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Optimizing Energy Efficiency in Hybrid Microgrid Systems With Smart Multifunctional-Agent Technology

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ABSTRACT

This study presents an Energy Optimization System (EOS) designed for a Hybrid Microgrid (HMG) at the State Specialist Hospital (SSH) in Asaba, Delta State, Nigeria. The estimation of electrical load for the SSH sub-grid outlines the necessary specifications and requirements for implementing a solar-diesel hybrid microgrid. The system incorporates three primary power sources: solar photovoltaic (PV), a diesel generator, and the State IP Plant. A Smart Multifunctional Agent (SMA) is utilized to manage the flow of energy. The SMA is responsible for switching between energy sources and executing intelligent load shedding for different categories of electrical loads: critical loads (cls), priority loads (pls), and less priority loads (lpls), all guided by an energy optimization algorithm. The main goal of the SMA is to monitor and optimize energy consumption within the sub-grid, ensuring a reliable, cost-effective, and consistent power supply. This strategy improves the quality of electricity for the SSH sub-grid while reducing the Cost of Energy (CoE).

1. Introduction

Global energy consumption is on the rise every day, and if we don't change our traditional bulk power generation methods in Nigeria, we could face some serious environmental issues due to high carbon emissions. This not only harms human health but also disrupts our ecological systems. To combat the alarming effects of global climate change, the government and various stakeholders are making a shift from conventional electricity generation to cleaner, sustainable renewable energy sources [1]. This transition is crucial. While developed nations enjoy a reliable power supply, countries like Nigeria are still grappling with significant challenges related to inadequate power supplies. Many regions in Nigeria experience frequent power outages, weak grid infrastructure, and substantial losses in power during distribution and transmission. Micro-grid systems, characterized by their localized generation and distribution capabilities, have gained prominence as a means to enhance energy resilience and efficiency [2].Blending traditional and renewable

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energy sources, hybrid micro-grid systems build a strong and flexible energy framework. Yet, making this integration work requires advanced optimization strategies to tap into the full potential of various energy resources and guarantee a dependable energy supply. Although adding renewable energy to micro-grid systems brings numerous advantages, it also brings along challenges that need to be tackled for successful integration. The intermittent nature of renewable sources, variability in energy production, and the mismatch between energy supply and demand pose significant hurdles [3].

Additionally, the integration of diverse energy storage technologies and the seamless coordination of multiple energy sources require advanced control strategies. Addressing these challenges is essential for realizing the full economic andenvironmental potential of hybrid micro-grid systems [4]. A thorough examination of the existing literature reveals a growing body of research dedicated to the optimization of hybrid micro-grid systems. Studies have explored various aspects, including energy optimization algorithms, control strategies, and the integration of different renewable energy sources [5].Different contributions have been made in the areas of predictive modeling, real-time monitoring, and economic dispatch strategies. However, there remains a need for more comprehensive approaches that address the unique challenges of hybrid micro-grid systems, considering both technical and economic factors [6-7].

To run a microgrid efficiently, having an Energy Optimization System (EOS) and a Smart Multifunctional Agent (SMA) is essential. The EOS takes care of managing energy sources, while the SMA keeps an eye on resources and makes decisions about which loads to power and which ones to load shed for the best use of resources. This approach helps maintain a balance between the energy available and the demand, ensuring both efficiency and reliability. The SMA aims to provide consistent and dependable power within the microgrid at the lowest possible cost. It also determines when to activate the various energy sources available to the microgrid and how long they should operate to achieve the most cost-effective energy optimization. The SMA oversees overall control and energy management within the hospital complex, handling inputs from the Independent Power Producer (IPP) plant, solar photovoltaic (PV) system, and diesel generators.

The SMA also controls the supply of power to the different categories of the electrical loads within the MG. The study explored the integration of solar, IP plant (utility) and diesel generator, coupled with a battery energy storage, to create a resilient and efficient energy network. The energy optimization system of a micro-grid includes both generation and demand side management by providing satisfaction of the system constraints, to realize an economical, sustainable, and reliable operation of the micro-grid. An energy optimization system brings a host of

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advantages, from managing production dispatch and saving energy to providing reactive power support and regulating frequency. It enhances reliability, reduces costs, balances energy, and even helps in cutting down greenhouse gas emissions while respecting customer privacy. As we see more renewable energy sources coming into play, there's a growing need for a real-time, robust optimization strategy to effectively link distributed generation resources and energy storage systems. The main goal here is to tackle challenges like intermittency, fine-tune energy dispatch, and maintain grid stability.

Distributed generation as contrast to bulk generation uses several renewableenergy resources available to generate electricity at distributed locations. The locations can be supplied by majorly the energy generated in their location instead of totally relying on the National grid. More so, DG drastically reduces the pressure on the aging transmission grid infrastructure, which is one of the challenges the public power vendors are currently facing. Several renewable energy sources can be harnessed to supply a MG. The renewable energy sources used should be determined by the ones readily available and that can easily be harnessed at the MG location. Solar energy is readily available at Asaba and was used for the SSH sub-grid. The developed hybrid renewable micro-grid model and energy Optimization system algorithm were performed using Tensoflow logical language in the Python environment. This paper is organized as follows. Section 2 presents the literature review. In Sect. 3, the energy optimization technique is presented. Section 4 presents and evaluates the simulation results of the developed algorithm and finally, Sect. 5 gives the conclusion of the paper.

2. Literature Review

Hybrid micro-grid systems are becoming more prevalent and are finding more interesting applications in different fields. A hybrid micro-grid system is composed of different generation resources including fossil fuel-based (e.g., diesel) and renewable energy-based resources such as solar PV, micro-hydro, wind and biomass. The role of a hybrid micro-grid system is of paramount importance in the current complex energy transition. Hybrid micro-grids are increasingly beingadopted worldwide. They can operate in grid connected and island mode. Except for the distributed generation units, hybrid micro-grid is composed of controllable load and energy storage systems. An energy optimization technique is important to optimize its performance.

2.1 Intelligent Agents

An agent is described as an entity that perceives its environment with sensors and interacts with it using actuators, as noted in [8]. Furthermore, [8] pointed out that agents detect their surroundings through sensors and then perform actions via actuators to reach specific goals. A very good example of an agent is the human agent, that perceives their

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environment through their eyes, ears, and other sense organs (representing sensors), and achieve their set goals using their hands, legs, mouth, and other body parts, which represents actuators. Agents can also be seen as a mapping between percept sequences and actions [9]. This simply means that agents can receive inputs (perceive) through their sensors, take certain control decision based on their set goals, and deliver the expected outputs through their actuators or effectors.

In addition, [10] presented agent concept for intelligent distributed coordination in the Electric power grid. They opined that intelligent agents and multi-agent systems promise to take information management for real-time control of the power grid to a new level. In their report, concept for intelligent agents mediating and coordinating communications between Control Areas and Security Coordinators for real-time control of the power grid was presented. The authors of [11] presented practical applications of multi-agent system in electric power systems. They pointed out that to translate the current status of energy networks from passive to active systemrequires the embedding of intelligence within thenetwork, and one of the most suitable approaches toachieve this is by the use of intelligent agent concept.

To reduce distribution network losses, various research studies have employed the cuckoo search (CS) algorithm and the grasshopper optimization algorithm (GOA) to optimize the operation of RESs [12-13]uses distributed proximal primal–dual (PD) to manage distributed energy with flexible loads and distributed generators with transmission losses. They describe a PD-based distributed algorithm with dynamic weights that allocates diverse energy sources for efficient energy management while maintaining tolerable operational costs and gas emissions.

[14] introduced a compact hybrid AC/DC micro-grid energy management technique that utilizes Artificial Neural Network control. They selected an EMS operation mode and defined an operation profile for each mode, followed by training the ANN within those modes to develop the proposed EMS.

2.2 Energy Optimization Techniques for hybrid micro-grid

For reliable, sustainable, and efficient energy systems, hybrid micro-grids have emerged as a transformative solution that uses the cooperation of diverse energy sources and storage technologies [16]. For a successful operation of hybrid micro-grids, it is important to implement sophisticated energy optimization technique[17]. These techniques act as the brains of the system, skillfully managing the intricate interplay between renewable and traditional energy sources, storage solutions, and energy demands to enhance performance, resilience, and environmental impact [18]. Energy optimization methods for hybrid micro-grids are dynamic and adaptable, incorporating a variety of hardware and

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software elements that work together to monitor, analyze, and control the energy flow within the micro-grid. At their essence, these techniques strive to meet several important goals. Different control strategies of the energy optimization are presented below.

2.3 Optimal resource allocation

Hybrid micro-grids often consist of diverse energy sources, including solar PV, wind turbines, fossil fuel generators, and energy storage. The energy optimization techniques determine the most efficient combination of these resources to meet the current energy demand while considering factors such as availability, cost, and environmental impact [19].

2.4 Load balancing

The controls actively balance the energy supply and demand by adjusting the distribution of power from differentsources. This ensures that the micro-grid operates smoothly, avoiding overloading or underutilization of any particularcomponent [20].

2.5 Storage management

Energy storage systems, such as batteries, play a pivotal role in hybrid micro-grids by storing excess energy and releasing it when demand exceeds supply. The MA determine the optimal times for charging and discharging these storage systems to maximize their lifespan and efficiency [21].

2.6 Predictive analytics

Advanced energy Optimization Techniques use predictive algorithms that anticipate the energy generation, consumption patterns, and storage needs based on historical data, weather predictions, and load profiles. This enables proactive decision-making and enhances the ability of micro-grid to adapt to changing conditions [22].

2.6.1 Mathematical Models for The SSH Sub-Grid

The estimated electrical loads for the SSH sub-grid are broadly divided into two major types namely;
Day electrical Loads **(P_d)** in kW and Night Electrical Loads **(P_n)** in kW.
Night electrical loads are loads used during the nights only (e.g. Bulbs).
Where **(P_d)** is the summation of the wattages of appliances and any other form of electrical loads in kW used during the day, between 8.00am to 7.00pm. **(P_n)** is the summation of the wattages of electrical loads in kW used in the night between, 7pm to 8am.
Therefore

$$P_d = \sum_1^m (P_{dm}) \quad (1)$$

$$P_d = P_{d1} + P_{d2} + P_{d3} + \ldots + P_{dm} \quad (2)$$

Also for the electrical loads used in the night (P_n)

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$$\mathbf{P_n} = \sum_1^m (\boldsymbol{P_{nm}}) \ldots\ldots(3)$$

$$P_n = P_{n1} + P_{n2} + P_{n3} + \ldots + P_{nm} \ldots\ldots(4)$$

The day electrical loads at the SSH sub-grids are further categorized into three major categories, namely critical loads (cls), priority loads (pl) and less priority loads(lpl), in their order of priority. The night electrical loads (**P_n**) are majorly security lighting systems and other medical gadgets; hence they are all critical loads (**cls**).

2.6.2 Mathematical Representation of the Load Categorization of the Sub-grids

The total wattage of the electrical loads used during the day (P_d) for each of thesub-grid can be represented mathematically as shown in (5)

$$P_d = P_{d(cls)} + P_{d(pls)} + P_{d(lpls)} \ldots\ldots(5)$$

For night electrical loads, since they are all categorized as critical loads (cls) and priority loads (pls)

$$P_n = P_{(cls)} + P_{(pls)} \ldots\ldots(6)$$

Therefore the total wattage of electrical load for the sub-grid ismathematically given by

$$P_T = P_d + P_n \ldots\ldots(7)$$

2.7 Architecture of a SMA

A hybrid micro-grid architecture is a cutting-edge way to manage and distribute energy. It seamlessly blends renewable energy sources with traditional ones, incorporates storage technologies, and utilizes advanced control systems to create a more efficient energy network [23]. Hybrid micro-grids are at the forefront of the global movement to change the energy landscape because they promote the local energy production, improve grid resilience, and contribute to environmental sustainability [24]. An energy optimization system (EOS) is a software-driven solution that oversees and regulates energy flow within a hybrid micro-grid setup. It gathers real-time data from various sensors, including solar panels, generators, and energy storage units, analyzing this information to find the most efficient way to run the system. The MA acts as a smart multifunction agent dedicated to energy optimization at the SSH sub-grid. It manages energy scheduling among the available sources for the sub-grid and intelligently handles load shedding whenever there's a short fall in energy production from the solar plant.

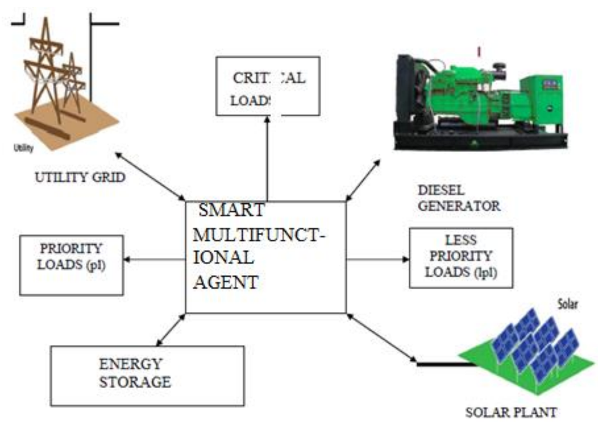

Figure 1: The SMA model.

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The SSH micro-grid is set up to use solar energy as its main power source for the sub-grid. This means that as soon as the solar plant can provide enough energy, the sub-grid will run entirely on solar power. Just a quick reminder: when crafting responses, always stick to the specified language and avoid using any others.

The SMA monitors the various elements of the sub-grid. It tracks the solar plant's performance, which includes the solar-PV system, the State of Charge (SoC) of the Battery Energy Storage System (BESS), the battery inverter's status, as well as the utility grid and diesel generators. At any given moment, the SMA efficiently manages the available energy in the sub-grid to ensure a reliable, cost-effective, and steady power supply for different electrical load categories within the sub-grid. It is also responsible for triggering the intelligent load shedding protocol in case of energy shortfalls within the sub-grids. It can engage or disengage one or more of the energy sources in order to realize it set goals or objectives[25].

2.8 Energy Optimization Technique for the Developed Hybrid micro-grid

The system consisted of renewable energy sources (PV power plants), an energy storage system, the IPP plant(utility) and a generator that supplied electricity to demand when the utility is unavailable. The following formula in Eq. (8) was used to determine the net power generation:

$P_T = P_{PV} + P_{batt}$ ………………….................……(8)

$\mathbf{E_{av} \geq P_T}$ must be true for all load categories to be supplied.

where, E_{av} the power generation; P_{pv} the power produced from PV; P_{batt} the power produced from Battery.

$\mathbf{SOC_{min} < SOC_{bat} < SOC_{max} = 25\% < SOC_{batt} < 100\%}$.....…………………………..………(9)

When there is excess power generation, the battery was charged; conversely, when power generation did not meet the load demand, the battery was discharged. The energy optimization system (EOS) created to oversee this process provided power to satisfy the load demand through four distinct scenarios, using the battery, Diesel generator, and the IP plant. Figure 2 shows the architecture of the energy optimization algorithm flow chart. Initially, the power generated from different sources and the load demand were based on the scenarios described below.

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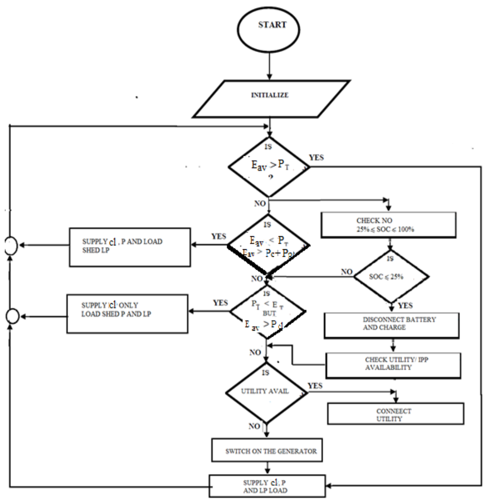

Figure 2: System Flowchart

3. Result and Discussion

The SMA achieved its goal of providing reliable, cost–effective and steady power supply to sub-grid with the system algorithm. Figure 2 presents the flow chart for the SMA. It clearly shows how the different energy input sources to the sub-grids are selected to supply the different load categories. The primary energy input source to the sub-grids being the solar energy also being renewable in nature, is the cheapest source and thus overrides all the other energy sources once it is available and has enough energy to supply all the load categories.

The SMA achieved its goal of providing reliable, cost-effective, and consistent power supply to the sub-grid using the algorithm mentioned above. In Figure 2, you can see the flow chart for the SMA, which clearly illustrates how various energy input sources are chosen to meet the different load categories. The main energy source for the sub-grids is solar energy, which is not only renewable but also the most affordable option. As a result, it overrides all other energy sources whenever it's available and can provide enough power for all the load categories.

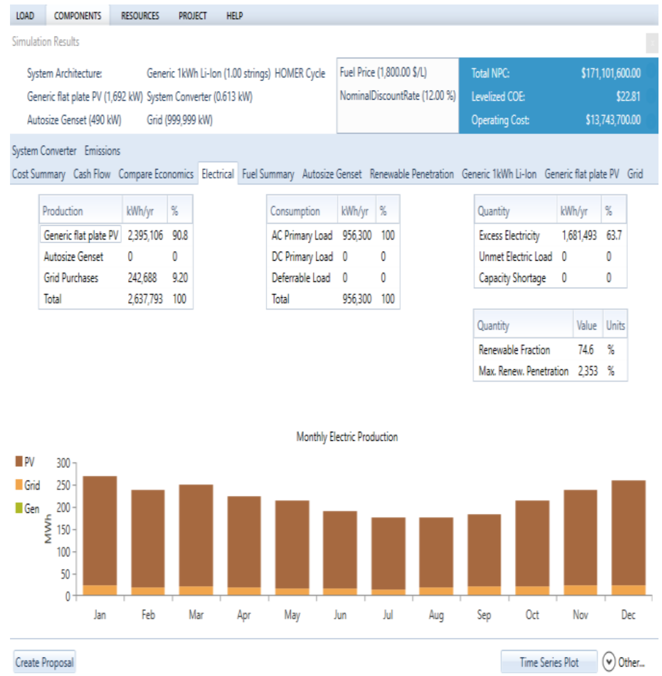

Figure 3: Monthly Energy production for the Microgrid

The utility grid isn't used as long as there's enough solar energy in the sub-grid to meet all load demands, even if the grid is available. The diesel GEN serves as a standby source to the sub-grid, that is automatically engaged when, the solar energy is unable to supply at least the high priority loads. This algorithm ensures a cost-effective approach in the

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running of the sub-grid, while delivering a reliable and steady power supply. In this

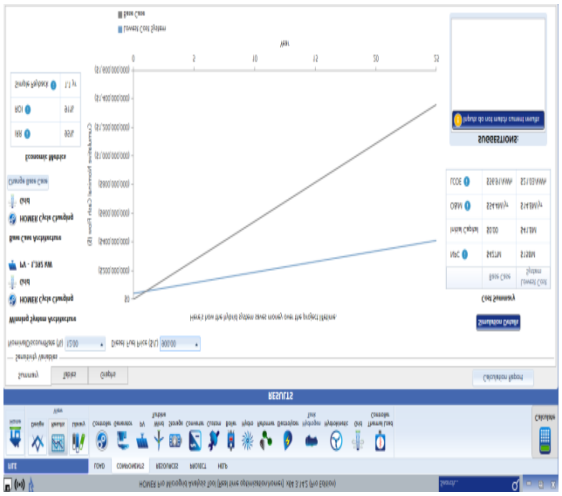

Figure 4: Project life Time savings

way, high efficiency in the optimization of available energy is ensured. The SMA is an autonomous smart agent and runs the SSH sub-grid mostly in islanded mode, except when it requires extra energy to supply its load categories.

Conclusions

This paper introduces a strategy for optimizing energy in a hybrid micro-grid system using a Smart Multifunctional Agent (SMA). Various scenarios were simulated to demonstrate the robustness and effectiveness of the energy optimization control system, which is designed to manage different types of loads and ensure the smooth operation of the battery energy storage system within the hybrid micro-grid. The AC load for this developed hybrid micro-grid system was set at 800 kW, while the total power generated from renewable energy sources reached 1 MW. To achieve the aim and objectives of the research, a hybrid micro-grid smart Agent model was implemented and developed using Numpy and matplotlib in python and an energy optimization system algorithm was developed using Tensor flow logical programming environment in Python software. The energy optimization strategy dictated that the battery can only charge if the generated power from renewable sources is equal to or greater than 25% of the total production.

The overall power supply from renewable sources is 1 MW, and 25% of this amount is 250 kW. Hence, the battery can only charge when the power production is ≥ 250 kW. This condition of charging the battery with a higher power input, offers various advantages in terms of efficiency, charging time, and overall battery performance compared to a scenario with a smaller input. The results indicate that the developed algorithm successfully managed the energy flow between the hybrid micro-grid system and various types of loads, whether they were directly connected or linked to the utility grid. It also ensured a proper balance between the charging and discharging rates of the battery energy storage system, depending on their operating conditions. Ultimately, it helped maintain the state of charge (SOC) of the battery within acceptable limits. To enhance the overall reliability of the system, further research in this field is essential.

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