the selected site.

iv. The dynamic simulation of the campus microgrid would be done on MATLAB/Simulink software.

v. To design the reduced order model of the campus microgrid system with the aid of MATLAB/Simulink software.

vi. To design the monitoring system for the campus microgrid.

1.11. Thesis Overview

This thesis is organized as follows: Chapter 2, present system design and sizing of a microgrid system for a university community in Nigeria with the aid of Homer Pro. OpenSolar, PVWatts and REopt software were used to achieve optimal PV size of the selected site. Chapter 3, present dynamic simulation of the campus microgrid using MATLAB/Simulink software. In chapter 4, with the help of MATLAB/Simulink software, the reduced order model of the microgrid system is presented. Chapter 5 provides an overview of the design of the monitoring system for the microgrid system. In Chapter 6, the conclusion and recommendations of the research is then presented.

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Co-authorship Statement

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

Chapter 2

Design and Sizing of a Microgrid System for a University Community in Nigeria

Preface

A version of this manuscript has been published in ***2022 IEEE 12th Annual Computing and Communication Workshop and Conference (CCWC), 26 – 29 January,2022****. I am the primary author and carried out most of the research works, including the literature reviews, system sizing , design and result analysis. I prepared the original manuscript and also revised the final manuscript based on feedbacks from the co-author and the peer-review process. The Co-author, Dr. M. Tariq Iqbal, supervised the entire research work, reviewed, made corrections and contributed research ideas for the actualization of the manuscript.*

This chapter is a version of "Design and Sizing of a Microgrid System for a University Community in Nigeria", S. Ogbikaya and M. T. Iqbal, *2022 IEEE 12th Annual Computing and Communication Workshop and Conference (CCWC), 26 – 29 January, 2022.*

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Abstract

Due to the epileptic power experienced in Nigerian national grid system, an on-grid microgrid system consisting of PV panels, inverter, grid system and diesel generator set is designed and sized for a university community in Nigeria. In this paper, the load profile (kWh) of the campus was determined based on the electric load of the campus. The electric load obtained was used to design and size a campus microgrid system for the university community with the aid of “HOMER” Pro software and the dimension of the area required for the installation of the PV panels was determined by PVWATT software. Results from simulation indicates that the dimension of the area required for the PV installation is 17,696m2 and the daily power generated from the microgrid system is always above the electric load of the system. Further analysis shows that 88.0% of the annual energy generated to supply the electric load of the campus can be produced by the PV panels and 12.0% by the grid system. This in turn reduces the amount being spent on electricity bill by the university campus by 88.0%. Economically, the cost of installation of the microgrid system is ₦295M with a simple payback of 3 years 5 months which may be more based on uncertainty and rate of inflation at the time of installation.

2.1. Introduction

Paper [1] states that despite its long history, electricity generation has been very slow and had deteriorated over the years in Nigeria. This is rarely expected given the country’s enormous endowment in natural resources that facilitate and enhance electricity production. While the generation, transmission, and distribution (GTD) deteriorated, the demand for electricity exponentially increases continuously. This has led to the electricity company been incapable of providing minimum acceptable international standards of electricity service reliability, accessibility, and availability for the past three decades. In [2], the writer indicated that Nigeria power system is faced usually with problems of insufficient generation and transmission lines, resulting in the overloading, and stressing of the network beyond their thermal limit because of the increasing load demand. This has led to consistent blackout nationwide. The epileptic nature of electricity generation in Nigeria associated with the existing 330kV network has become unbearable to most Nigerians, especially in the big cities. It has posed a constant threat to the growth of the country's economy. The existing 330KV network has series of drawback ranging from inadequate generation, weak and fragile transmission lines that is not robust enough to wheel out the generated power in the network. The high load demand on the network makes the network prone to voltage instability which causes voltage limit violation in some of the buses that may lead to voltage collapse in the entire network. Voltage collapse is characterized by an initial slow progressive decline in the voltage magnitude of the power system buses and a final rapid decline in the voltage magnitude. The voltage problems associated with the network are caused by long distance power transmission (ie load centres far away from generating stations) and overloading of the transmission line (ie transmission lines carrying load beyond their available transfer capacity). The high load demand on the existing 330KV network resulting to system insecurity and several voltage collapses on the network has made it necessary for a microgrid system in Nigeria. Paper [3] stated that the solar energy is available for everybody, hence if harnessed, can sustain the electrical energy need for meaningful development in Nigeria. Although the initial cost implication may be high, but on the long run, it is more economical because of its renewable nature, less maintenance cost and its environmental friendliness. Hence, for sustainable development to take place in Nigeria, the government, corporate bodies, and individuals should focus on photovoltaic power generation as one of the most viable options that could drive the civilization for ever. This research is focused on the design and sizing of a microgrid system for a university campus in Nigeria taking Edo State University Uzairue, Auchi, Edo State, Nigeria as a case study. Site details, load date and design of a microgrid system are presented below.

2.1.1. Definition of Microgrid

Microgrid are decentralized group of electricity sources and loads that normally operates, connected to and synchronous with the traditional wide area synchronous grid (microgrid), but can disconnect from the interconnected grid and function autonomously in "island mode" as technical or economic conditions dictate. A microgrid has self-sufficient energy system that serves a discrete geographic footprint, such as a business center, or neighbourhood, college campus and hospital complex. The United States Department of Energy Microgrid Exchange Group defines a microgrid as a group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both connected or island-mode.

2.1.2. Types of Microgrids

Three types of microgrids exist: remote, grid-connected, and networked microgrid.

2.1.2.1.Remote Microgrids

These refers to the off grid-microgrids which are physically isolated from the utility grid and always operate in island mode due to the lack of available and affordable transmission or distribution (T&D) infrastructure nearby. Renewables, such as wind and solar, typically provide a more economic and environmentally sustainable distributed energy resources (DER) solution for these microgrid to operator. Additionally, many remote microgrids are considering battery energy storage systems for backup power in lieu of conventional generators.

2.1.2.2.Grid-connected Microgrids

These microgrids have a physical connection to the utility grid through a switching mechanism at the point of common coupling (PCC), but they also can disconnect into island mode and reconnect back to the main grid as required. In this case, the microgrid is effectively integrated with the utility service provider to provide grid services (e.g., frequency and voltage regulation, real and reactive power support, demand response, etc.) to help address potential capacity, power quality and reliability and also voltage issues on the utility grid. In islanded mode, local voltage and frequency controls are required within the microgrid and can be provided by energy storage (e.g., battery, flywheel) or a synchronous generator (e.g., natural gas, fuel cell diesel). Due to its ability to perform multiple functions for grid services and emergency backup power, battery energy storage systems have been gaining popularity for microgrids that need to operate in both grid connected and island modes. When serving a relatively small geographic area, grid-connected microgrids demonstrate economic viability for educational campuses, medical complexes, public safety, military bases, agricultural farms, commercial buildings, and industrial facilities.

2.1.2.3.Networked Microgrids

These type of microgrids consist of several separate distributed energy resources (DERs) and/or microgrids connected to the same utility grid circuit segment and serve a wide geographic area. Networked microgrids are typically managed and optimized by a supervisory control system to operate and coordinate each grid-connected or island mode at different tiers of hierarchy along the utility grid circuit segment. Community microgrids, smart cities and new utility adaptive protection schemes (e.g., closed-loop self-healing) are examples of networked microgrids.

This research focuses on the grid-connected microgrid.

2.2. Literature Review

This paper [4] stated that the increasing demand for electricity and the inability of the current generation systems to meet the demand, urges for more renewable electrical energy systems in South Africa. The Rand West Municipality was a community that has a slow-paced rural electrification and was subject to multiple power cuts weekly thereby affecting the households, farms, and businesses in the area. It was therefore taken as a case study for the investigation of a Renewable Energy Sources (RES) microgrid. Simulation, optimization, and sensitivity analyses were conducted to determine the feasibility and optimal RES mix for the location using the Hybrid Optimization Model for Electric Renewable "HOMER" software. The simulations yielded an optimal microgrid system consisting of a combination of Solar Photovoltaic (PV) panels, Solar Concentrated Photovoltaic system, Battery Energy Storage System, and a Diesel Generator with a Cost of Energy (COE) of \$0.068/kWh, compared to the grid COE of \$0.12/kWh for this area.

Paper [5] analysis a stand-alone Poly generation Microgrids (PMG), which caters for electrical, thermal and hydrogen loads. The stand-alone PMG consisting of solar photovoltaic field, fuel cell, solid state hydrogen storage and electrolyzer was modelled using commercial software "HOMER". An hourly simulation was conducted to analyse its annual performance. A case study was carried out for a typical Indian village of about 50 households needing electrical energy of 100 kWh/day. It was found that, for the given load profile having 7.69 kW peak power demand and 100 kWh/day of electricity requirement, a PV system size of about 45 kW was needed to meet the load demand during daytime and for production of hydrogen for the fuel cell. The optimized component sizes of the microgrid are PV – 45 kW, Electrolyzer – 25 kW, fuel cell – 8 kW, AC/DC Converter – 8 kW and Hydrogen Storage – 5 kg. Significant thermal output at about 60 °C was an added benefit.

A methodology of designing a localized hybrid Microgrid for a rural area in the Pacific Island Countries (PICs) was presented in [6]. Nasau village was the chosen location for this design since necessary information of the village was provided by a local renewable energy sources (RES) installer. Typical loads found in rural villages were used to estimate the energy demand. This was accomplished using the bottom-up modelling strategy. Energy demand was then classified into three categories: typical village household, typical residential and commercial shop. Total energy demand of the village was then estimated from the product of each classification with respective quantities present in the village.

This estimated energy in conjunction with input parameters were used in "HOMER" for the final simulation. The system configuration satisfies the design parameters and Sustainable Energy Industry Association of the Pacific Island (SEAPI) guidelines. It was observed that the proposed microgrid design was feasible after comparing the supply behaviour of the sources (PV, Battery Energy Storage System (BESS) and diesel generator) with the load profile.

Studies in paper [7] focused on the economic power generation model mainly based on solar resources to minimize the electricity cost and provide income for the excess energy produced. This study covers on-grid power system with PV, battery, and converter. Moreover, the study resulted in a low cost (four times cheaper), reliable, and affordable grid connected PV and battery microgrid model for a residential home with a minimum daily load of 5.467 kWh. The simulation results based on economic comparison analysis found the levelized cost of energy (LCOE) and net present cost (NPC) for each power-generated model by using Hybrid Optimization Model for Electric Renewable ("HOMER") pro software. Their results shows that the LCOE for electricity production by each of the Grid connected-PV-Battery system, Diesel GenSet-PV-Batteries, and PV-Batteries systems was 0.0645 US$/1 kWh, 1.38 US$/1 kWh and 1.82 US$/1 kWh, respectively, compared with 0.2621 US$/1 kWh, the current residential electricity price (2020) for Rwanda.

Their research [8] stated that due to high investment and maintenance costs, the government of Bangladesh was unable to provide sufficient support for grid extension and supplying electricity to remote or rural areas. The deficit in electricity introduces a crisis in powering irrigation systems, which negatively influences the country's dominant income generating sector, agriculture. Islanded microgrids with solar photovoltaic (PV) cells was one of the most attractive solutions for providing power to rural areas due to their cost effectiveness, reliability, and environment-friendly attributes.

Paper [9] aims at the optimal designing of a stand-alone microgrid (PV/wind/battery/diesel) system, which can be utilized to meet the demand load requirements of a small residential area in Kasuga City, Fukuoka. The simulation part was developed to estimate the electrical power generated by each component, considering the variation of the weather parameters, such as wind, solar irradiation, and ambient temperature. The optimal system design was then based on the Particle Swarm Optimization (PSO) method to find the optimal configuration of the proposed system, using the least cost perspective approach.

In work [10], a comparative study on decentralized and clustered hybrid renewable energy system microgrids in the Polillo group of islands in the Philippines, using "HOMER" Pro, was performed. Microgrids comprising solar photovoltaics, lithium-ion battery energy storage, and diesel generators were designed on each island. Clustered systems encompassing multiple islands in the island group were simulated by also considering the least-cost interconnection paths. The techno-economics of each decentralized or clustered system and the four-island system were evaluated based on the levelized cost of electricity (LCOE). Reliability was assessed using the change in LCOE upon the failure of a component and during weather disturbances. Transitioning from diesel-only systems to hybrid systems reduces generation costs by an average of 42.01% and increases the renewable energy share to 80%. Interconnecting the hybrid systems results in an average increase of 2.34% in generation costs due to the cost of submarine cables but improves system reliability and reduces the optimum solar photovoltaic and lithium-ion storage installations by 6.66% and 8.71%, respectively. Their research serves as a framework for the interconnection pre-feasibility analysis of other small off-grid islands.

Paper [11] presents an economical expediency of grid connected hybrid (PV/Wind turbine) power system for remote village in Khurdha District, Odisha (20.1301°N,85.4788° E) in India. Their work was an approach towards the betterment of rural areas providing a cleaner eco-friendly environment by using renewable energy resources to meet the load requirements. Analysis was carried out by investigating the potentials of wind and solar energy and collecting data from different sources. Hybrid Optimization Model for Electric Renewable "HOMER" Pro software was used to analyse the available data and economic feasibility of the proposed hybrid power system. In this research, two types of models named off-grid and on grid were designed and optimized for comparison purposes. Also, sensitivity analysis was performed for each model to determine the effect of variations in grid energy cost on its total cost. Their simulation results indicate that the proposed grid connected hybrid (PV/Wind turbine) power system was most suitable and cost competitive for the mentioned region.

2.3. Methodology

Firstly, literatures on microgrid system were reviewed. Secondly, the load profile in kilo watt hour (kWh) of the selected university community was determined based on the electrical load of the campus. Thirdly, the load profile obtained was then used to design and size a campus microgrid for the university community consisting of PV panel, grid system, generator, inverter, and electrical load with the aid of “HOMER” Pro software. Fourthly, the dimension of the area required for the system installation was determined with the aid of PVWatt software.

2.3.1. Campus Location

In this paper, a microgrid is designed for a university community in Nigeria. Edo State University Uzairue, Auchi, Edo State, Nigeria (7° 8'8.25"N, 6°18'28.13"E). Edo State University, Uzairue (abbreviated EDSU) is a state government-owned tertiary institution founded in 2016. The university is located at Km7, Auchi-Abuja Road, Iyamho-Uzairue, Edo State, Nigeria. On 23 March 2016, the university was approved by the National Universities Commission as Nigeria's 41st state university. Edo State University offer undergraduate, postgraduate and research programmes in the following faculties: Medicine, Engineering, Law, Sciences and Social Sciences. Figure 2.1 shows the google map of part of the university campus and Figure 2.2 shows an overview of part of the university campus.

Fig. 2.1: Google map of part of the University campus

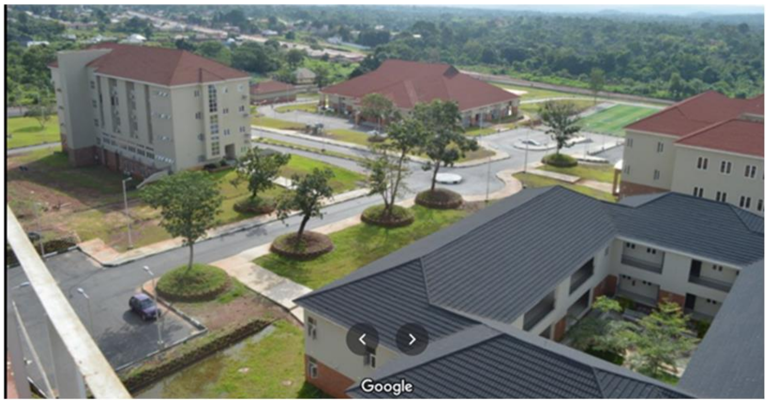


Fig. 2.2: Overview of part of the University campus

2.3.2. Load Profile of University Campus

An electrical load can be AC or DC; however, most used electrical components are AC powered. The electrical load which are mainly AC of various buildings in the university are summarized in Table 2.1 showing the total installed load of the university.

Table 2.1: Summary of maximum possible electrical load installed in the university

S/N	Description	Total electrical load in Kilowatts (kW)
1	Administrative building	269.238
2	Faculty of Law building	64.008
3	Male hostel	370.6
4	Female hostel	207.636
5	Auditorium building	168.796
6	Engineering workshop building	152.135
7	Faculty of science building	225.608
8	Faculty of social science building	84.938
Total load		1542.959

In kVA, total electrical load installed $= \frac{1542.959}{0.8} = 1928.699kVA$

The university is connected to 33kV utility grid system with an operating frequency of 50Hz. The installed capacity of the transformer feeding the school is 2.5MVA and generator capacity of 1.5MVA as backup.

2.3.3. Energy Consumption

The annual energy consumption of the institution based on the monthly meter reading (kWh) from October 2020 to September 2021 is tabulated in Table 2.2. The rate of electricity charge per kilo watt hour (kWh) for the university campus is ₦52.18.

Table 2.2: Energy consumption of Edo State University Uzairue from October 2020 to September 2021

Month	Previous meter reading (kWh)	Present meter reading (kWh)	Energy consumption (kWh)	Cost of energy consumption (₦)
October	3635000	3655000	20000	1,043,600.00
November	3655000	3689000	34000	1,774,120.00
December	3689000	3781000	92000	4,800,560.00
January	3781000	3836000	55000	2,869,900.00
February	3836000	3893000	57000	2,974,260.00
March	3893000	3986000	93000	4,852,740.00
April	3986000	4097000	111000	5,791,980.00
May	4097000	4254000	157000	8,192,260.00
June	4254000	4324000	70000	3,652,600.00
July	4324000	4411000	87000	4,539,660.00
August	4411000	4516000	105000	5,478,900.00
September	4516000	4604000	88000	4,591,840.00
Annual energy consumption			969000	50,562,420.00
Daily energy consumption			2654.795	138,527.20

2.3.4. Modeling and Sizing

The area chosen for this analysis was located in "HOMER" google map as shown in Figure 2.3 and this area has an average energy consumption of 2654.80 kWh/day and the peak load 443.89 kW. Figure 2.4 shows commercial daily average load variations for January month, Figure 2.5 shows the commercial seasonal (monthly) average load variations.

Fig. 2.3: Location of University campus on "HOMER" google map

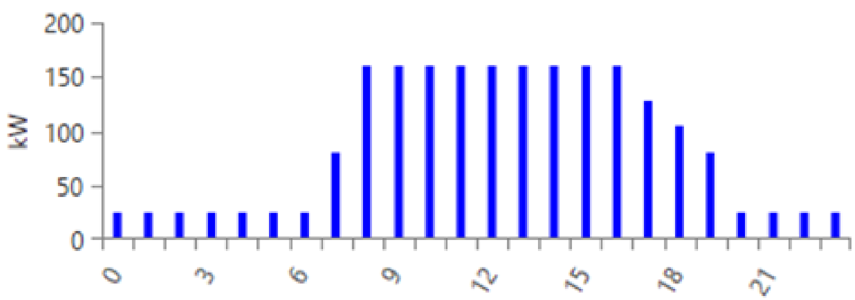


Fig. 2.4: Commercial daily load profile of campus

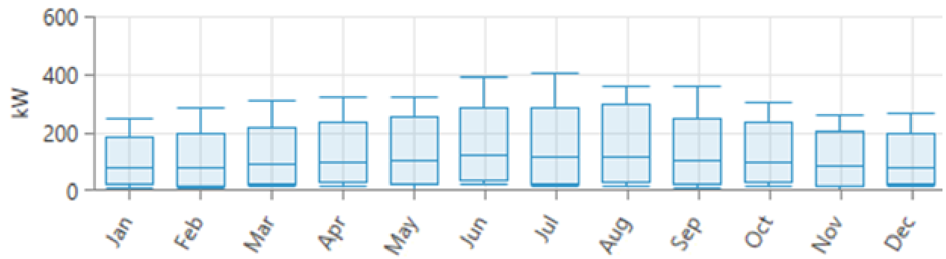


Fig. 2.5: Commercial seasonal load profile of campus

Load is higher when campus is in used and classes are happening (9am – 5pm). During the nighttime, load is below 25kW, that is mainly for lighting. During dry season months, load is higher since some building use air conditioners during normal working hours. Heating is not needed in that part of the world.

2.3.5. Solar Irradiance

The average solar radiation per annum is 5.10 kWh/m2/day for the site location. Figure 2.6 shows graph of average monthly Global Horizontal Irradiance (GHI) Data for the considered site. It is observed from the Figure 2.6 that the average monthly solar radiation is highest in the months of February, January and March which are 5.840 kWh/m2/day, 5.770 kWh/m2/day and 6.803 kWh/m2/day. The time series detail analysis of global solar monthly average of the site is shown in Figure 2.7.

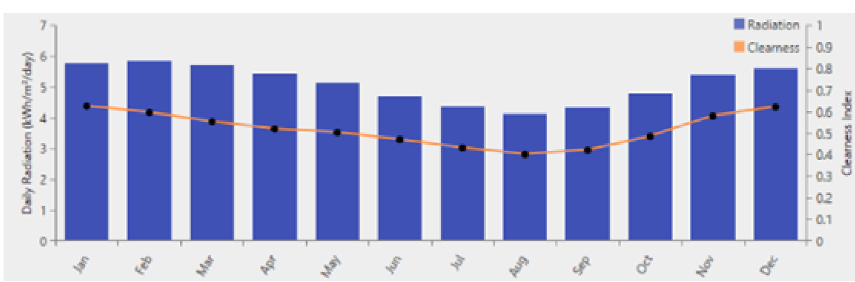


Fig. 2.6: Graph of monthly solar irradiance of the selected site

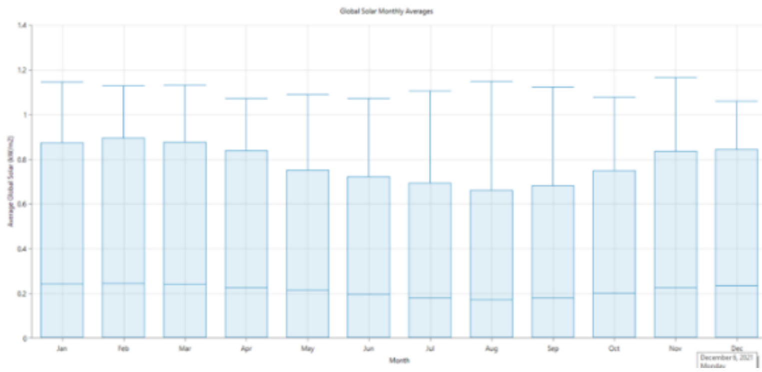


Fig. 2.7: Time series detail analysis of global solar monthly average of the site

Based on the load profile of the selected site, the components size is chosen. A hybrid power system of the site consisting of the grid system, solar panel of 0.5kW, diesel generator of 1.5MVA and inverter of 500kW is designed and simulated with the aid of "HOMER" Pro Energy software to accommodate its annual energy (kWh). The schematic diagram of the hybrid power system obtained is shown in Figure 2.8.

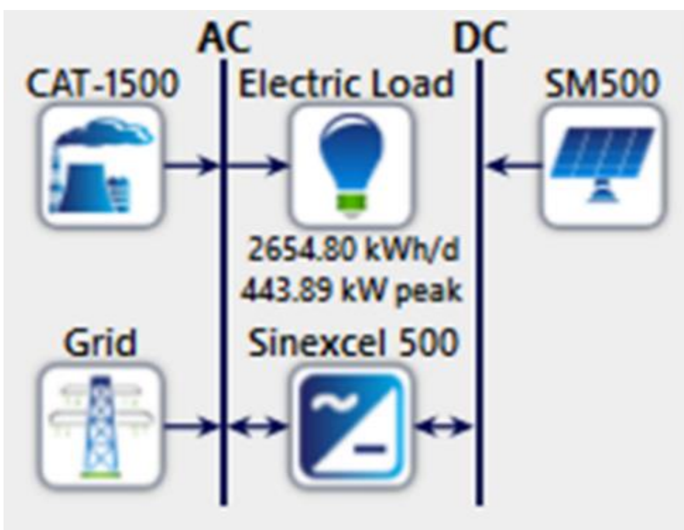


Fig. 2.8: Schematic diagram of hybrid power system

Battery backup was also considered but cost was too much. In the final proposed design, no battery backup is used in the grid connected system. The designed system will need 3,726 PV solar modules of 500W. Figure 2.9 shows the location of the site where the solar panels will be installed on the campus using PVWatt software. With the aid of this software, the dimension required for the installation of the PV panels is determined.

Fig. 2.9: Location of the installed solar system on campus using PVWatt software

Based on the system design on PVWatt software, the dimension of the area required for the system installation is 17,696m2 as shown in Figure 2.9. Required land is available for use next to the campus building.

2.4. Result and Discussion

Simulated results shows that the daily power generated from the microgrid system is always above the total electrical load of the system as shown in Figure 2.10. Figure 2.10 also depicted that most of the power generated to accommodate this electrical load comes from the PV panel while the remainder is from the grid. The generator in this case does not generate any power to the system, it is used as emergency backup.

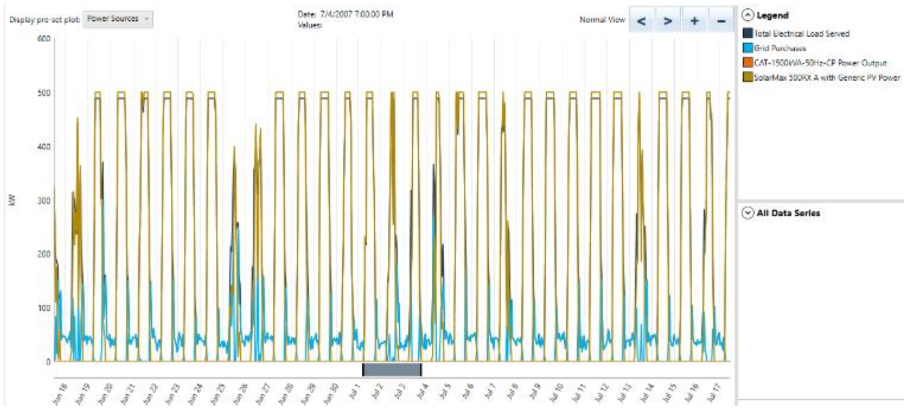
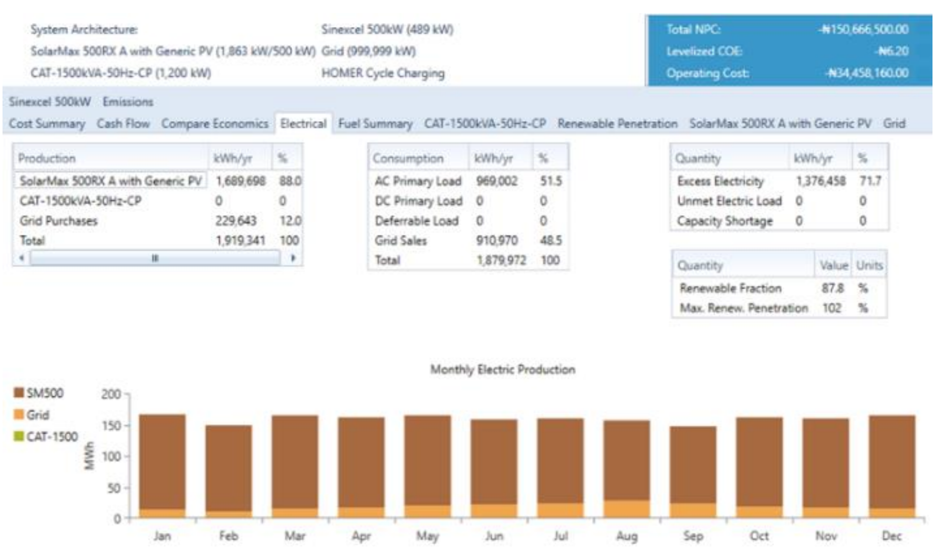


Fig. 2.10: Graph showing power generation and total electrical load served for one month

Analysis also shows that 88.0% of the annual energy generated to supply the electric load of the campus is produced by the installed solar panels and 12.0% is from the grid system as shown in Table 2.3. This in turn will reduce the amount spent on electricity bill by university campus. This indicates that energy consumed by the school is produced mainly by both the PV module and the grid system. This system is an on-grid system. The generator is a backup (Figure 2.10) in case both the solar and grid system fails.

Table 2.3: Simulated result of system sizing by "HOMER" Pro



System Architecture:
SolarMax 500RX A with Generic PV (1,863 kW/500 kW)
CAT-1500kVA-50Hz-CP (1,200 kW)
Sinexcel 500kW (489 kW)
Grid (999,999 kW)
HOMER Cycle Charging

Total NPC: -₦150,666,500.00
Levelized COE: -₦6.20
Operating Cost: -₦34,458,160.00

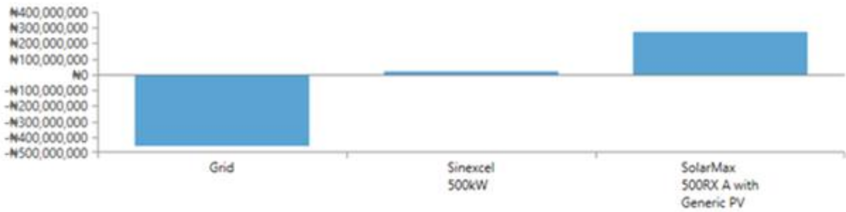
Sinexcel 500kW Emissions
Cost Summary Cash Flow Compare Economics Electrical Fuel Summary CAT-1500kVA-50Hz-CP Renewable Penetration SolarMax 500RX A with Generic PV Grid

Production	kWh/yr	%
SolarMax 500RX A with Generic PV	1,689,698	88.0
CAT-1500kVA-50Hz-CP	0	0
Grid Purchases	229,643	12.0
Total	1,919,341	100

Consumption	kWh/yr	%
AC Primary Load	969,002	51.5
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	910,970	48.5
Total	1,879,972	100

Quantity	kWh/yr	%
Excess Electricity	1,376,458	71.7
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	87.8	%
Max. Renew. Penetration	102	%



Component	Capital (₦)	Replacement (₦)	O&M (₦)	Fuel (₦)	Salvage (₦)	Total (₦)
Grid	₦0.00	₦0.00	-₦459,594,017.08	₦0.00	₦0.00	-₦459,594,017.08
Sinexcel 500kW	₦15,290,947.59	₦13,508,598.46	₦1,976,739.80	₦0.00	-₦1,831,533.27	₦28,944,752.59
SolarMax 500RX A with Generic PV	₦279,500,976.56	₦0.00	₦481,767.13	₦0.00	₦0.00	₦279,982,743.70
System	₦294,791,924.15	₦13,508,598.46	-₦457,135,510.14	₦0.00	-₦1,831,533.27	-₦150,666,520.79

Fig. 2.11: Cost summary of system

Table 2.4: System economics

Architecture									Cost	
				SM500 (kW)	SM500-MPPT (kW)	CAT-1500 (kW)	Grid (kW)	Sinexcel 500 (kW)	NPC (₦)	Initial capital (₦)
						1,200	999,999		₦654M	₦0.00
				1,863	500	1,200	999,999	489	-₦151M	₦295M

Metric	Value
Present worth (₦)	₦804,314,300
Annual worth (₦/yr)	₦62,217,230
Return on investment (%)	24.8
Internal rate of return (%)	29.0
Simple payback (yr)	3.43
Discounted payback (yr)	3.95

Charts...

In terms of economics, the capital cost of the 500kW inverter is ₦15.3M and the cost of the 3,726 solar panels of 0.5kW each is ₦279.5M bring the total initial capital installation cost of the system to ₦295M and a replacement cost of ₦13.5M as shown in Figure 2.11 and Table 2.4 with a simple payback of 3 years 5 months as shown in Table 2.4. This cost of installation and simple payback time may be more due to uncertainty and rate of inflation at the time the system is installed.

2.5. Conclusions

In this research, a microgrid consisting of the grid system, 3,726 solar panel of 0.5kW, diesel generator of 1.5MVA and inverter of 500kW installed in an area of 17,696m2 at a cost of ₦295 with a simple payback of 3 years and 5 months was designed with the aid of "HOMER" Pro to meet the load demand of the university community at a reduced cost of electricity bill by 88.0%. Site details, load data and microgrid system design has been presented. Analysis indicates that the proposed system makes economic sense and will greatly help the university bring down its electricity bill, this will also help the university reduce its CO2 emissions.

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Chapter 3

Dynamic Simulation of a Microgrid System for a University Community in Nigeria.

Preface

A version of this manuscript has been published in ***2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), 01 – 04 June, 2022.*** *I am the primary author and carried out most of the research works, including the literature reviews, system design, dynamic simulation and result analysis. I prepared the original manuscript and also revised the final manuscript based on feedbacks from the co-author and the peer-review process. The Co-author, Dr. M. Tariq Iqbal, supervised the entire research work, reviewed, made corrections and contributed research ideas for the actualization of the manuscript.*

This chapter is a version of "Dynamic Simulation of a Microgrid System for a University Community in Nigeria", S. Ogbikaya and M. T. Iqbal, *2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), 01 – 04, June, 2022.*

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Abstract

In this research, the optimal PV size of the system was first determined with the aid of OpenSolar, PVWatts and REopt software for an annual energy consumption of 969,000kWh as compared to that obtained from HOMER Pro software. The result obtained was then used to design and simulate the dynamic model of the campus microgrid system in MATLAB/Simulink environment. The designed system in Simulink consists of PV size of 675.2kW comprised of 1350 modules each of 500W, with 25 connected in series and 54 in parallel, a utility grid of 50Hz, 6MVA, 33 kV transmission network with a power transformer of 2.5MVA, 33/11 kV and a distribution transformer of 750 kVA, 11/0.415 kV and a backup generator of 1.5 MVA rating. The system dynamics was considered under three conditions which includes PV + grid mode, PV + generator mode and only generator mode. Simulated results include transient responses observed when the utility grid and the generator were connected to the network separately through their respective toggle switches. Waveform of power, voltage and current through the varied electric load of the system for various conditions are presented in this paper.

3.1. Introduction

A microgrid consist of a network of electricity consumers with a local source of supply usually attached to a centralized national grid but it can function separately. In this case the consumers include residential homes, stores, streetlights, health centres, churches and even schools. Microgrids are more efficient, low-cost, clean energy, resilient, and improve the operation and stability of grid system. They can be classified into remote, grid connected and networked type. In this research, the dynamics of a microgrid system for a university community in Nigeria that is grid connected is considered.

3.2. Literature Review

Research [1] work explain that for future power systems, the deficiency in power supply can be solved by a microgrid system which consists of renewable power sources such as wind, solar and hydro. In this research, a microgrid system with wind and solar power sources was used to solve the issues relating to operation, control, and stability of the system. With the aid of MATLAB/Simulink, the system was modeled and simulated based on the renewable power generation units to know the relevant technical issues associated with the operation of a microgrid system.

The paper [2] reveals that microgrid application at different voltage levels for power system networks are in the increase. To increase energy efficiency, reduce electricity bills and reduce the problems with power delivery to customers, community microgrid systems are encouraged. In that work, a simulation-based electricity analysis scheme for a community microgrid with the aid of proposed modelling methodology, simulation mechanisms, and a power balancing control strategy in MATLAB environment was developed. That paper also presents an effective simulation mechanism using MATLAB/Simulink software for the electricity analysis in microgrid systems which can be flexibly modified to comply with different simulation requirements when faced with various system topologies.

In paper [3], a solar PV powered DC microgrid that was proposed and designed in Nigeria at Umuokpo Amumara community with a household population of 800 was presented. The component sizes selected always meets the load demand of the community with energy requirement of 3.16MWh/day. A battery capacity of 21,944Ah was sized as the battery storage to meet the energy required by the community for one day without any renewable energy source. In this research, the dynamic model of the microgrid was simulated in MATLAB/Simulink to observe the system's dynamic response in view of the power quality, load impact, and battery storage charging. Results obtained from simulation indicates that the stand-alone DC microgrid can meet the daily electric energy of the system with relatively good voltage stability.

Study [4] stated that the main aim of microgrid MG) system was to integrate micro sources and load into a controlled system to supply electric energy to the end consumers. In this work the dynamic characteristics of a grid connected system associated with power conditioning system (PCS) to regulate it power was discussed. The system investigated consists of grid, micro sources, lumped static loads and other components. To cater for the dynamic behaviour of the system, a detailed model of the system was developed in MATLAB/Simulink in which two operational modes were investigated which includes: four-quadrant operation of PCS and use of PCS to control the power of MG. Simulation results indicates that MG can operate satisfactorily in these operational modes.

Paper [5] presents the dynamic operation of a low-voltage microgrid system with various distributed energy sources and the system consists of a low-voltage microgrid with a 30 kVA micro-hydro generator, a 30 kVA diesel engine generator, a 30 kVA gas engine generator, and a 15 kVA micro-wind turbine generator including the loads. In this research, the individual components of the system were modeled and integrated to form a microgrid system whose dynamic simulation was simulated in MATLAB/Simulink environment. Results obtained provides information on the dynamic characteristics of AC low voltage microgrid systems and help in the development of microgrid system in Taiwan.

In this paper [6] the development of a micro sources' booster converter and PWM inverter in MATLAB/Simulink and combining them to form a microgrid was presented. The system was designed such that it can operate both in islanding mode and in grid mode. The purpose of this work was to lay foundations which allows further investigation and development of more complex microgrid models to know the behaviour of microgrid systems.

In paper [7], the design of a network-based scheme for inverter-based sources was studied. This scheme provides proper current control when connected in grid and voltage control during islanding mode. In that work, the algorithm for international islanding detection and synchronization controller needed for the grid connection was developed. When the dynamic modeling and simulation of system was conducted in Simulink, results reveal that the controllers provide the microgrid with a deterministic and reliable connection to the grid.

In this work [8] behaviour of hybrid AC/DC microgrid system was analyzed when it was grid tied. The microgrid in this case was developed by photovoltaic system, wind turbine generator and battery. For proper coordination from AC sub grid to DC sub-grid, a control mechanism was developed for the converters. The system was simulated with the results obtained in MATLAB/Simulink. The results obtained indicates that the hybrid grid system provides efficient power with high quality and more reliable power to the consumers which may be feasible for small isolated industrial plants with both PV systems and wind turbine generator as the major power supply.

In research [9], the modeling and performance of a microturbine generating (MTG) system in grid connected and islanding mode was analysed with the aid of MATLAB/Simulink software. Based on the various conditions considered in that study, simulated results shows that MTG system follows the load with variation of fuel flow, power, and temperature of the system. It was also observed that the MTG system contributes clean, reliable, and cost-effective energy for future distributed generation (DG) systems.

In paper [10], the design and operation of a microgrid (MG) for the main campus of the Technical Institution Hawija was considered. That microgrid design includes a battery energy storage system (BESS), photovoltaic (PV) generation system, and controllable loads. The efficacy of their intended design was simulated in MATLAB/Simulink. Simulated results indicates that the distribution system obtained is more robust, reliable, and resilient against weather disaster or technical issues.

In this research, the dynamic simulation of a microgrid system for a university community in Nigeria is presented. The system consists of a PV size of 675.2 kW comprising of 1350 modules each of 500W, with 25 connected in series and 54 in parallel with a utility grid system and a diesel generator set is incorporated in case of emergency. The system was then designed and simulated in MATLAB/Simulink environment to test its dynamics. This work is novel in a sense that it provides a Nigeria case study, include design, dynamic modeling and simulation.

3.3. Methodology

Based on the campus annual electric loas (kWh), a microgrid for the university community was designed in HOMER Pro software to obtain the PV size (kW) of the system. Further design from OpenSolar, PVWatts and REopt softwares were done based on the same annual energy consumption (kWh) of the selected site to determine the optimal PV size (kW) of the system as compared to that obtained from the HOMER Pro software. Based on the optimal PV size selected, the system was then simulated in MATLAB/Simulink software to determine its dynamics.

3.4. System Design

The university campus (7° 8'8.25"N, 6°18'28.13"E) at Kilometer 7, Auchi-Abuja Road, Iyamho-Uzairue, Edo State, Nigeria is located as shown in Figure 3.1 and the annual energy consumption of the site selected was determined as 969,000kWh based on the monthly energy consumption of the campus as shown in Table 3.1.

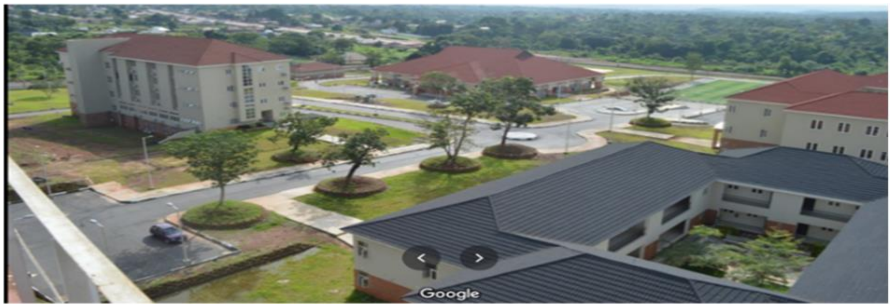

Fig. 3.1 Overview of university campus

Table 3.1: Summary of Monthly Energy Consumption of The Selected Site from October 2020 to September 2021

Month	Previous meter reading (kWh)	Present meter reading (kWh)	Energy consumption (kWh)
October	3635000	3655000	20000
November	3655000	3689000	34000
December	3689000	3781000	92000
January	3781000	3836000	55000
February	3836000	3893000	57000
March	3893000	3986000	93000
April	3986000	4097000	111000
May	4097000	4254000	157000
June	4254000	4324000	70000
July	4324000	4411000	87000
August	4411000	4516000	105000
September	4516000	4604000	88000
Annual energy consumption			969000

The load profile of the designed system based on HOMER Pro software is shown in Figure 3.2 and the solar irradiance of this site is shown in Figure 3.3. The average solar irradiance per annum of this location is 5.10 kWh/m2/day.

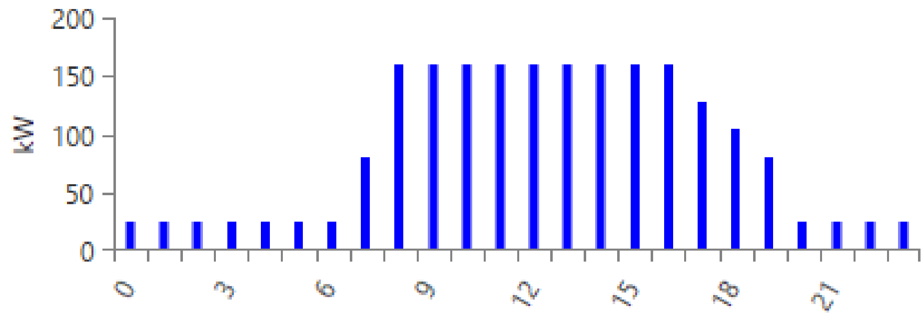

Fig. 3.2 Load profile of university campus

Fig. 3.3 Monthly solar irradiance of university campus

Based on this annual energy consumption and selected components, a microgrid system of the site was designed. This microgrid consist of solar panel of 0.5kW, the grid system, diesel generator of 1.5MVA rating and inverter sinexcel 500 with the aid of HOMER Pro Energy software to accommodate the annual energy consumption (kWh). The schematic diagram of the microgrid system obtained is shown in Figure 3.4.

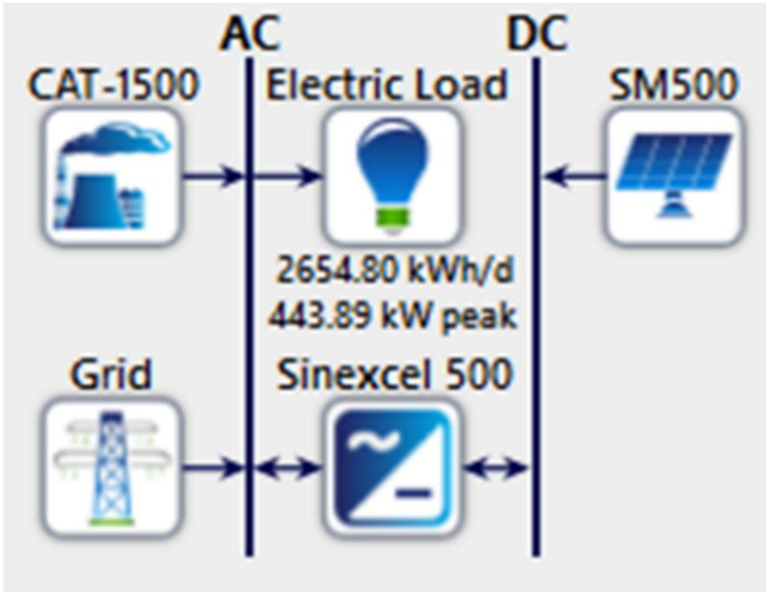

Fig. 3.4 Schematic diagram of microgrid system

The result obtained from the HOMER Pro software indicates that the system would need 1,868kW PV size for system installation to meet the 87.8% consumption of the proposed microgrid system as shown in Figure 3.5.

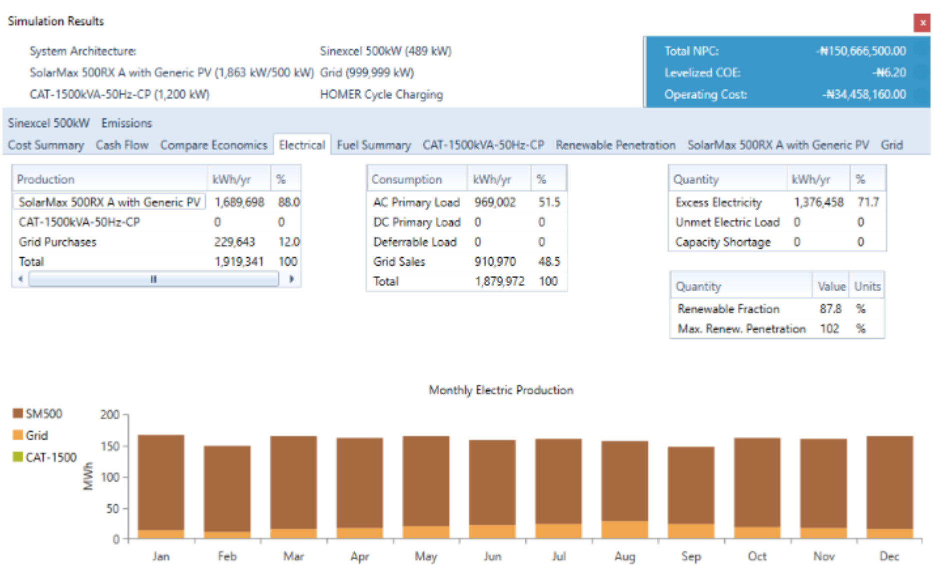

Fig. 3.5 Simulated result from HOMER Pro showing system PV size

To determine the optimal PV size of the microgrid system of the site with the same annual energy consumption (kWh) for dynamic simulation, PVWatts, OpenSolar and REopt were used to design the system.

3.4.1. PVWatts Simulation

Based on the site location and energy demand of the campus, PVWatts was used to design and simulate the system to determine the PV size that would be required. Result obtained indicates that the system would require 670.5kW PV size for the system installation this is depicted in Figure 3.6 and Figure 3.7.

PVWatts Calculator

RESULTS

967,113 kWh/Year*

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	5.53	85,879	11,164
February	5.80	81,845	10,640
March	5.96	92,340	12,004
April	5.51	83,657	10,875
May	5.05	78,874	10,254
June	4.65	71,768	9,330
July	4.51	72,440	9,417
August	4.66	74,950	9,744
September	5.01	77,664	10,096
October	5.31	83,995	10,919
November	5.42	81,916	10,649
December	5.25	81,785	10,632
Annual	5.22	967,113	$ 125,724

Location and Station Identification

Requested Location	Edo State University Uzairue, Auchi, Nigeria
Weather Data Source	(INTL) ACCRA/KOTOKA INTL, GHANA 436 mi

Fig.3.6 Simulation from PVWatts showing system annual energy consumption

Requested Location	Edo State University Uzairue, Auchi, Nigeria
Weather Data Source	(INTL) ACCRA/KOTOKA INTL, GHANA 436 mi
Latitude	5.6° N
Longitude	0.17° W
PV System Specifications *(Commercial)*	
DC System Size	670.5 kW
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt	8°
Array Azimuth	180°
System Losses	14.08%
Inverter Efficiency	96%
DC to AC Size Ratio	1.2
Economics	
Average Retail Electricity Rate	0.130 $/kWh
Performance Metrics	
Capacity Factor	16.5%

Fig. 3.7 Simulation from PVWatts showing system PV size

3.4.2. OpenSolar Simulation

Figure 3.8 show that 683.645kW PV size would be required for the same energy demand of the campus when OpenSolar software was used to simulate the system.

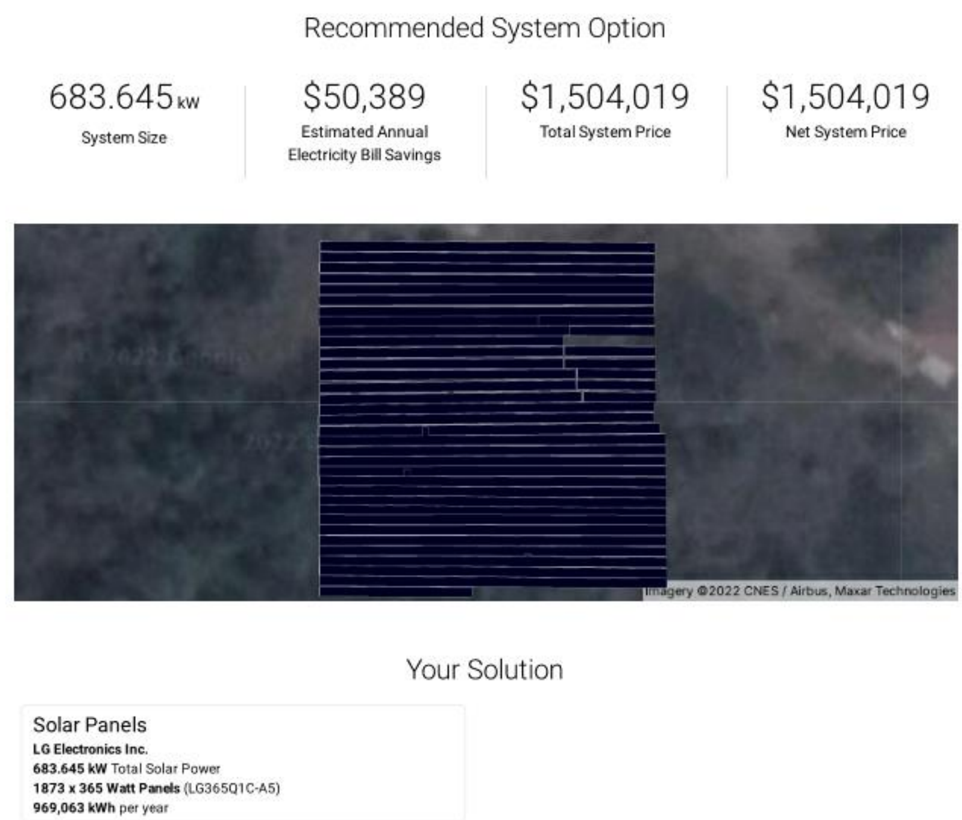

Fig. 3.8 Simulation from OpenSolar software showing system PV size

3.4.3. REopt Simulation

When REopt software was used to design the system as shown in Figure 3.9, the PV size recommended for this design was 658kW as represented in Figure 3.10.

Technologies Selected	
PV	

Site and Utility	
Site Location	Auchi, Nigeria (7.066864499999999, 6.274773400000001)
PV & wind space available	Land
Annual energy charge ($/kWh)	$0.13
Annual demand charge ($/kW/month)	$1.05

Load Profile	
Typical electric load profile type	simulated campus
Campus total electric energy consumption (kWh)	969,000
Building #1	SecondarySchool (100% of total energy consumption)

Fig. 3.9 Simulation from REopt showing system annual energy consumption

Results for Your Site

REopt

Your site at Auchi Nigeria evaluated on February 13, 2022

These results from REopt summarize the economic viability of PV, wind, battery storage, and/or CHP at your site. You can edit your inputs to see how changes to your energy strategies affect the results.

Your recommended solar installation size

658 kW

PV size

Measured in kilowatts (kW) of direct current (DC), this recommended size minimizes the life cycle cost of energy at your site.

This optimized size may not be commercially available. The user is responsible for finding a commercial product that is closest in size to this optimized size.

Fig. 3.10 Simulation from REopt software showing system PV size

The resulting PV sizes obtained from these software as compared to that of the HOMER Pro software is summarized as shown on the comparison table in Table 3.2. We believe results of REopt from NREL are more reliable and we used that for the next section.

Table 3.2: Comparison Table Showing the Simulated Results Obtained from the Different Software used to Determine the System PV Size for the Microgrid System of the University Campus

S/N	Software Used	Annual Energy Consumption (kWh)	System PV Size (kW)
1	Homer Pro	969,000	1868.00
2	OpenSolar	969,063	683.65
3	PVWatts	967,113	670.50
4	REopt	969,000	658.00

3.5. Dynamic Simulation

The dynamic system design of the university campus microgrid was then carried out with the aid of MATLAB/Simulink software. The system consists of a PV size of 675.2kW comprised of 96 cell modules each of 500W, with 25 connected in series and 54 in parallel. To ensure that the PV gives maximum power, MPPT is applied to the PV. Figure 3.11 shows the simulation results of I-V and P-V curves of the PV output. The inverter of the system was selected based on the PV size as 700kW. Since the microgrid system is an on-grid system, a utility grid of 50Hz, 6MVA, 33 kV transmission network with a power transformer of 2.5MVA, 33/11 kV and a distribution transformer of 750 kVA, 11/0.415 kV was incorporated to the network through breaker 2, which is controlled by toggle switch 2. Also incorporated into the network is a permanent type 1.5MVA rating generator through breaker 3, that is controlled by toggle switch 3. This stands as a backup when the PV and grid system fails. The electric load of the university campus is also connected and varied through breaker 4 which is controlled by toggle switch 4 to network. Figure 3.12 shows the diagram of the dynamic simulation of the entire system in MATLAB/Simulink environment.

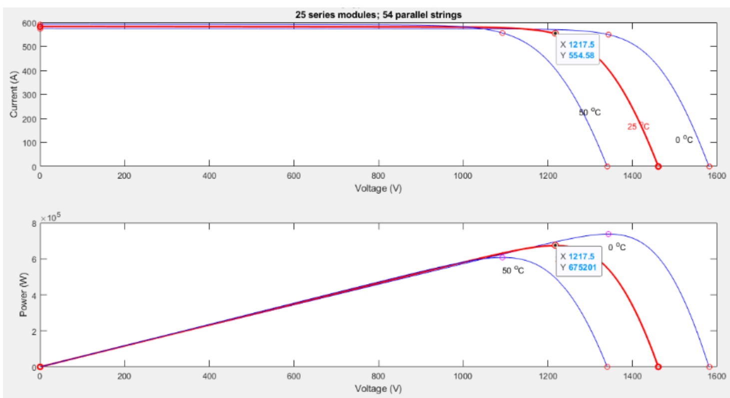

Fig. 3.11 Irradiation, temperature, power, voltage and duty cycle signal of PV module

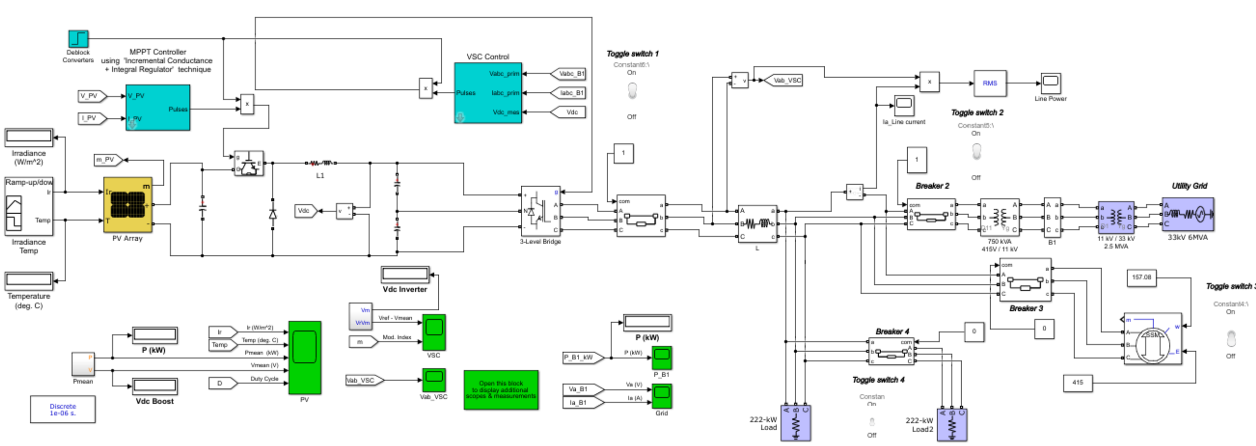

Fig. 3.12 Dynamic simulation of campus microgrid in MATLAB/Simulink software

3.6. Simulation Results

The Irradiation, Temperature, Power, Voltage, and duty cycle graphs of the PV module are shown in Figure 3.13. Simulated results shows that the duty cycle varies according to the solar resources and the MPPT is able to track the variation of the solar input.

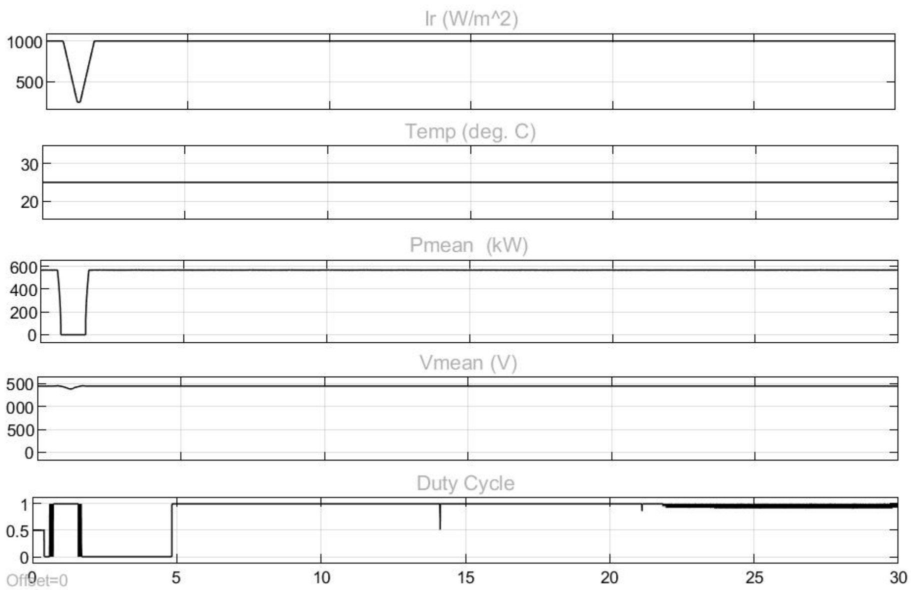

Fig. 3.13 Irradiation, temperature, power, voltage, and duty cycle signal of PV module for 30 seconds

Dynamic modeling and simulation of systems shows how the system behaves under proposed conditions using Simulink. In this case, the dynamic simulation shows the behaviour of the campus microgrid system when the utility grid and generator are connected to the network separately. For the purpose of analysis, the system dynamics are considered in three cases.

i. PV + Grid mode i.e normal operating condition of the proposed system.

ii. PV + Generator mode i.e when the grid fails.

iii. Generator only i.e when the generator supplies energy to the entire load of the system.

The behaviour of the system based on the three cases stated above are illustrated as depicted in the respective graphs.

i. PV + grid mode

This mode is achieved when the toggle switches 1 and 2 are in closed state as shown in Figure 3.12. This is the normal operation of the system. In this case, the PV modules and the grid system supplies energy to the electric load of the network. Figure 3.14 shows the power curve and Figure 3.15, and Figure 3.16 shows the voltage and current through the load during this mode. The dynamic behaviour of the network is summarized as follows. The PV and grid generate energy to accommodate the load of the system which is divided into two by breaker 4 controlled by toggle switch 4. The variation in the ac power, voltage, and current curves between the offset time t = 1.15secs to t = 1.53secs was when the balance half of the load was connected to the network through the toggle switch 4.

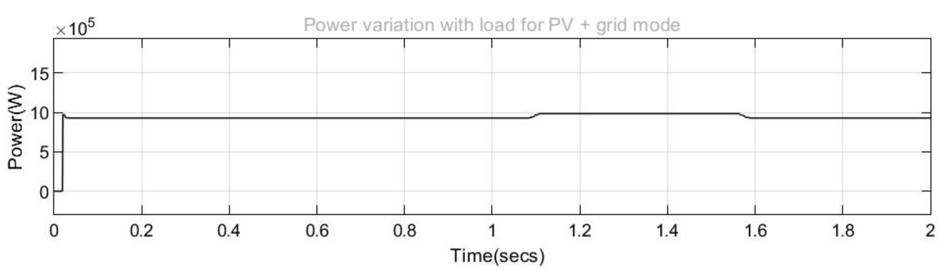

Fig. 3.14 Power variation with load for PV + grid mode

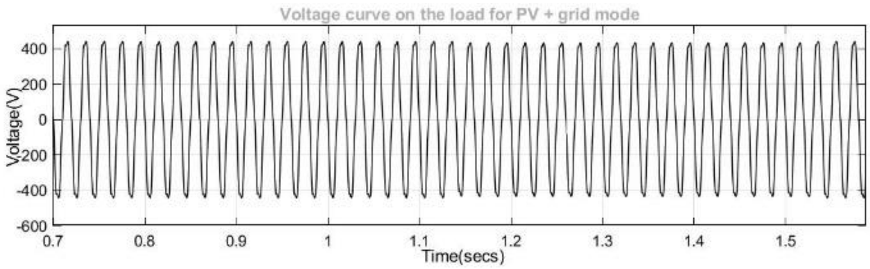

Fig. 3.15 Voltage curve on the load for PV + grid mode for a changing load

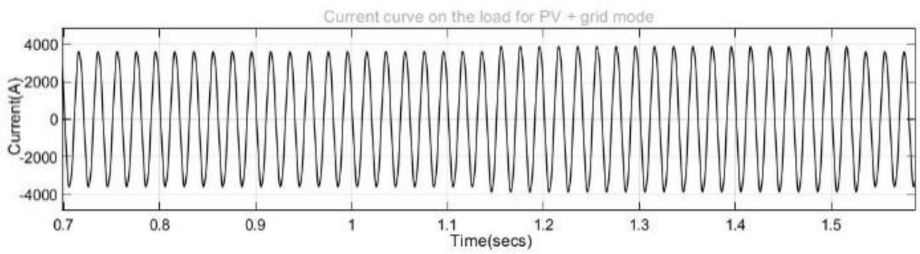

Fig. 3.16 Current curve on the load for PV + grid mode for a changing load

ii. PV + Generator mode

PV + generator mode is achieved when the toggle switches 1 and 3 are in the closed state while breaker 2 is open as shown in Figure 3.12. In this case, the switches were closed throughout the simulation while the electric load was varied through breaker 4. The transient behaviour of the system in response to this new state is depicted in Figure 3.17, Figure 3.18 and Figure 3.19 which shows the power curve and the voltage and current curves across the electric load. Load varies from 222kW to 272kW at t = 0.95secs and t = 1.43secs.

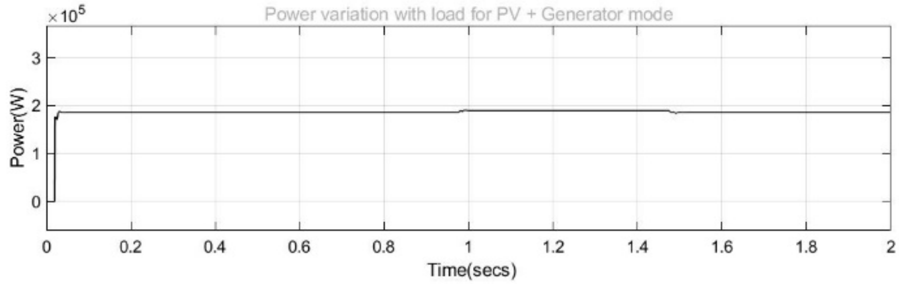

Fig.3.17 Power variation with load for PV + Generator mode

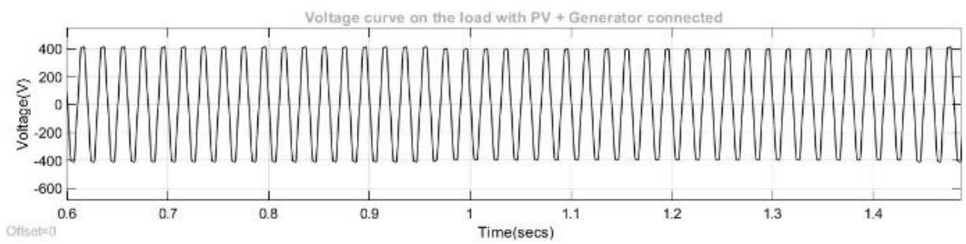

Fig. 3.18 Voltage curve on the load for PV + Generator mode for a changing load

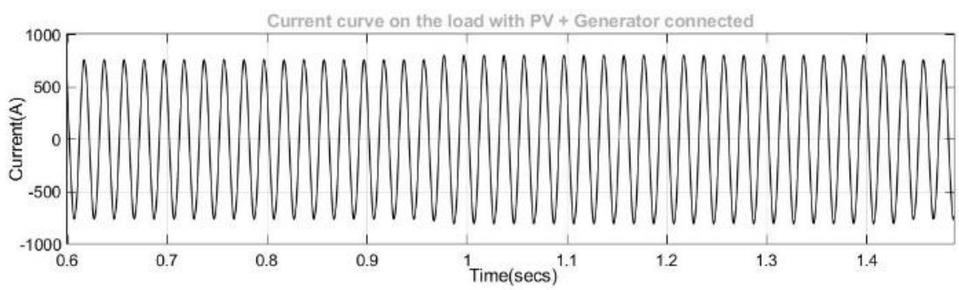

Fig. 3.19 Current curve on the load PV + Generator mode for a changing load

iii. Generator only

The generator is introduced into the network as an emergency backup in case the grid system fails when the PV system is not generating energy to supply the system load. Toggle switch 3 controls the generator circuit in the network. When it is ON, the generator is connected to the network and when it is OFF, the generator is out of the system. Figure 3.20, Figure 3.21, and Figure 3.22 shows the graphs of the power and voltage and current through the load when the electric load of the system is varied through toggle switch 4. This transient response on the graphs indicates the behaviour of the system when only the generator is connected to the network. At t = 1.0sec and t = 1.32secs, load increased from 222kW to 444kW.

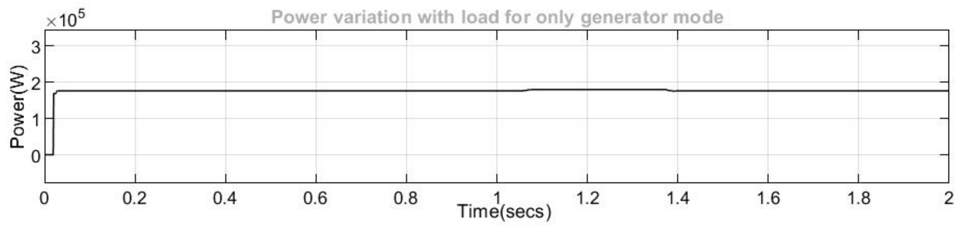

Fig. 3.20 Power variation with load for only generator mode

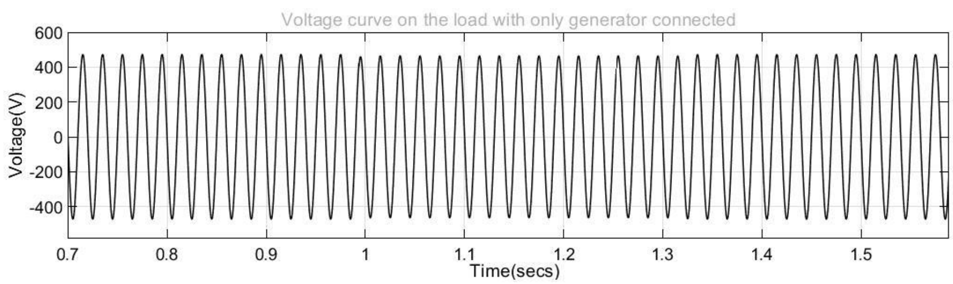

Fig. 3.21 Voltage curve on the load for only generator mode for a changing load

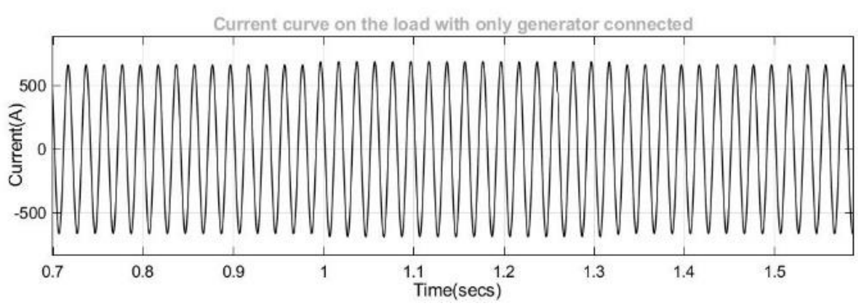

Fig. 3.22 Current curve on the load for only generator mode for a changing load

3.7. Conclusion

In this research, the dynamic simulation of a microgrid system for a university community in Nigeria is presented. The system designed was simulated in MATLAB/Simulink environment. The system consists of a PV size of 675.2 kW comprising of 96 cell modules each of 500W, with 25 connected in series and 54 in parallel. Also, a utility grid system and a diesel generator set in case of emergency were connected through toggle switches 2 and 3. Simulated results indicates that the system realized has acceptable dynamics as it responds appropriately when a new state was introduced to the network by varying the electric load of the network for three different cases. This was shown by the transient responses indicated on the system when the toggle switch 4 was turned ON and OFF to vary the electric load during simulation to meet the load demand of the university campus. We recommend Nigerian university community to find funds for implementation of such a system to have a reliable low-cost electricity.

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3.8. References

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Chapter 4

Reduced Order Model of a Microgrid System for a University Community in Nigeria

Preface

A version of this manuscript has been accepted for publication in the ***Jordan Journal of Electrical Engineering.*** *I am the primary author and carried out most of the research works, including the literature reviews, system design, dynamic simulation of the reduced order model and result analysis. I prepared the original manuscript and also revised the final manuscript based on feedbacks from the co-author and the peer-review process. The Co-author, Dr. M. Tariq Iqbal, supervised the entire research work, reviewed, made corrections and contributed research ideas for the actualization of the manuscript.*

This chapter is a version of "Reduced order model of a microgrid system for a university community in Nigeria", S. Ogbikaya and M. T. Iqbal, *the manuscript has been accepted for publication in the Jordan Journal of Electrical Engineering which will be available in the next issue of the journal this year.*

Abstract

This study presents the reduced order model of a microgrid system for a university community in Nigeria. In this paper, the designed microgrid system of the campus by Homer Pro software was simulated in MATLAB/Simulink environment to determine the system dynamics. The dynamic system obtained was then reduced to a single block subsystem with multiple input and a single output using system linearization. The microgrid model was then linearized with the aid of linearization tool in MATLAB/Simulink using linearized perturbation method. The transfer function of the multiple input with respect to the single output of the microgrid system was determined in MATLAB environment. The transfer functions obtained for both inputs were then incorporated to the subsystem to linearize the entire system. The linearized system obtained was reduced with the help of model reducer using the balanced truncation method in Simulink. Simulated results indicate that the system response of the linearized model obtained is linear when compared to the step response of the nonlinear microgrid model of the campus. Results also shows that the reduced order model obtained has lesser states with more than 4 times faster simulation response time. The step-by-step process of linearizing the nonlinear microgrid model of the university community using linearized perturbation method and the reduced order model with model reducer in MATLAB/Simulink are presented.

4.1. Introduction

System linearization is the process whereby a nonlinear real system is linearized about an operating point to improve responses. This include creating linear approximation of the nonlinear system in Simulink to produce a linear state space or transfer function model of the nonlinear system. This linearized model analyses stability, disturbance rejection and reference tracking of the system.

The reduced order model of a university campus microgrid is analysed and presented. In this case, linearization tool in MATLAB/Simulink environment that uses perturbation method was used to reduce the nonlinear model of the campus microgrid to a simplified linear model runs faster than full nonlinear system.

4.2. Literature Review

In publication [1], a reduced order model for modeling the inverter based microgrid system, which is computationally efficient and accurate was proposed. With the aid of developed reduced-order model, the main factor affecting microgrid stability were analysed. It was revealed that the stability limits for conventional droop-based system ($\omega - P/V - Q$) were determined by the ratio of inverter rating to network capacity, resulting into a smaller stability region for microgrids with shorter lines. This was also verified theoretically on the simplified and generalized network configurations. Their research revealed that the proposed reduced-order model not only maintain the modeling accuracy, but also computational efficiency was enhanced. Both frequency and time domain were used to verify detailed model. The linearization of each model was not considered in their analysis.

In paper [2] inverter-based microgrid reduced-order model was reviewed with the accuracy of their predictions for stability investigated by comparing it with a corresponding detailed average model. Their studies show that the simplified reduced order models affect the accuracy in various regimes of the line R/X ratios, and that inappropriate model choices would result in substantially inaccurate stability results. Finally, reduced order models for the stability analysis of microgrids was recommended. This work did not reveal the simulation time for the reduced order model obtained with respect to the microgrid system.

In paper [3] an ac microgrid consisting of inverter-interfaced distributed generators (IIDGs) was studied. This is a nonlinear complex system with multiple time scales which includes time delay measurements, frequency control and electromagnetic transients. Droop control-based IIDG in an ac microgrid was selected as the objective for this study which includes voltage and current-loop controllers, power droop controller and filter and line. Based on singular perturbation theory, the multi-time scale characteristics of the detailed IIDG model were divided. In addition, the IIDG small signal model the use of quadratic approximation method of the stability region boundary, and the static and transient stability consistency of the IIDG model order reduction were all demonstrated. By Prony transformation, the dynamic response consistencies of the IIDG model order reduction were evaluated using the frequency damping and amplitude. Results obtained were applicable to a simplified model for the dynamic characteristic analysis of IIDG systems in AC microgrid. With the aid of the eigenvalue comparison, the transient stability index comparison, and the dynamic time-domain simulation the accuracy of this proposed method was verified. The difference in the speed of simulation between the original microgrid system and the reduced order model was not considered.

In research [4], a reduced order modeling method of inverter-based microgrid for stability analysis was presented. In this work, a singular perturbation method was applied to reduce the full order model of the microgrid system. Based on the participation analysis of the original model, the dynamic system was divided into two subsystems with the state that has considerable effect on the dominant dynamics preserved and the state with negligible impact eliminated. The reduced order obtained in this work was verified by using numerical simulation and eigenvalue analysis to compare both original model and reduced models but the simulation time for each model was not taken into consideration.

A generic reduced-order modeling method suitable for exploring the dynamic stability of DC voltage control with two modes was proposed in paper [5]. It was discovered that each droop-based DC voltage control unit could be modeled as an RLC parallel circuit in these two modes. The essential causes of system dynamic stability difference and the physical control parameters for the two modes were revealed. Analysis also revealed that a modified RLC model could be used to obtain it influence if the inner current control with slow dynamic could not be ignored. Analytical solutions of dynamic performance indexes were obtained based on reduced-order model through the impact of the control parameters on the dynamic performance of the DC bus voltage. Detailed and experimental results were used to verify the effectiveness of the proposed reduced-order model. In this analysis, the linearization of the reduced order model obtained was not discussed.

Paper [6] present the dynamic behavior of a microgrid system using system identification techniques and eigen analysis. In this study, a nonlinear microgrid was developed in MATLAB/Simulink environment that was used to achieve linear approximation to perform eigen analysis. System identification technique was used to analyse system dynamic responses. The results obtained was then compared and evaluated in their work, but the speed of simulation was not considered for each case.

In the work presented in [7], a new distributed secondary control method for voltage and frequency regulation in islanded microgrids was presented. A large-single dynamic model of inverter-interfaced distributed generation (DG) was formulated with multi-input multi-output nonlinear system, that was converted to a partly linear one using input–output feedback linearization. The linear-distributed model predictive controller was then designated in each DG to realize the secondary voltage control by incorporating the forecasted behaviours of the local and neighbouring DG units. With the nonlinear DG dynamics transforming into a first-order linear system, a distributed proportional integral algorithm was introduced in the frequency restoration while maintaining the accurate active power sharing. The effectiveness of the proposed control methodology was verified in the simulation results obtained but time for simulation of each model was not presented.

In article [8], a single perturbation method and particle swarm optimization were used to simplify the model of an islanded microgrid system. The paper also presents two model order reduction methods through direct truncation were sixth order was reduced to fourth order approximation and particle swarm optimization further reduces the model order to the power of 2. Comparing various responses, simulated results shows that the second order reduction with particle swarm optimization shows more improved response than the other methods used.

The study in [9] presents an optimal reduction technique where 36th order model microgrid system was reduced to the 9th order approximant with the significant dynamics of the original system retained. Results obtained indicates that the proposed method was superior to the balanced truncation method in time and frequency domain. For the system stability, state perturbation in state space model was considered in full as well as reduced order dynamics and eigenvalue analysis.

Paper [10] presents a reduced-order dynamical modelling of droop-controlled inverter-based on low-voltage AC sub-microgrid in a hybrid AC/DC microgrid system. In their work, non-linear dynamical and algebraic equations were derived for the low-voltage AC side which was then linearized around an operating point. Simulated results for the developed model in MATLAB/Simulink was validated with that obtained from PSCAD. Validated results of the developed comprehensive reduced-order model can be used for fault detection. The speed of the reduced order model obtained relative to that of the nonlinear microgrid was not taken into account.

4.3. Methodology

The reduced order model for a university community microgrid is considered in this paper. A microgrid for a university community with electrical load consumption of 969,000kWh was designed in Homer Pro software. The dynamics of the microgrid system obtained from Homer Pro software was then simulated with the aid of

MATLAB/Simulink software. The dynamic system realized was then linearized by linearized perturbation method and finally, the reduced order model of the linearized system was obtained by model reducer using the balanced truncation method in MATLAB/Simulink environment. The speed of simulation of the reduced order model as compared to the full microgrid system was determined.

4.3.1. System Design

The selected campus for the system design is Edo State University Uzairue, Auchi, Edo State, Nigeria (7° 8'8.25"N, 6°18'28.13"E) located at Kilo-meter 7, Auchi-Abuja Road, Iyamho-Uzairue, Edo State, Nigeria. The pictorial and google map view of cross section of the university campus are shown in Figure 4.1 and Figure 4.2.

Fig. 4.1. Pictorial view of cross section of university campus

Fig. 4.2. Google map view of cross section of university campus

Based on the energy consumption of the university community as tabulated in Table 4.1, a microgrid was designed with the aid of Homer Pro software. This system consists of PV cells, utility grid, inverter, generator, and electric load. The schematic diagram of the microgrid system obtained from Homer Pro software is depicted in Figure 4.3. The work was presented in paper [11].

Table 4.1. Annual Energy consumption of Edo State University Uzairue from October 2020 to September 2021

Month	Previous meter reading (kWh)	Present meter reading (kWh)	Energy consumption (kWh)
October	3635000	3655000	20000
November	3655000	3689000	34000
December	3689000	3781000	92000
January	3781000	3836000	55000
February	3836000	3893000	57000
March	3893000	3986000	93000
April	3986000	4097000	111000
May	4097000	4254000	157000
June	4254000	4324000	70000
July	4324000	4411000	87000
August	4411000	4516000	105000
September	4516000	4604000	88000
Annual energy consumption			969000

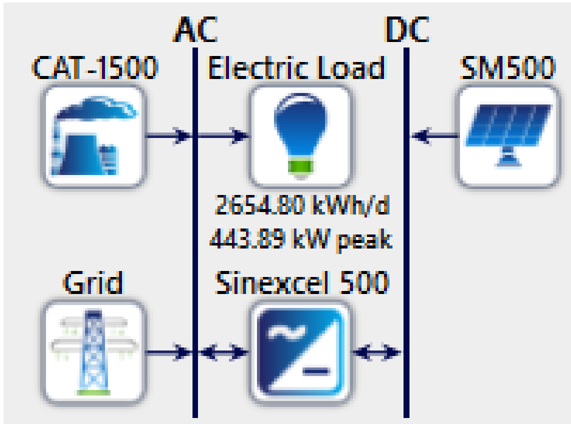

Fig. 4.3. Schematic diagram of microgrid system

4.3.2. Dynamic Simulation

The system obtained from Homer Pro design was simulated in MATLAB/Simulink environment to determine the dynamics of the system. The system consists of a PV size of 675.2kW comprised of 96 cell modules each of 500W, with 25 connected in series and 54 in parallel. Based on the PV size, an inverter of 700kW was used, also utility grid and generator were incorporated in the system. Figure 4.4 shows the diagram of the dynamic simulation obtained.

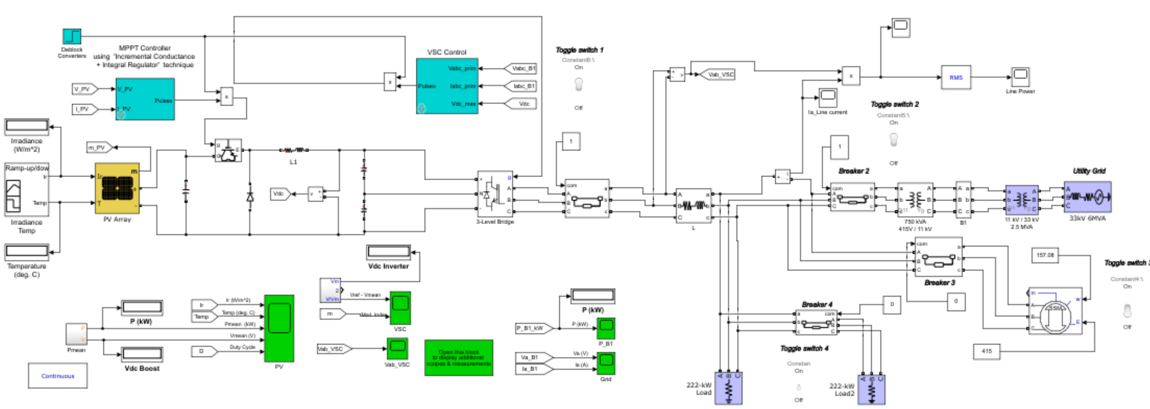

Fig. 4.4. Dynamic simulation of microgrid system

4.3.3. System Linearization

Linearization of the dynamic system was carried out in MATLAB/Simulink environment with the aid of model linearizer using linearized perturbation method. Linearization was done based on the system multiple inputs (irradiance and temperature) and a single output which is the power (i.e., current × voltage). The transfer functions of the inputs with respect to the output was determined by linearized perturbation method. The resulting transfer function obtained was incorporated into the subsystem block of the nonlinear system to linearize the system as shown in Figure 4.5.

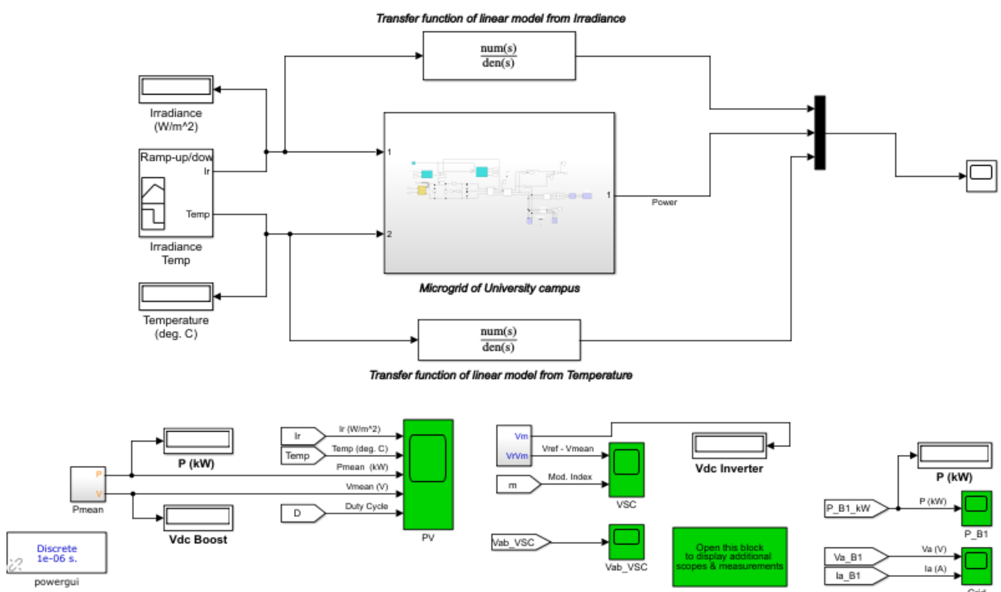

Fig. 4.5. Linearized microgrid model

With the aid of perturbation method, the linearized microgrid system was then simulated to determine the system response as compared to the step response of the nonlinear microgrid system.

4.3.4. System Reduction

The transfer function of the linearized model for both inputs as obtained in MATLAB environment with a simulation time of 81 secs at sample time set at 2 secs was first obtained as follows:

```
tf =

  From input "Irradiance Temp/1" to output "Subsystem/Power":

  -2.201e-11 z^17 + 2.106e-10 z^16 - 8.715e-10 z^15 + 1.984e-09 z^14 - 2.501e-09 z^13 + 1.142e-09 z^12

        + 1.45e-09 z^11 - 2.771e-09 z^10 + 1.668e-09 z^9 + 1.957e-10 z^8 - 9.087e-10 z^7 + 5.181e-10 z^6

                  - 4.447e-11 z^5 - 8.629e-11 z^4 + 4.652e-11 z^3 - 1.025e-11 z^2 + 8.781e-13 z - 1e-16

  ---------------------------------------------------------------------------------------------------------

  z^18 - 10.76 z^17 + 50.96 z^16 - 137.1 z^15 + 219.9 z^14 - 183.8 z^13 - 11.32 z^12 + 214.2 z^11

        - 233.3 z^10 + 82.52 z^9 + 55.89 z^8 - 77.02 z^7 + 31.78 z^6 + 1.713 z^5 - 7.309 z^4 + 3.224 z^3

                                                                  - 0.6452 z^2 + 0.0517 z + 1.193e-05

  From input "Irradiance Temp/2" to output "Subsystem/Power":

  -1.295e-11 z^17 + 1.239e-10 z^16 - 5.128e-10 z^15 + 1.167e-09 z^14 - 1.471e-09 z^13 + 6.714e-10 z^12

        + 8.533e-10 z^11 - 1.63e-09 z^10 + 9.811e-10 z^9 + 1.153e-10 z^8 - 5.347e-10 z^7 + 3.048e-10 z^6

                - 2.611e-11 z^5 - 5.078e-11 z^4 + 2.737e-11 z^3 - 6.027e-12 z^2 + 5.156e-13 z + 3.583e-17

  ---------------------------------------------------------------------------------------------------------

  z^18 - 10.76 z^17 + 50.96 z^16 - 137.1 z^15 + 219.9 z^14 - 183.8 z^13 - 11.32 z^12 + 214.2 z^11

        - 233.3 z^10 + 82.52 z^9 + 55.89 z^8 - 77.02 z^7 + 31.78 z^6 + 1.713 z^5 - 7.309 z^4 + 3.224 z^3

                                                                  - 0.6452 z^2 + 0.0517 z + 1.193e-05
```

Then the reduced order model of the linearized model was achieved by model reducer with the help of balanced truncation method in MATLAB/Simulink with it 20 states reduced to 5 states as shown in bode diagram Figure 4.6. As shown in Figure 4.6, two results match well up to frequency of 100rad/s.

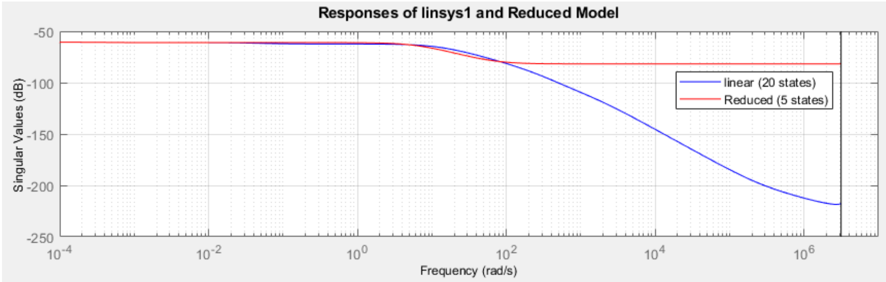

Fig. 4.6. Graph showing linear and reduced order model states

The large difference in the curves after frequency of 100rad/s between the two states as shown in Figure 4.6 is a result of the change in states from 20 to 5. The transfer functions for both inputs of the reduced order model as obtained in MATLAB environment with a simulation time of 48 secs at sample time set at 2 secs are as follows:

```
tf =

  From input "Irradiance Temp/1" to output "Subsystem/Power":
  7.043e-05 z^5 - 0.0003522 z^4 + 0.0007043 z^3 - 0.0007043 z^2 + 0.0003522 z - 7.043e-05
  ---------------------------------------------------------------------------------------
                        z^5 - 5 z^4 + 10 z^3 - 10 z^2 + 5 z - 1

  From input "Irradiance Temp/2" to output "Subsystem/Power":
  4.146e-05 z^5 - 0.0002073 z^4 + 0.0004146 z^3 - 0.0004146 z^2 + 0.0002073 z - 4.146e-05
  ---------------------------------------------------------------------------------------
                        z^5 - 5 z^4 + 10 z^3 - 10 z^2 + 5 z - 1
```

4.4. Result and Discussion

Simulated results obtained from the full microgrid system were compared to those obtained from the reduced order model. The comparison shows that the results of line voltages; Figure 4.7 and Figure 4.10, as well as the results of line currents; Figure 4.8 and Figure 4.11 are in close agreement. However, the output power waveform are shown in Figure 4.9 and Figure 4.12.

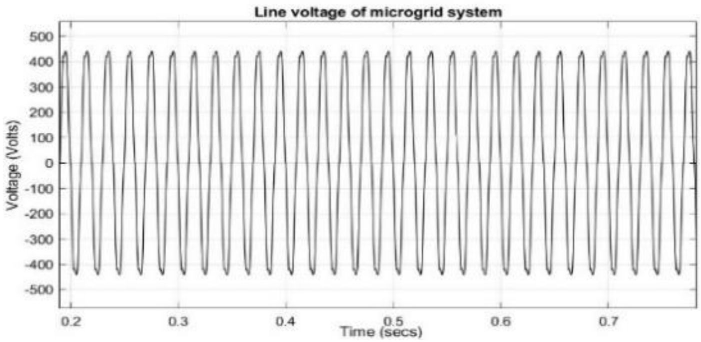

Fig. 4.7. Line voltage of microgrid system

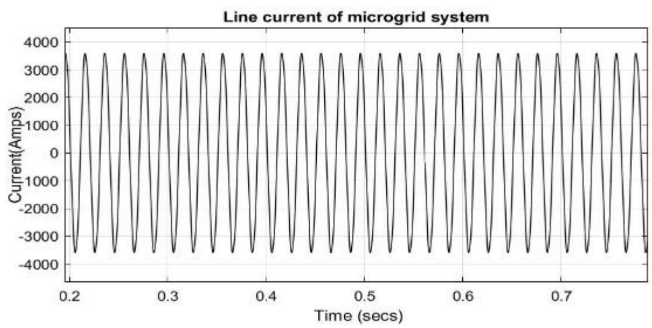

Fig. 4.8. Line current of microgrid system

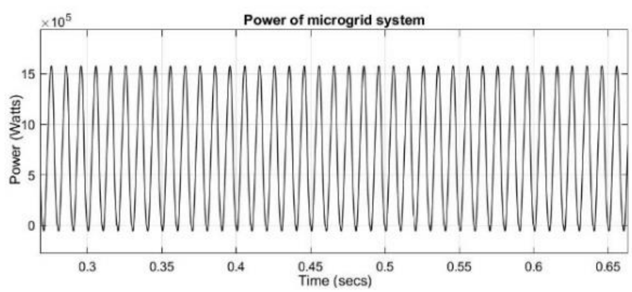

Fig. 4.9. Output power of microgrid system

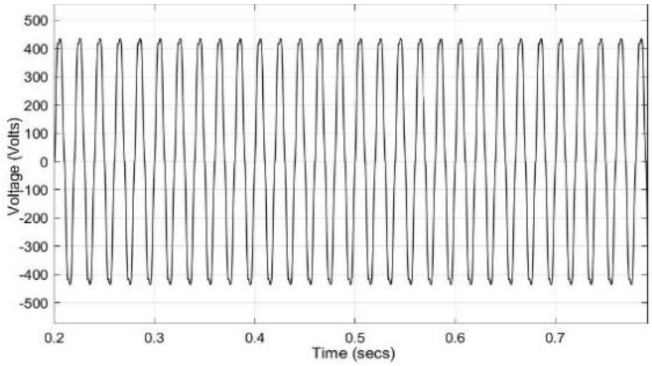

Fig. 4.10. Line voltage of reduced order model

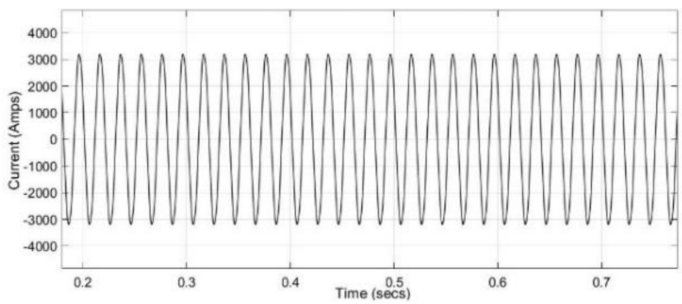

Fig. 4.11. Line current of reduced order model

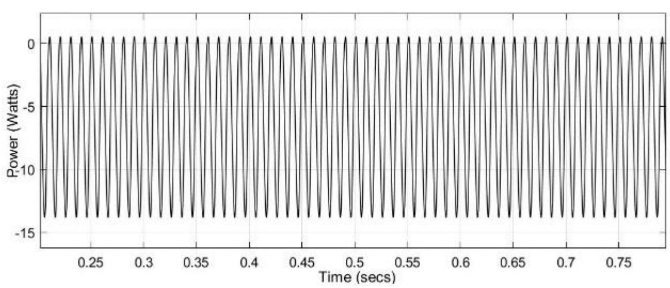

Fig. 4.12. Output power of reduced order model

Results also indicates that the nonlinear response of the full microgrid system of the university community as shown in Figure 4.13 and linearized as depicted in Figure 4.14 using linearized perturbation method in MATLAB/Simulink environment. The discrepancy of both figures is that Figure 13 has a step response of the nonlinear system while Figure 14 has a response of the linearized system.

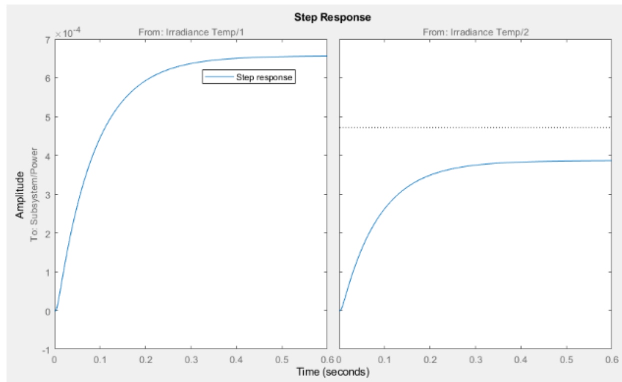

Fig. 4.13. Step response of nonlinear model

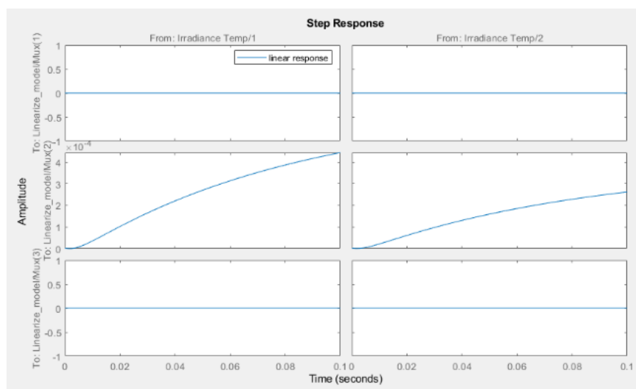

Fig. 4.14. Step response of linear model

The speed of simulation with three different sample times for the microgrid system and the reduced order model is shown in Table 4.2. It can be noticed that the reduced order model is 4 times faster as compared to the nonlinear microgrid model.

Table 4.2. Comparison table showing speed of simulation between university microgrid and the reduced order model for different sample time

Sample time (secs)	Microgrid model	Reduced order model
	Simulation time (secs)	Simulation time (secs)
1.0	86	20
2.0	222	48
5.0	589	120

4.5 Conclusion

In conclusion, the step-by-step linearization of a nonlinear microgrid model for a university campus in Nigeria was realized using linearized perturbation method in MATLAB/Simulink. The linearized model obtained with 20 states was then reduced to 5 states with the aid of model reducer using truncation method in Simulink. The results of the line voltage and current for the two model are very close. Moreover, the simulation time response of the reduced order model runs 4 times faster than that of the nonlinear microgrid model on the same computer.

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Chapter 5

Design of Monitoring System for Campus Microgrid System

5.1. Introduction

Monitoring of microgrid system includes real-time monitoring of distributed generation and supervisory control. Power monitoring technique provides an easy and reliable way to automatically retrieve and analyse the power quality of a system. Such power monitoring system automatically indicates if there is a potential danger to the system equipment. Monitoring of a microgrid system consist of a network of meters connected to the Internet to provide real time data on the power system facility. These systems feed an online software system that allows the service providers to identify any potential dangers on the electrical systems. Electrical equipment in power system network are aways connected to monitoring system. Hence, the system is essentially a monitoring tool that is connected to the Internet. Like a computer, the tools have large storage capacity that can continually monitor power and other physical quantities of a solar PV system.

The software management system of the microgrid system obtains information from sensors directly which are made available in real time that may trigger an alarm or send notification email when the power system malfunctions. Monitoring system can also serve as a proactive measure in term of energy management, system protection from damaging currents, voltages, surges, and overheating.

The fundamental infrastructure for modernization of power system is efficient monitoring mechanism for power quality (PQ) disturbances [1]. With power system monitoring, the problems of power quality distortion that results to constant power outages is taken care of by real time monitored cost-effective, high accuracy, responsive systems which respond quickly to imbalances in the microgrid system [2]. The knowledge of smart grid in power system operation needs intelligent monitoring of the various components of the network with quick responses as demanded. With smart monitoring and intelligent control, a microgrid with renewable sources can be built with smart grid technology [3] also, to ensure economic and reliable operation of microgrid system, smart monitoring of the relevant components is required [4].

To analyse the power flow of the system, monitoring is essential which in turn can be used as fault detection and localization when the device malfunctions [5] hence, monitoring of the microgrid system is inevitable for reliable, stable, and safe operation of a microgrid system. There are various monitoring techniques used in power system design, these includes SMA monitoring technique, ABB monitoring techniques, ATS monitoring techniques, Schneider monitoring techniques, Groov RIO monitoring technique etc.

5.2. Design of Monitoring System

Based on the campus microgrid system sizing and design (presented in previous chapters) consisting of a PV size of 675.2kW which comprise of 96 cell modules each of 500W, with 25 connected in series and 54 in parallel, an inverter of 700kW, a utility grid of 50Hz, 6MVA, 33 kV transmission network with a power transformer of 2.5MVA, 33/11 kV and a distribution transformer of 750 kVA, 11/0.415 kV, a 1.5MVA rating generator and the electric load of the university campus. A detailed instrumentation layout of a proposed monitoring system for each component of the microgrid system is shown in Figure 5.1.

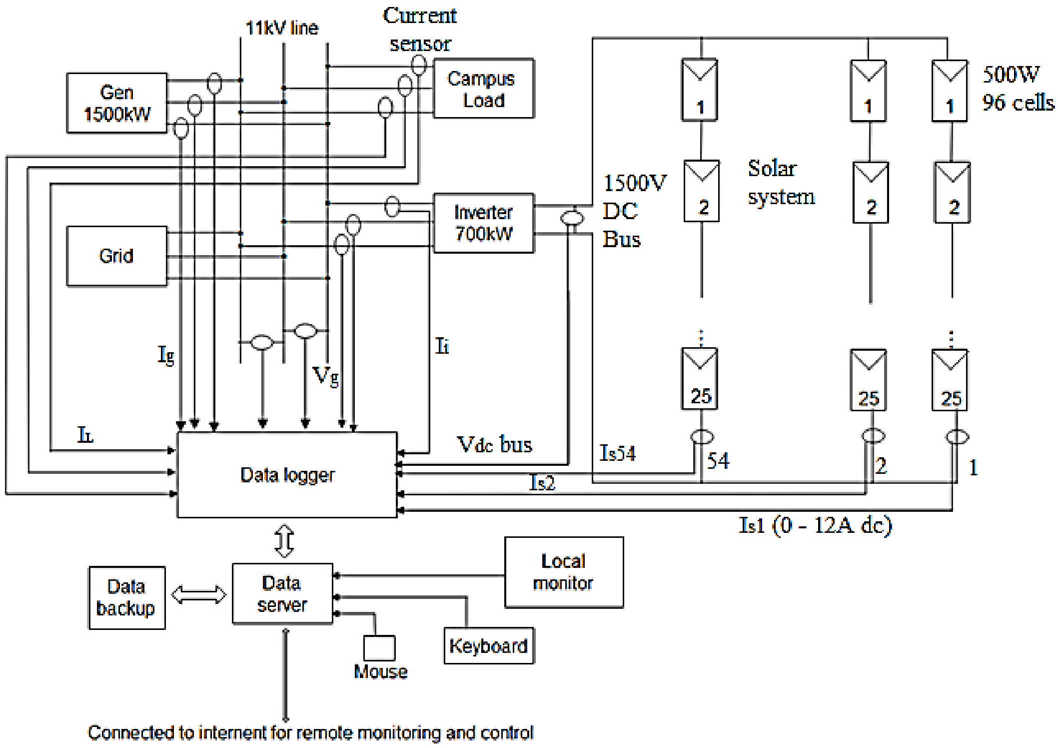

Fig. 5.1. Instrumentation layout of the monitoring system of campus microgrid system

From the design, each of the 25 series PV strings is connected to 54 number dc current sensor of (0 – 12) A to monitor the current from each of the 54 parallel PV cells to ensure that each string generates the appropriate design current. A dc voltage sensor is connected across the series string of the PV cells to ensure that the dc bus voltage is maintained at 1500V, which is the input of the inverter. To monitor the output current of the inverter, 3 number ac current sensor (0 -150) A are connected to each phase of the inverter and 2 number 11kV ac voltage sensor are connected across each phase of the inverter. To monitor the generator output of the microgrid system, ac current sensor of (0 -150) A are connected to each phase of the generator output and 11kV voltage sensor are connected across the generator output voltage. For the campus electrical load, the load current and voltage are monitored by (0 – 150) A ac current sensor and 11kV ac voltage sensor. All these sensors are connected to a central data logger where any abnormality can easily be detected. The data logger is connected to a data server (central processing unit) with a data backup where data can easily be recovered for analysis. The data server is connected to a local monitor for visual display, a keyboard, a mouse and finally to the internet for remote monitoring and control.

Based on the system monitoring design shown in Figure 5.1, the list of the components required for the microgrid system is tabulated in Table 5.1.

Table 5.1: List of components for microgrid monitoring

S/N	Components	Type of sensor	Make	Ratings	Number required	Unit price ₦	Total cost ₦
1	Solar panel	DC Current sensor	Cymatics 850-124	(0 - 12) A	54	14,946.65	807,119.10
		DC Voltage sensor	Phoenix contact	1500V	1	87,425.91	87,425.91
2	Solar inverter	AC Current sensor	Sensaphone FGD	(0 -150) A	3	47,817.57	143,453.73
		AC Voltage sensor	KEMET	11kV	2	36,124.01	72,248.02
3	Generator	AC Current sensor	Sensaphone FGD	(0 -150) A	3	47,817.57	143,453.73
		AC Voltage sensor	KEMET	11kV	2	36,124.01	72,248.02
4	Electric load	AC Current sensor	Sensaphone FGD	(0 -150) A	3	47,817.57	143,453.73
		AC Voltage sensor	KEMET	11kV	2	36,124.01	72,248.02
5	Data logger		ATS SmartDER			94,579.89	94,579.89
Total							1,636,230.15

In addition of above proposed custom monitoring system, the following types of commercial systems can also be used.

5.2.1. Groov RIO energy monitoring unit

The Groov RIO energy monitoring unit (GRV-R7-I1VAPM-3) is designed as an intelligent, distributed power and energy monitoring module. Based on the in-built configuration, commissioning, and flow logic software including support for multiple output and input protocols, the Groov RIO energy monitoring unit offers flexibility to fit into various projects, especially those that need energy data acquisition or communications, or traditional energy management control systems. Figure 5.2 shows the pictorial view of Groov RIO monitoring unit.

Fig. 5.2: Groov RIO Energy Monitoring Unit (GRV-R7-I1VAPM-3)

The groov RIO is designed to measure simultaneously volts AC (RMS) and amps AC (RMS) up to 400 VAC (wye) or up to 600 VAC (delta) circuits. It can also monitor three-phase AC current using 0.333 V, 1 V, or 5 A current transformers (CT). For signal accuracy, each phase can be configured to ignore signals below a specified threshold in power measurement and energy accumulation. Based on the two measured field inputs, the module automatically calculates a total of 64 data values, comprising of voltage and current; active, reactive and apparent power; power factor, frequency, net energy, and other values which may include accumulated energy values for all phases The groov RIO energy monitoring units (EMUs) can be applicable either as an edge energy monitoring unit communicating data between loads and data destinations or as a traditional energy monitoring unit configuring channels through control programs. It has a communication processor with two switched Gigabit

Ethernet interfaces, one capable of power over Ethernet connections and the other supplying power to the groov RIO. The commercial cost of Groov RIO Energy Monitoring Unit (GRV-R7-I1VAPM-3) is $895 which is very expensive as compared to the ATS SmartDER monitoring device.

5.2.2. ATS SmartDER monitoring device

The monitoring techniques adopted for the microgrid system obtained in this work is the ATS SmartDER monitoring, and control device based on the characteristics and low cost of the device. In this case, the output of each component of the microgrid system are connected to a meter and each of these individual meters are connected to a central monitoring system as depicted in Figure 5.3 while Figure 5.4 shows an ATS SmartDER device.

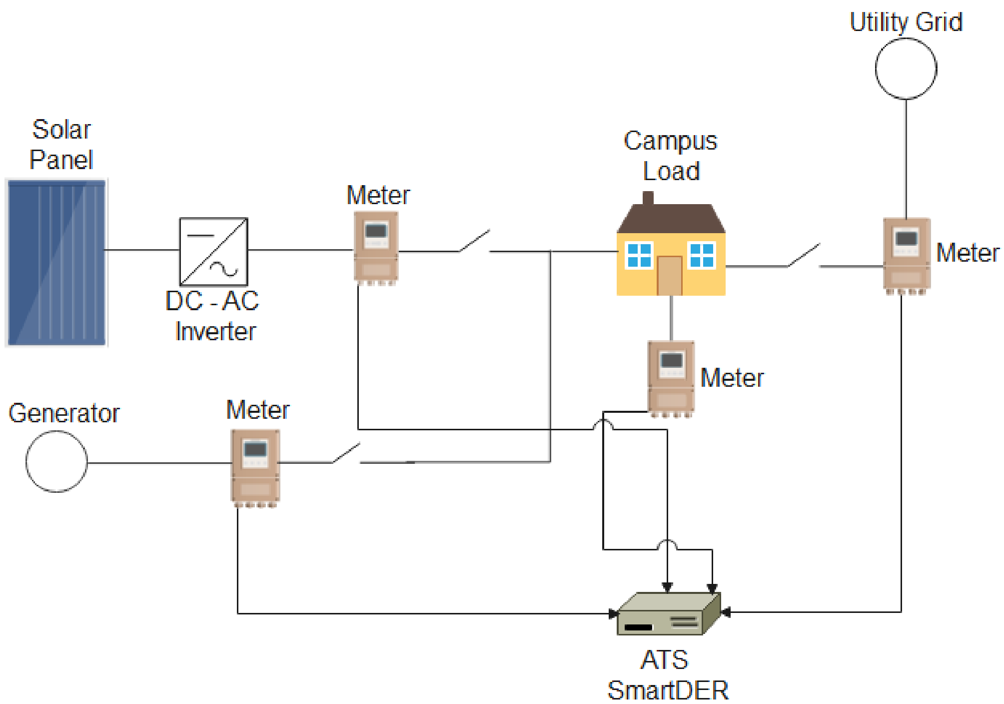

Fig.5.3: Monitoring system of a campus microgrid by ATS SmartDER device

Fig. 5.4: ATS SmartDER Device

ATS Smart distributed Energy Resource (DER) is a monitoring and control device for reliable connection, monitoring and grid-compatible power control of distributed energy resources which may include rooftop solar power farms. SmartDER provides the ability to connect various devices from the microgrid system with the aid of standard protocols and works as data exchange interface between plants and dispatch centers. These data can share with dispatch centers and customer's interface through a safe and secure connection channel (Internet/3G/4G VPN) to ensures that the power plant runs efficiently and helps stabilize the utility grid. The commercial cost of ATS module compared to Groov RIO energy monitoring unit is $296.67 which is less expensive.

An ATS SmartDER can be connected to the various metered output of the generating stations to monitor the microgrid system and information is sent to the dispatch center for proper analysis. Figure 5.5 shows the pictorial view of a typical communication diagram for connection of SmartDER.

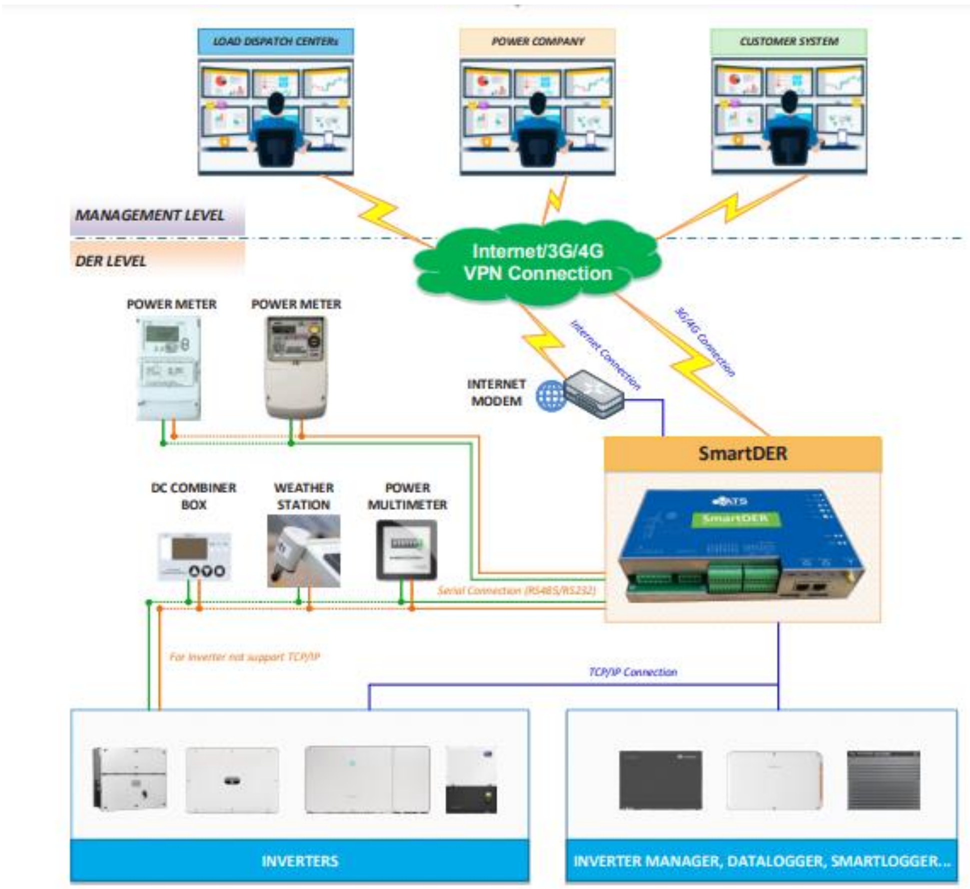

Figure 5.5: Pictorial view of a typical communication diagram for connection of SmartDER

5.3. Conclusion

In conclusion, for easy, stable, reliable, and safe operation of the university campus microgrid system, a monitoring system is an essential tool. This monitoring scheme consist of 54 number of dc current sensors, one dc voltage sensor for monitoring of the dc part of the microgrid system. To monitor the ac part of the system, 9 number ac current sensors and 6 number ac voltage sensor would be required. These sensors are connected to a data logger (ATS SmartDER) based on the characteristics and low cost of the ATS SmartDER device, this is then connected to a computer system (data server with backup, local monitor, keyboard, mouse) with internet for remote monitoring and control purposes. A custom system design is recommended to avoid data security issues and cost of software license always associated with commercial options.

5.4. References

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Chapter 6

Conclusions and Recommendations

6.1 Conclusions

Nigeria is a developing nation with enormous oil, gas, hydro, and solar resources for the generation of electricity for the geometric increasing population. Presently, she has a population of over 216 million people with a potential of generating 12,522MW from the existing grid network but only 4,000MW can be dispatched due to her weak transmission capacity. This has led to massive load shedding and frequent power outages on the grid network. More also, the rate of charge of 1kWh of electrical energy is very high, hence, communities, businesses and industries find it difficult to cope with this high price of electricity to maximise profit. To eradicate these challenges of constant power blackout and high electricity tariffs, a microgrid system is proposed.

In this thesis, design and simulation of a microgrid system for a university community in Nigeria is presented. The proposed site location for this research is Edo State University Uzairue, Auchi, Edo State, Nigeria (7° 8'8.25"N, 6°18'28.13"E) located at Kilo-meter 7, Auchi-Abuja Road, Iyamho-Uzairue, Edo State, Nigeria. Presently, the campus suffers regular power outages from the grid network and pay as much as ₦52.18 as electricity charge per kilo watt hour which is too exorbitant.

Firstly, a microgrid consisting of the grid system, 3,726 solar panel of 0.5kW, diesel generator of 1.5MVA and inverter of 500kW installed in an area of 17,696m2 at a cost of ₦295 with a simple payback of 3 years and 5 months was designed with the aid of "HOMER" Pro to meet the load demand of the university community at a reduced cost of electricity bill by 88.0%. The site details, load data and microgrid system design in this case was presented. Analysis indicates that the proposed system makes economic sense and will greatly help the university bring down its electricity bill, this will also help the university reduce its CO_2 emissions. The challenges in this design were the large PV size of 1,863kW required for system installation.

To solve this problem of large PV size obtained in system design with the aid of Homer Pro software, other software such as OpenSolar, PVWatts and REopt were used to design the same system to obtain optimal PV size. The optimal PV size of the system obtained consists of a PV size of 675.2 kW comprising of 96 cell modules each of 500W, with 25 connected in series and 54 in parallel. Also, a utility grid system and a diesel generator set in case of emergency were connected through toggle switches 2 and 3. The system was then simulated in MATLAB/Simulink environment to determine the dynamics of the university microgrid system. Simulated results indicates that the system realized has acceptable dynamics as it responds appropriately when a new state was introduced to the network by varying the electric load of the network for three different cases. This was shown by the transient responses indicated on the system when the toggle switch 4 was turned ON and OFF to vary the electric load during simulation to meet the load demand of the university campus.

Dynamic simulation of the system was extremely slow. To solve that issue, a step-by-step linearization of the nonlinear microgrid model for a university campus in Nigeria was realized using perturbation method in MATLAB/Simulink. The linearized model obtained with 20 states was then reduced to 5 states with the aid of model reducer using truncation method in Simulink. The linear model obtained has a linear response when compared to the step response of the entire microgrid system. Also, the reduced order model achieved is more than 4 times faster in terms of simulation response time.

The monitoring technique consist of 54 number of dc current sensors (0 – 12) A, one dc voltage sensor (0 - 1500) V for monitoring of the dc part of the microgrid system. To monitor the ac part of the system, 9 number ac current sensors (0 – 150) A and 6 number ac voltage sensor of 11kV would be required. These sensors are connected to a data logger (ATS SmartDER device) which is connected to a computer with internet for remote monitoring and control of the entire microgrid system.

6.2. Research Contributions

- Identification of power challenges faced by Edo State University Uzairue, Auchi, Edo State, Nigeria based on interruption and high cost of electricity.
- System design and PV sizing of a microgrid system for a university community in Nigeria with Edo State University Uzairue as a case study.
- Dynamic simulation of the campus microgrid system to determine the system response with variance in the electrical load.
- Design of a reduced order model for the university microgrid system to increase the speed of simulation of the system.
- Design of monitoring system for both the PV (dc) and the ac network of the campus microgrid system.

6.3. Further work

- Nigerian university communities are recommended to find funds for the implementation of microgrid system to have a reliable low-cost electricity that is readily available and stable with an affordable low initial capital cost of installation.
- In system design with PV sizing, optimization of the PV size (kW) should be considered by various software for the system sizing to obtain the optimal PV size required for the installation of the PV cells.
- It is also recommended that the dynamic behaviour of the designed system should be determined to know how the system would respond to variation in electrical load on the network. This would help the engineer to know how the system would react to changes in electrical load in the network as electrical load is dynamic.
- In designing a microgrid system, the monitoring system for both the dc and ac network should be considered to detect any abnormalities in the operation of the system.

6.4. Publications

- S.Ogbikaya and M. T. Iqbal "Dynamic Simulation of a Microgrid System for a University Community in Nigeria" *2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS),* 01 – 04 June 2022, 10.1109/IEMTRONICS55184.2022.9795822.

- S. Ogbikaya and M.T. Iqbal, "Design and Sizing of a Microgrid System for a University Community in Nigeria" *2022 IEEE 12th Annual Computing and Communication Workshop and Conference (CCWC),* 26 – 29 January 2022, 10.1109/CCWC54503.2022.9720908.
- S. Ogbikaya and M.T. Iqbal, "Design of a hybrid power system using Homer Pro and iHOGA", *30th IEEE NECEC conference,* 18 November 2021.
- S. Ogbikaya and M.T. Iqbal, "Reduced order model of a microgrid system for a university community in Nigeria", *manuscript has been accepted for publication in the Jordan Journal of Electrical Engineering which will be available in the next issue of the journal this year.*