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Integration of Solar Energy Optimization for Grid System Improvement

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ABSTRACT–Power supply in the rural areas has been insufficient due to inability of power generation companies to generate and supply constant power to these communities; as a result of this, there have been greater number of migrations from rural to urban areas. Commercial activities have been in the decline as business operators have turned to fossil fuel to power their generators to keep their businesses running. There have also been wastages of agricultural produces as a result of inconsistency in power supply. Despite all of these, there has been enough sunlight which when tapped will solve this challenge, hence the need for this research work. In this work, solar energy, storage energy from the battery and power from the grid system were integrated and optimised for efficient power supply. Manta Community in Abak Local Government Area of Akwa Ibom State, Nigeria was the study location for this research work. The load consumption rate for this site was 3.11MWper day/month/year. Particle Swarm optimization (PSO) was used for the optimization of the power rating, and the time of the operation of the micro-grid sources were: the power from the national grid system operated from 12 midnight to 8am(8 hours), the solar PV operated from 8am to 5pm(9 hours),while the energystorage from the battery operated from 5pm to 12 midnight(7 hours). Techno-economic analysis was conducted and a comparative analysis carried out before and after optimization shows that the Internal Rate of Return (IRR) increased from 18.722%to20.631% after optimization; Payback Period (PP) shoots up from 0.333year to 0.325year. Net Presence Value (NPV) grows from ₦277,155,657 to ₦289,024,685. The outcome showed that the optimal design performed better than the design without optimization.

KEYWORDS: Electricity, Optimization, Integration, Solar energy, Particle Swarm optimization (PSO).

I. INTRODUCTION

The power system grid is defined as a system that comprises of distributed energy sources, which are: the main power source, power storage systems and power loads. The distributed energy sources were mainly renewable sources and fossil fuel. In recent times, government across nations have embarked on plans to eradicate or possibly reduce the utilization of generators with fossil fuel sources; and to introduces the renewable sourced energy to increase environment and atmospheric friendliness. A micro-grid can also be defined as part of component of a power distribution system where the power generation sources and the present loads can form an isolated electrical power system. At normal operating condition, a micro-grid can be connected to the AC grid especially when the power source is a DC source. The type of current generated from renewable sources is a DC source hence, the need for the introduction of an inverter (or a Converter) to the micro-grid to ensure that the current was converted to AC current for onward transmission to the loads. However, the use of converter for conversion of current from AC to DC to ensure the availability of power in the storage device. Storage devices remain one of the components that makes up the micro-grid. The use of converter was necessary especially when the power generated is higher than the load available; Next, the remaining energy is made into direct current (DC) and put into the storage cells to serve when the power demand goes up. The use of converters is to ensure that the different energy sources utilized is properly interfaced. In some cases, when there is excess power, one or more of the sources will be disconnected and utilized as an island mode (a situation where the power source is rendered nonoperational, dormant model or utilized as an energy source in another location which implies boosting the voltage rating for onward transmission to the location of interest). The power system grid

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can be operated in two modes namely; grid connected mode or islanded mode. In grid connected modes, the micro-grid trades power with the existing utility grids to generate high number of profits and increase power availability to consumers. With no links to the main electrical network, an islanded microgrid acts independently all by itself. Because of this, it doesn't need the main grid and can keep producing energy, keeping the service steady in the event of an outage. That distribution energy sources installation can be always considered as a micro grid when it contains clear electrical boundaries, supplies critical loads and when operated by an appropriate controller as a single unit. Some authors carried out further analysis on the possible components of the smart grid and found that smart switches, protective devices, communication devices and automation systems were part of the smart grid.

In this paper, a smart grid is designed and integrated with solar system. Additionally, storage cells and converter will be introduced for energy storage and conversion of DC-AC-DC. The location of interest would be to the integration of the renewable system to the 33kV utility grid in Uyo (precisely at Manta community located in Abak Local Government Area, Akwa Ibom State, Nigeria). Hence, the amount of load will be obtained, integration model be determined with an optimization technique utilized to optimize the grid. This will make power available at a lower cost and also lower uncertainty issues. Hence, the operational economic analysis and the rate of power would be obtained at the various levels of the optimization (while ensuring power availability, the economic analysis and the power flow progress would be the objective function to the optimization technique because the higher the amount of power available, the higher the level of power congestion on the lines which results in the increase in power losses).

II. MICRO-GRID SYSTEM

Better electricity supply over the 20th century made it possible for society to develop and become healthier. Nevertheless, access to electricity is not the same everywhere, since many nations continue to have low or no electrification, low electricity use per person and unstable power supply (Table 1). Because they have fewer people and are isolated from many services, as well as dealing with high absenteeism from school, poor access to health and insufficient clean water, rural communities face many challenges. All these elements keep rural living standards way below those found in urban areas [1]. The difficulty in electrifying rural areas is also caused by the high expenses of adding power lines which the local market does not find profitable. Because of the drive to give everyone energy, more interest has emerged in using decentralized electrification methods. Off-grid small-scale electricity generation provides a good option, be it the initial part of electrification or a basic base for enlarging the grid in the future. IEA believes that, to reach universal access, off-grid power systems will account for almost two-thirds of the extra electricity needed. It is expected that off-grid solar systems will make a big difference in places that are without electricity, since most rural areas are now using renewable energy and mini-grids.

Table 1 Continental Aggregate to Power Access [1]

Continent	Population without power (millions)	Rate of Electrification	Urban Electrification	Rural Electrification
Africa	600	43	65	28
Developing Asia	615	83	95	75
Latin America	24	95	99	81
Middle East	19	91	99	76
Developing Countries	1252	76.5	90.6	65.1
Transition economies	1	99.9	100	99.7
World	1258	81.9	93.7	69.0

Small scale Power generation systems

More attention is being given to small-scale generation systems in electric utility plans in developed and developing countries. Still, psychologists have used this method for some time. In the beginning of the electrical era, there were a number of small power plants that stored power in batteries to feed DC grids to heavily populated places. Following AC grids and progress in power plants, the initial phase of small-scale generation finished and extensive transmission networks along with large plants were built. After the changes, there were vertically integrated state monopolies and this became the primary organizational model for centralized power systems [2]. Even though centralization was implemented in both types of countries, developed nations succeeded in providing electricity to remote areas. Unlike ACs, DCs are still facing difficulties by generating more electricity and boosting electrification rates (Table1). The needs of those who live in rural places are overlooked since the government usually pays more attention to urban areas where most jobs are found. The high costs of extending the main power lines make many companies hesitant to provide electricity to rural people.

The influence of large controlling utilities in developed countries reduced because competition emerged in the electricity market. In the same way, developing countries (DCs) made changes to lure foreign private investors and help their power systems operate more efficiently and electrify more people. Once the reforms had taken place, a new trend saw many small-scale generation systems emerging mainly from renewable energy sources. Besides rivalry in the market, extra reasons led to the revival of decentralized generation methods. The review of literature shows that these factors can best be organized into five groups: environmental, economic, technical, political and social (as indicated in Table 2). Though all of these variables are important, certain circumstances in DCs and rural areas encourage the usage of these small plants even more [3].

- Small-scale renewable systems are favoured in remote locations because the main grid is very expensive to reach.
- Small-scale generation is good for rural parts of the world without electricity because they show low use and demand for energy.
- International institutions started to emphasize poverty-based strategies from the mid-1990s and introduced tools like the Millennium Development Goals and making 2012 the International Year of Sustainable Energy for All. They made it apparent that modern energy is essential for improving where people live and what they need in life. Consequently, electricity was recognized as crucial for rural areas and choosing to generate it on a small scale was regularly considered the best option.
- It is believed that by using advanced technologies, DCs can skip some parts of history that developed nations had to go through. Small-scale generation technologies such as those for photovoltaic systems, have often been set up as the standard for rural electrification and regarded as a case of leapfrogging despite criticism.

The trend in developed nations is for small-scale generation systems, called distributed generation, to link closely with the major central grid. Off-grid small-scale generators are having an important impact on rural electrification in developing nations [4].

Table 2 Factors leading to interest on small scale generation [4]

Factors	Description
Environmental	The increase in worries about releasing more greenhouse gases, negative impacts on nature and the disapproval of new power line construction are urging more people to choose environmentally friendly energy options like mini-grids, solar panels and energy-efficient distribution services to minimize pollution and address climate problems.
Economic	In order to circumvent Transmission and Distribution costs, handle the risk of making big plant investments, use CHP for reduced plant costs and improve profits in the competitive market.
Technical	Both small power energy devices' performance and the technology of measuring and controlling them are better today and people now demand more reliable power.
Political	To make less use of fossil fuels, to use various energy sources and to avoid depending entirely on one system for resources.
Social	More people now want to support environmentally friendly technologies, focus on communities that manage their own energy and care about sustainability.

Electricity for Production

Being able to use energy helps fulfill people's basic requirements and boosts their economic activities. A shortage of energy could prevent some people from receiving important services and similarly, if energy is both inconsistent and costly, it may deny poor people the opportunities to make a living. Energy use in agriculture and rural areas is crucial for the development of DCs by helping their economies. Since agriculture is a major income source, it is necessary to boost agricultural practices to help DC's economies. In the countryside, being able to make an income and secure enough food usually depends on farming [10]. By providing energy services, farmers in rural areas can improve their lives by doing things such as preparing the land, irrigation, planting, harvesting and processing their crops after harvesting. Small farmers usually create micro and small enterprises (MSEs) and a large share of these are run by women in the household. The businesses in this industry are milling, food processing, curing tobacco, making pottery and similar activities. Rural industries are important for economic growth and keep people from leaving villages by assisting various shopkeepers, bakers, smiths and brickmakers [11,16]. MSEs need energy for their activities and the amount of electricity they take can be anywhere from a few kilowatts to more than a few hundred. Even though there is a lot of research on small-scale generation systems, there is no universal way to define or classify them. Most systems for classifying development centre on wealthy countries, not focusing much on rural electrification in DCs. Therefore, a new category of taxonomy is introduced that meets the needs of rural DCs for energy resources. At the start, the framework outlines the fundamental aspects, then describes the Off-grid Systems Matrix and later gives various classifications along with their definitions. This taxonomy relies on two main points:

- In most rural areas, it is challenging to use centralized energy systems which is why off-grid approaches are preferred. Consequently, our classification includes only systems that work separately from the public electricity grid which are called off-grid systems.
- As rural areas can have limited power sources and consistently high rates for electrification described in the literature, we set the maximum power allowance for off-grid systems at 5MW which is the level other researchers call small scale distributed generation.

The Off-grid Systems Matrix shows how small off-grid systems are sorted, listing different perspectives in each row and column [12].

Table 3 Off-grid Systems Matrix for rural electrification systems [12]

OFF - GRID SYSTEMS MATRIX	**DECENTRALIZED**		**DISTRIBUTED**
Rural Energy Uses	**Stand- alone System**	**Micro – Grid Systems**	**Hybrid Micro – Grid Systems**
Household basic needs	Home – based System	System including a distribution grid	System including a distribution grid
Community services	Community based Systems		
Productive uses	Productive – based Systems		
Consumer Number	Single	Multiple	Single OR Multiple
Energy Sources	Single		Multiple

The shown columns represent the major categories of small-scale generation systems. They are organized in this way because while energy is used in different places, the way it is changed, moved and sent to customers is done in a planned way. So, systems differ in this way because they address these points in various ways. The rows feature three more elements that matter specifically in each community. Besides what was discussed before, this classification also covers how many people are using the off-grid system and which energy sources they use. This point shows how different single-source systems are from multi-source off-grid systems.

Solar PV system Integration to the Grid

PV systems are made of various items, for example, solar cells, support structures and management systems for handling electricity. Whenever there is plenty of sunlight, the system can produce its highest amount of power, measured in kW. Local utility grids receive electricity provided by grid-connected solar energy systems. Though many home systems for solar exist, large solar installations can create thousands of gigawatts. [8]Jainlooked at how PV is integrated into the electricity grid using experience curves and said that knowing the total PV shipments worldwide can help determine the point where PV is cost-effective. Sunlight duration was studied in Saudi Arabia to assess the cost-effectiveness of a 5 MW grid-connected solar farm. encourage Kuwait to have solar PV systems to handle their peak electricity demand. Wei et al. discovered that PV stations help handle the extra need for energy at daylight hours and decrease the overall amount of energy used. Ito et al. examined the feasibility of a 100 MW PV system built in the Gobi Desert by checking its energy payback time, carbon dioxide emissions over the design life and costs during operation. He examined the financial aspects of FSCPP by looking at cash flows during their 100 MW plant's entire operating time.

Under the PERMER project, supported by public-private collaborations, [18] Zhao investigated the use of small-scale PV plants in households, schools and community buildings in rural areas, who were switching from traditional ways of getting energy. He talked about how 3kwp PV plant was installed for a school, health centre, staff housing. The cafeteria at Indian Institute of Technology, he was provided with a 25kwp solar PV array placed on its roof and facing 15°. He looked into a PV system with solar air collectors and a shading system that was installed on a high school's rooftop.

HRES include using both solar PV and an alternate energy source such as a typical generator or wind generators. Such systems try to decrease the use of resources that are not available after depletion. Barton et al. built a model that makes sure wind turbines and solar PV arrays can adjust to the changing electricity demand. They followed this method by using time-stepping with different power ratings, efficiencies, wind turbine capacities and solar PV capacities. They checked and adjusted the sizes and water flow plans of wind, solar and mixed systems according to the local conditions of the off-grid regions. According to El-Ela [1], approaches to model and review HRES emphasized that using solar-wind solutions together is becoming more common, though there are hurdles related to their connection to modern power grids. Thanks to being built in multiple locations, these systems give people better and more reliable energy. The researchers evaluated how well wind-solar energy storage could be used for cellular base stations. He built a model to provide reliable energy by improving wind-PV-battery systems using key factors such as LUC, REPG and UEP. [1.13] came up with a group of photovoltaics and fuel cells, plus an electrolyser to make hydrogen and a fuzzy regression model to help them extract most solar energy, even when there were changes in sunlight intensity. [18]Zhaocame up with a solar-hydrogen model, tested it with MATLAB/Simulink and studied how it handles grid disconnection and connection. The researchers analysed how to choose an RFC, how much battery storage is necessary, different charging and discharging patterns and what system limitations might be.

Kennedy [9] performed an economic evaluation comparing systems with wind/PV/battery energy with those containing wind/PV/fuel cell (FC) elements designed for residential areas in the US Pacific Northwest. The study demonstrated that having a wind/PV/battery system was more economical than having a wind/PV/FC/electrolyser system which underlines the importance of making progress in fuel cell and electrolyser technologies. Al-Thani suggested linking PV, wind and fuel cells in a hybrid energy system that is fully improved through the use of fuzzy logic control for maximum performance. Thanks to their model, both PV and wind sources efficiently send power to a fixed DC voltage bus.

III. MICRO GRID MODEL

For the design of the micro-grid, the following postulations were made:

- All sources of power supply match the power needed by the equipment.
- Power from the batteries can supply homes for an average of 4 hours.
- The system works for 8 hours a day.
- Power is supplied by the national grid for the rest of the day during the night.

Power rating of the solar PV system.

.$P_{pv} = a_o + a_1 P_{load}$ Equation (3.1)

Where:

P_{pv} Represents Power from the solar PV,

P_{load} Represents Power from the load,

a_0 and a_1 Represents rise in load with time period.

The current signal required is shown in equation 3.2.

$$i_{pV} = \frac{2.33 \log (P_{PV})}{nV^2}$$

Equation (3.2)

Where:

n Represents the sunshine hours.

V Represents the voltage signal of the solar PV.

The power output from the battery storage is shown in equation 3.3.

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$$P_{batt} = n * \frac{P_{PV}}{i_{PV} * V} * 2$$

Equation (3.3)

Where, P_{batt} Represents the power output of the battery.

PSO optimization

The model utilized for the objective function is shown in equation 3.4.

$$\text{obj fun}: f\left(P_{PV}, P_{batt}, P_{ng}\right) = x_0 P_{PV} + x_1 P_{batt} + x_2 P_{ng} - P_{load}$$

Equation (3.4)

Constrained to;

$$0 \leq x_o, x_1, x_2 \geq 1$$

Where, P_{ng}represents the power from the national grid.

The flow chart of the optimization of the grid system is shown in figure 1.

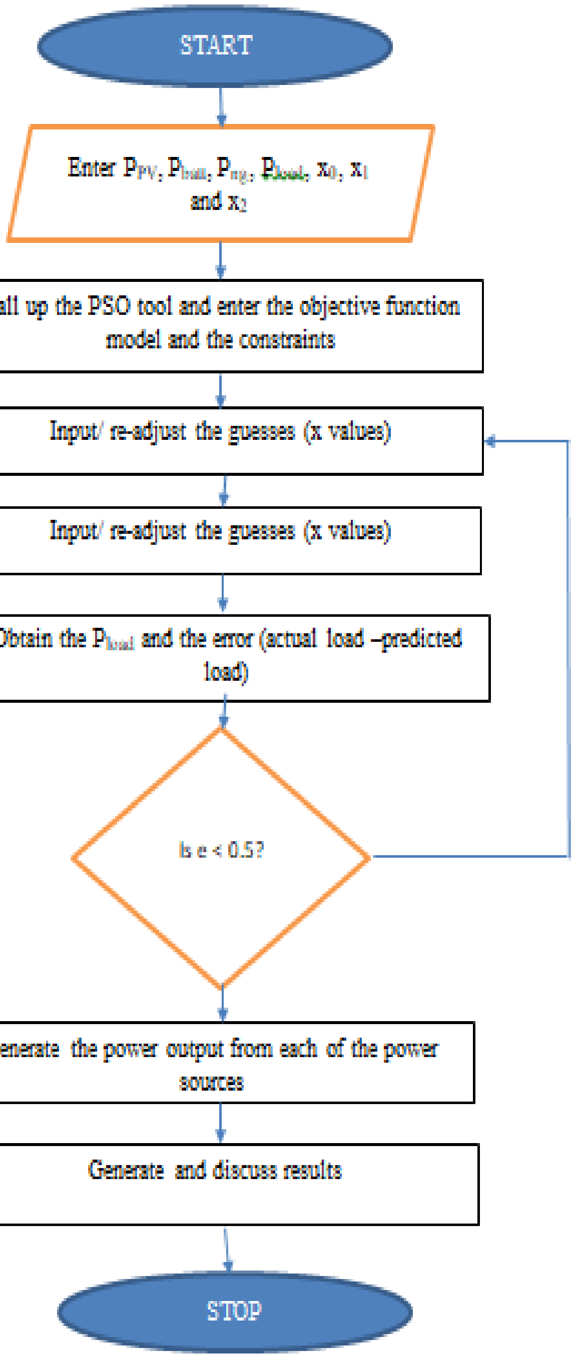

Figure 1 Flow chart of the optimization of the micro grid

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3.2 Economic Analysis

The financial review of the micro-grid involved using the following steps:

- Calculating what the parts of the micro-grid will cost.
- Evaluating the costs for running and maintaining the project to check its sustainability in the long term.
- Estimating the money that will be generated from the tariff system.
- Checking metrics about the financial health of the company, such as:

The calculation of Net Present Value (NPH) Internal Rate of Return is another name for it.

Payback Period

The way to write the capital cost (CC) equation is:

$$CC = N_{spv}\ C_{spv} + N_{batt}\ C_{batt} + N_{inv}\, C_{inv}$$ Equation (3.5)

Maintenance cost obtained was 15% of the Capital Cost (CC).

From site inspection carried out, it was found that residential user's average remittance was ₦4000/residents and the community approximately 2500 houses. The average tariff remitted by the commercial users was ₦22,000 and that 560 commercial outlets (including churches, schools, lock up shops and hospitals).

IV. RESULTS

Load demand of the case steady cites is shown in figure 2

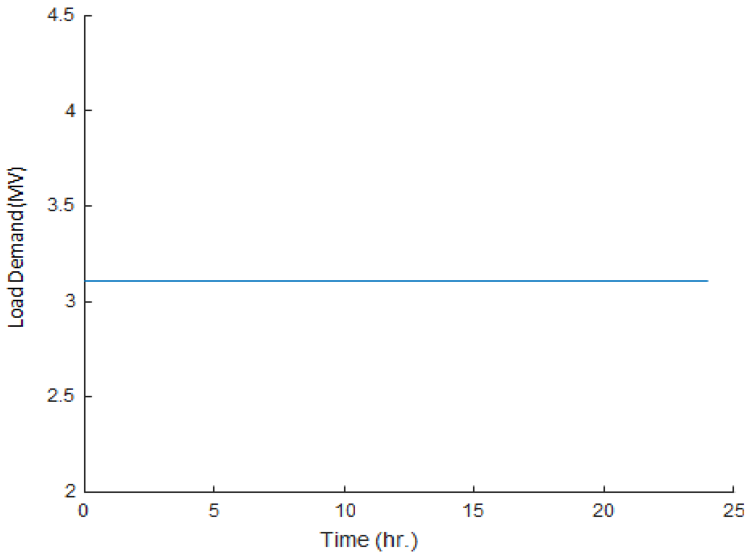

Figure 2 Load demand of the case study cite

The voltage signal of the Solar PV system is shown in figure 8

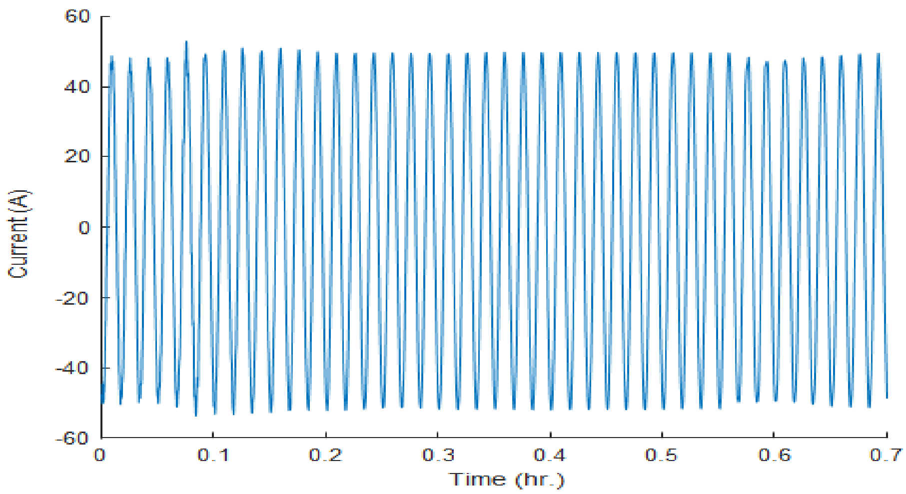

Figure 3 Current signal of the solar PV

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The current signal of the Solar PV system is shown in figure 9

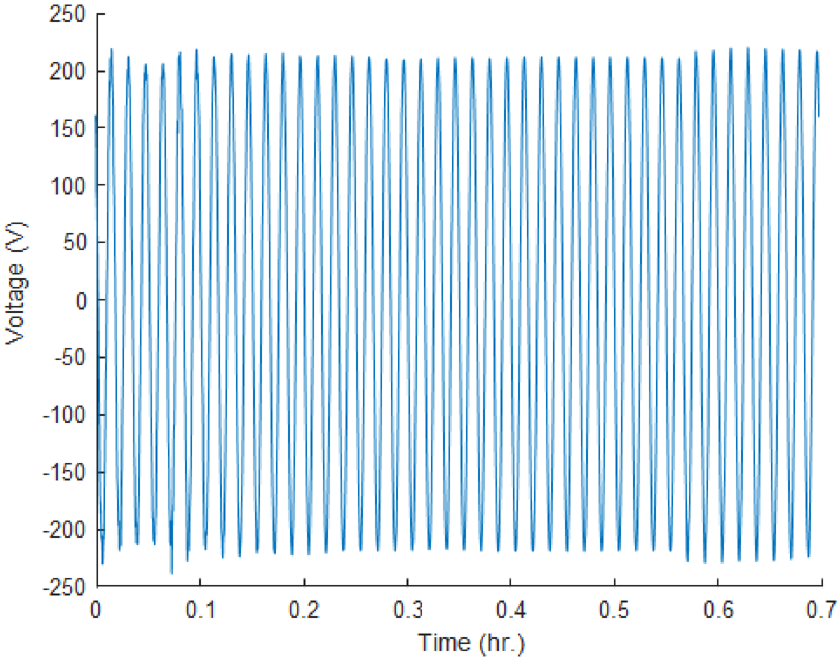

Figure 4 Voltage signal of the solar PV

The power output of the solar PV system is shown in figure 10

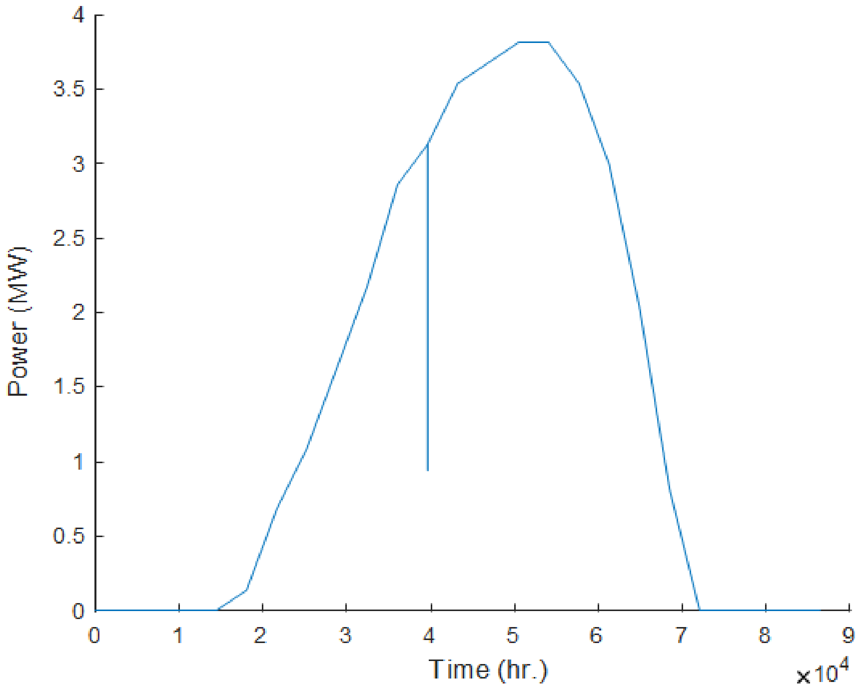

Figure 5 Power output of the solar PV

The power output of the national grid system is shown in figure 11

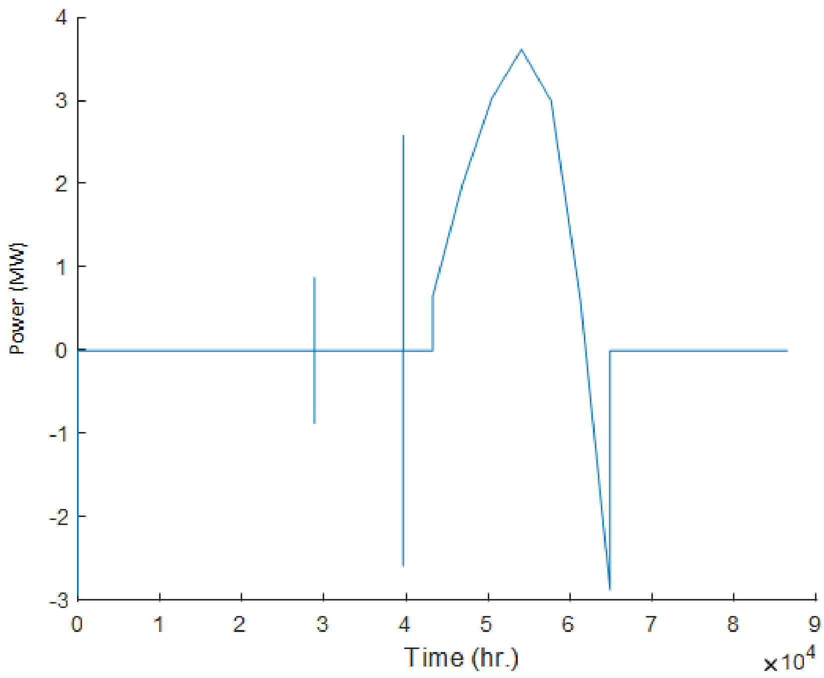

Figure 6 Power output of the national grid

The power output of the battery storage system is shown in figure 12

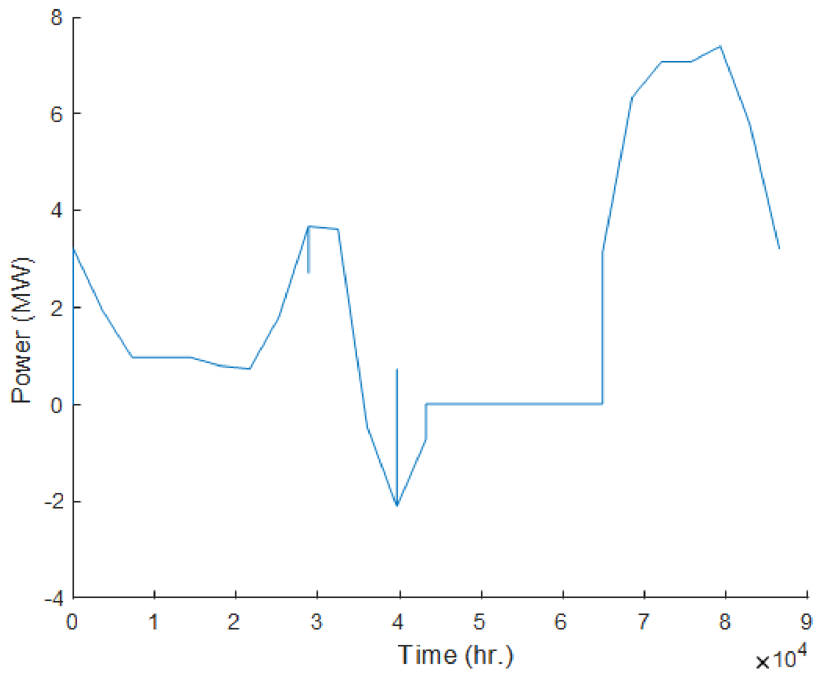

Figure 7 Power output of the battery storage system

The assumed micro grid operation is shown in figure 13

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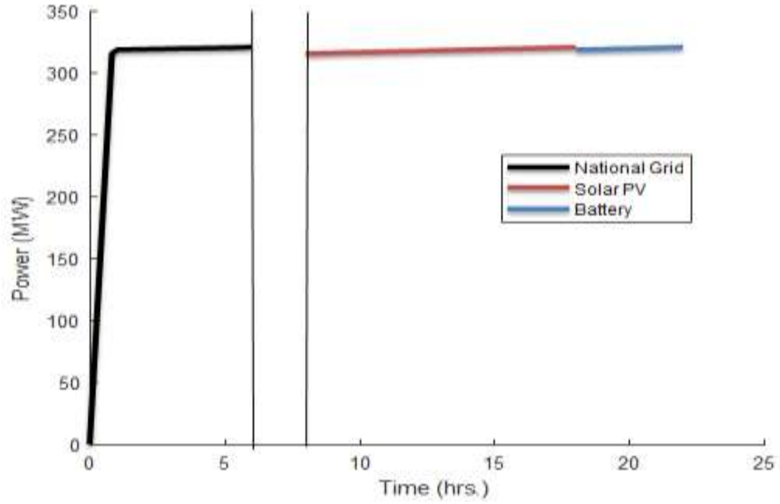

Figure 8 Assumed micro grid operations

The optimal grid operations generated with PSO is shown in figure 14

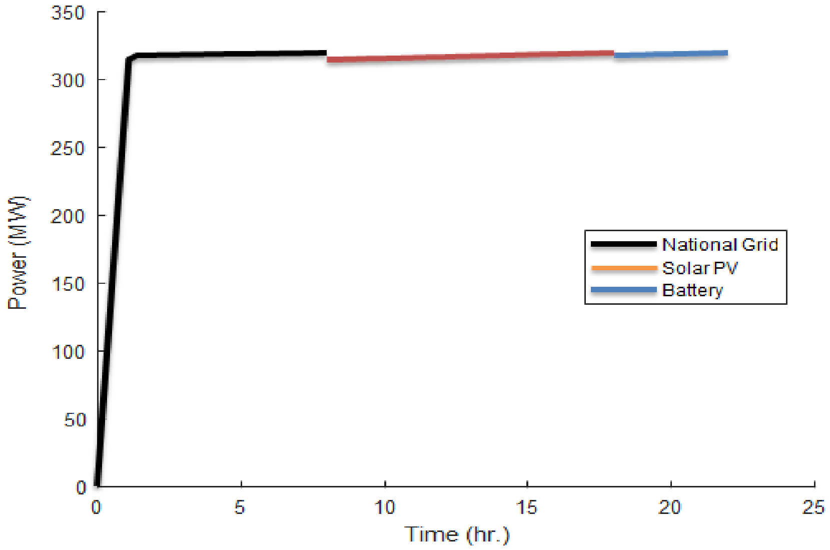

Figure 9 Optimization of the micro grid

Table 4 The economic analysis of the outcome of the optimized micro-grid operations

Parameters (units)	**Before optimization**	**After optimization**
Fix charge from Disco (₦)	1050	1050
Monthly unit Consumption (Least resident)	190	250
Cost per unit (₦/hr.)	20.14	20.14
Average unit consumed per day	930028	971554
Average cost of grid installation and operations (₦)	148,000,000	167,000,000
Estimated Income per day (₦)	446,413,440	478.825,920
Estimated Profit ₦)	298,413,440	311825920
IRR (%)	18.722	20.631
PP(years)	0.333	0.325
NPV (₦)	277,155,657	289,024,685

Discussion

- Figure 2 clearly demonstrates that the load given to the micro-grid works out to the same load as found during the physical inspection recorded in Chapter 3.1. For the whole 24 hours being studied, the load was steady and constant.
- Figure 3 demonstrates that the current of the solar PV system has some inconsistencies in its sinusoidal harmonics. Since the reading is zero, it could prove that there is a fault in the current signal, which is currently at 43 amps.
- The voltage signal from the solar PV system inside the micro-grid is shown in Figure 4 for a 0.25kV system. Looking at the harmonics will reveal that a voltage fault exists in the system.
- It is shown in Figure 5 that the micro-grid's solar PV system is producing 3.8MW in utility output.
- The amount of power coming from the national grid is represented by Figure 6 to be 3.32MW.
- Figure 7 reveals that the battery's output of power is unsteady, hinting that there is something wrong with the battery's source. The way power was supplied changed a lot through the years.
- Figure 8 shows the power that is being generated by the micro-grid from each energy source. There was a 4-hour shortage in electricity supply that happened when the system was operational and this needed to be improved to optimize efficiency. Because of this issue, companies suffered from tariff losses and made less profit. Improved how a micro-grid is operated.
- The micro-grid system shown in Figure 9 keeps working during both day and night with only few faults. According to the process, every energy type must deal with a maximum departure from the total load demand of up to 10%. Operational Schedule: Power came from the grid for 8 hours, between 12 midnight and 8 AM. The operation of the solar system started at 8 AM and stopped at 5 PM, for a total of 9 hours. The 7-hour (5 PM – 12 midnight) period was able to supply electricity from the battery system. Comparative Analysis: The table compares the system's performance to the results from literature that was examined before.

Table 5 Comparative analysis

AUTTHORS (YEARS)	INTERNAL RATE OF RETURN (IRR)	NET PRESENCE VALUE (NPV)	PAYBACK PERIOD (PP)
This research (2025)	20.631%	₦289,024,685	0.325
Adebanji et al (2022)	12.47%	₦201,442,180	1.07
Halim et al (2023)	6.78%	-	1.87
Mimica et al (2022)	14.31%	-	0.92

Engineering Implications of the Research

The outcome of the research would be the bedrock by which the power engineers would utilize to ensure constant availability of the rural electrification. The procedure implemented in the research would guide the power engineers to ensure proper installation of the micro grid with the source energy to ensure power availability in the localities

Contribution to Knowledge

The contribution to knowledge of the research was the fault reduction, economic improvement and energy improvement of the micro-grid using PSO.

V. CONCLUSION

The rural communities across the country have suffered lack of electricity as a result of lack of industries in the localities leading to lack of profit. Hence, the research focused on the design of micro-grid comprising of power from the national grid, solar PV system and battery. The location of interest was Manta village in Abak Local Government Area in Akwa Ibom State. The estimated load of the location was 3.13MW and the major consumers were residential and commercial. The on-grid system was modelled in SIMULINK and the simulated out was sent to MATLAB 2023a. The micro-grid outcome was optimized with the objective function being to optimize the time of the power source sent to the users. To proper execute the optimization process, first guesses were made but it failed to show the power generation process functional for the 24 hrs. After executing the optimization process, the time for the power generation for each of the energy sources was presented in table 6.

Table 6 Time of operation of the micro-grid energy sources

Energy sources	Power generated and time operated	
	Before optimization	**After optimization**
National Grid	8 hrs.	8 hrs.
Solar PV	7 hrs.	9 hrs.
Battery	5 hrs.	7 hrs.
Blackout	4 hrs.	0 hrs.

The outcome in table 6, the optimized system ensured that the electricity generation achieved 24hrs operation. Also, the outcome showed that the faults in the system generation and distribution process were reduced.

The project involves the implementation of particle swarm optimization on the micro-grid system which comprises of national grid, solar PV and battery. This was to ensure a 24-hr power generation of the system to the community. From the outcome of the research, the 24hr power availability was achieved which was attributed to the implementation of the PSO. The outcome not only generated 24hr electricity but also reduced the occurrence of fault in the power system network. Hence, the optimization of the on-grid system with PSO improved the energy and minimized fault in the system.

VI. RECOMMENDATION

In the design of the micro-grid system, it is important to ensure optimization of the power rating of the system and to obtain the time frame of the source operation of the energy sources of the micro-grid. In as much as it is important to install micro grid local communities, it is very essential to ensure that the system optimization was done to improve the energy of the micro-grid operations.

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