A Technical Analysis of a Grid-Connected Hybrid Renewable Energy System under Meteorological Constraints for a Timely Energy Management

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Abstract- Electricity demand can be met in a variety of ways, and the integration of renewable energy sources can be a reliable, environmentally sustainable, and cost-effective option. Energy needs in remote and isolated areas not served directly by the electrical grid are best met by hybrid systems employing many renewable energy sources. This is especially true in developing countries. Consequently, one of the greatest difficulties for developing nations is the establishment of grid-connected Hybrid Renewable Energy Systems (HRES). This is dependent on the findings of the feasibility study and, more importantly, the improvement of the constructed system. The purpose of this study is to lay forth a reliable structure for EMS-based tactics in order to optimize the energy available for the load. PV/Battery/Grid-Tied Loads are the main components. As a result of the solar panels being shaded, the resulting Hybrid Micro Grid System (HMGS) is vulnerable to environmental factors such as wind and rain. In this study, we employ a heuristic method based on State Machine Logic (the State Flow Method), as well as a more traditional technique, Linear Programming. MATLAB R2018a was used to put these techniques into action. Both sets of simulation results—under clear and cloudy conditions—are compared and contrasted in detail. In light of the aforementioned parameters, four possibilities are provided. Every day, a unique case study undergoes a real-time analysis.

Keywords: Microgrid, Energy Storage System, Solar Array, Linear Programming, Energy Management System.

1. Introduction

One of the world's greatest difficulties is bringing about widespread electrification. Every nation must have access to clean, reliable electricity. All facets of modern life will benefit from this [1]. Hybrid renewable energy systems (HRES) made up of multiple Renewable Energy Sources (RES) are one possible answer. Dependence on the usage of renewable energy sources has become vital for sustainable development [2]. Hybrid Micro Grid Systems (HMGS) are often composed of a combination of several power generation methods. However, it is crucial to stabilize the demand-supply balance within the system because of the unpredictability of RES [3]. When multiple RES are used, system reliability is increased, making hybrid systems a compelling option. Since multiple energy sources can be used instead of just one, this also allows the storage system to be made a little smaller. Therefore, the evaluation of an HMGS is primarily based on the criterion of reliability. Incorporating a storage mechanism into Hybrid Micro-Grid Systems (HMGS) presents a viable option for optimizing the utilization of Renewable Energy Sources (RES). This will facilitate the implementation of effective Energy Management System (EMS) tactics to ensure optimal operation of the HMGS. This is contingent upon a dependable, secure, and environmentally sound power production and dissemination system, even in the face of meteorological unpredictability. The issue of isolated urban centres in the southern region of Nigeria has been addressed by the authors [4] through the application of technical analysis, resulting in a satisfactory resolution. The data indicates that the utilisation of HRES has effectively achieved equilibrium between demand and supply. Additionally, researchers in reference [5] have conducted a study on the influence of Soot on the efficacy of photovoltaic panels. The implementation of a Smart Intelligent Monitoring System has yielded positive outcomes in terms of enhancing the operational efficacy of the solar panels that are integrated into the Hybrid Renewable Energy System (HRES).

For a long time now, several researchers have been working on new ways to make EMS techniques more effective. Constraints (linear or nonlinear), objectives (single or multi-objective), and variables (integer or discrete) make EMS a considerably more difficult problem. There are three main ways to address EMS issues in HRES: software tools, deterministic approaches, and metaheuristic algorithms. The most popular and effective software programs that have been utilized for this situation include HOMER, HOGA, RETscreen, PVSYT, TRYNS, etc. For many users, the HOMER software application is the go-to for system design, sizing evaluation, and cost-benefit analysis. The primary issues with the HOMER program are the inaccessibility of computations and the inability to modify the modeling equation and the sizing process and algorithms [6]. Many of the published studies on HRES employ deterministic strategies, such as analytical, iterative, graphical, probabilistic, and linear programming, which are more effective than software tools. Deterministic approaches, on the other hand, get stuck in these local optimum solutions and can't go on to the next best one. Recently, major implementations of several different metaheuristic algorithms for EMS in HMGS have been produced. Algorithms inspired by the workings of nature have the potential to outperform deterministic methods [7] in terms of optimal solution discovery, the avoidance of local optimum trapping, and the determination of optimal solutions. Several research projects have been conducted to optimize the components of various hybrid renewable system configurations utilizing various optimization strategies to accomplish the desired function while taking reliability into account.

There are a variety of methods for achieving high-quality HMGS in EMS. In [8], multi-Objective optimization of a grid-connected Hybrid PV/Wind Turbine (WT) based system was introduced to optimize costs, reliability, and GHG reduction. Mathematical models were used to estimate output power and the interrelationship between the grid and the proposed hybrid system was studied. Results were classified into economic, renewable energy usage, and environmentally optimal solutions. With the use of Genetic Algorithms, [9] details a cutting-edge Real-Time Energy Management System (RT-EMS) for Microgrid (MG) systems, one that may reduce energy costs and emissions while making the most of renewable power sources. The optimization algorithm is validated in an actual MG testbed by experimental testing. In order to operate the microgrid at the lowest possible operational cost, [10] provides a novel mix-mode energy management strategy (MM-EMS) and associated battery sizing approach. It was determined that the proposed MM-EMS and battery sizing method worked as intended, and it was examined how the optimal battery capacity changed across the spectrum of state-of-charge. In addition, a suggested initial SOC level was proposed. Work [11] proposed an EMS based on a co-simulation using a fuzzy logic program and Hybrid Optimization Model for Electric Renewable (HOMER). Khan et al. in [12] explore how hybrid renewable energy systems (HRES) can be controlled, sized, and optimized to satisfy the rising energy demand. It gives a comprehensive evaluation of the most effective methods for sizing, controlling, and managing energy consumption, as well as incorporating multiple renewable energy sources into a single hybrid system. To aid stakeholders in HRES planning, research, and development, numerous modeling strategies and software simulation tools have been developed. A full analysis is crucial to making the most of renewable energy possibilities and meticulously developing usable designs.

Considering the uncertainties that can influence the HMGS, several approaches have been carried out. In order to efficiently manage energy sharing in microgrids with PV prosumers, a Stackelberg game strategy is proposed in [13]. To handle the unknown quantity of PV energy and load usage, a system model, hour-ahead optimal pricing model, and billing mechanism have been implemented.) proposed EMS based on other artificial intelligent methods. [14] proposed an EMS based on stochastic and robust programming approaches. In order to maximize the use of all resources in an agricultural microgrid, including a pumped-storage unit, an irrigation system, and intermittent wind power generation, a new coordinating framework is presented in this research. With information on expected wind power, microgrid load demand, and irrigation water needs, the framework improves day-ahead scheduling of power exchange with the upstream network, pumped-storage unit, and irrigation system.

This paper examines a grid-connected hybrid microgrid system (HMGS). The system is composed of photovoltaic modules, energy storage units, and two categories of electrical loads: dynamic and static loads. As a result of the intermittent variability of solar irradiance, two scenarios can be distinguished: clear-sky and cloudy-sky conditions. Under these circumstances, it is imperative to enhance the efficiency of the HMGS. As a result of the dual anomalies (intermittent radiation and fluctuating demand), any surplus energy will be stored in batteries. In the event of an energy deficit, the batteries will compensate for the shortfall. The control methodology utilized in this study suggests that the Hybrid Micro-Grid System (HMGS) is not wholly reliant on the power output from the primary electrical grid. The solar power generation and storage capabilities are typically adequate to meet the power demands of the system. This document centers on two methodologies: the heuristic approach utilizing State Machine Logic (State flow method) and the optimization approach utilizing the linear programming method. The process of modeling and simulating the HMGS is executed through the utilization of MATLAB R2018a.

The primary focus of this research is optimizing power delivery to the battery pack in the face of unpredictable weather. As a result, the battery's stored energy will be used most efficiently. Here is how the rest of the paper is laid out: In Section 2, we go into the stochastic modeling of the HMGS. In Section 3, we'll talk about how to construct an EMS when solar and battery power are available. Section 4 also provides a synopsis of the two methods. In Section 5, we present our analysis and discussion of the four possibilities, and in Section 6, we offer some last thoughts.

2. System Modelling

This section provides a comprehensive analysis of the different constituents of the HMGS. This facilitates a better understanding of the system and its mode of operation.

2.1. Solar Modelling

Numerous classifications of materials for solar cells are utilized globally, however, presently, silicon is the dominant material employed in solar cells due to its impetus, versatility, and efficient light absorption. The present study employs a mono-crystalline photovoltaic (PV) array due to its superior performance in arid regions [15]. The photovoltaic (PV) array consists of 24 modules per array, each comprising of 2 modules per string connected in parallel and 12 strings in series. A solar panel with a power output of 535kW is achieved by connecting 72 photovoltaic cells in series. The photovoltaic (PV) power output is determined by the solar radiation that enters the surface area of the cells, the temperature of the cells, and the geographical location [16]. [17] proposes a mathematical equation for calculating the hourly power output of a photovoltaic (PV) system. in Eq. (1):

$$P_{PV} = f_v * P_r * \frac{G}{G_{ref}} * [1 + K_T\ (T_C - T_{ref})] \qquad (1)$$

Where P_r is the rated power expressed in kW, G_{ref} is the reference solar radiation (W/m²) whose value is 1kW/m², G is the solar radiation in W/m², f_v is the derating factor fixed at 0.9, T_{ref} is the temperature of the cell at reference conditions (◦C) with value 25◦C, K_T is the temperature coefficient with value - 4.1× 10^{-3}/◦C and T_C is calculated by the Eq. (2):

$$T_C = T_{amb} + (0.0256 * G) \qquad (2)$$

T_C represents the cell temperature and T_{amb} the ambient temperature both expressed in ◦C.

Figure 1 shows the block diagram of the Solar panel.

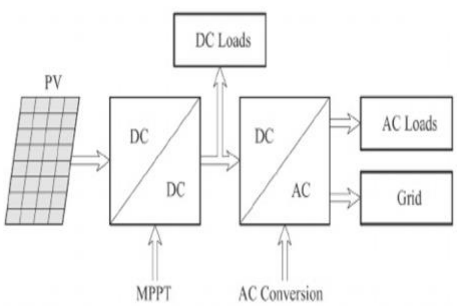

Fig. 1: Block diagram of the solar panel

The output power of the photovoltaic (PV) system is subjected to a real-time Maximum Power Point Tracker (MPPT) algorithm. The HMGS incorporates a DC-DC converter. The Maximum Power Point (MPP) varies based on daily conditions. The Incremental Conductance (INC) algorithm involves measuring the gradual change in solar panel conduction and differentiating the instantaneous conductance, which is defined as the ratio of current to voltage (I/V). According to [3], a comparison of the MPP results in a variation of the current (I) and voltage (V) positions.

2.2. Batteries Modelling

In the context of system modeling, batteries serve as energy storage components that receive surplus energy generated by HRES when the energy output exceeds the load demands. Conversely, the batteries release the stored energy to the system when the energy output is insufficient to meet the system's requirements. Two converter types will be employed based on the operational mode of the batteries: DC-DC for energy storage and DC-AC for energy transfer to the system. Equations (3) and (4) can be utilized to ascertain the battery's charge level during discharge and charge operations, correspondingly [18]:

$$SOC\ (t+1) = SOC\ (t) * (1-\sigma) - \left(\frac{P_l(t)}{\eta_{cnv}} - P_g(t)\right) * \eta_{BD} \qquad (3)$$

$$SOC\ (t+1) = SOC\ (t) * (1-\sigma) - \left(P_g(t) - \frac{P_l(t)}{\eta_{cnv}}\right) * \eta_{BC} \qquad (4)$$

P_l (t) and P_g (t) represent the energy demand and generated power, respectively. The symbols η_{BD} and η_{BC} denote the discharge and charge efficiencies of the battery, respectively. The parameter σ denotes the batteries self-discharge and has been assigned a value of zero in the present investigation [19]. η_{cnv} represents the conversion efficiency of the device.

A MATLAB-based model has been developed for a distributed battery with a capacity of 3000kWh. The equation (5) can be used to calculate the instantaneous available energy E_{avail} (t) for supply.

$$E_{avail}(t) = Q_{bat}(t) * V_{bat}(t) * SOC\ (t) \qquad (5)$$

Where Q_{bat} (t) and V_{bat} (t) denote the capacity and the voltage of the battery respectively.

This study specifies that the ESS has a rated power of 400 kilowatts and a capacity of 3000 kilowatt-hours.

2.3. Load Modelling

This study incorporates two distinct categories of loads, namely variable load and fixed load. The load that remains constant is a resistor with a power factor of 350 kilowatts. The load variable exhibits an active power of 200 kilowatts and a reactive power of 458.831 kilowatts. A dynamic load flow control technique is utilized to produce precise active and reactive power values for the varying load at each second of the day.

2.4. Uncertainties Modelling

Diurnal solar radiation exhibits temporal variability. This study takes into account two scenarios: one with clear weather conditions and the other with cloudy weather conditions. This will cause a perturbation to the solar panels. Therefore, the photovoltaic (PV) output power will vary based on the current level of radiation.

2.5. Power Grid Modelling

The present study employs a three-phase alternating current (AC) source with the subsequent specifications: The system operates at a phase-to-phase voltage of 13833 volts (RMS) and a frequency of 60Hz. A transformer with a step-down function is implemented in the circuit downstream of the AC power source, possessing the subsequent specifications: The primary voltage is measured at 13833 volts (RMS), while the secondary voltage is measured at 5000 volts (RMS). It is connected in a Y configuration.

The block diagram of the HMGS is depicted in Figure 2.

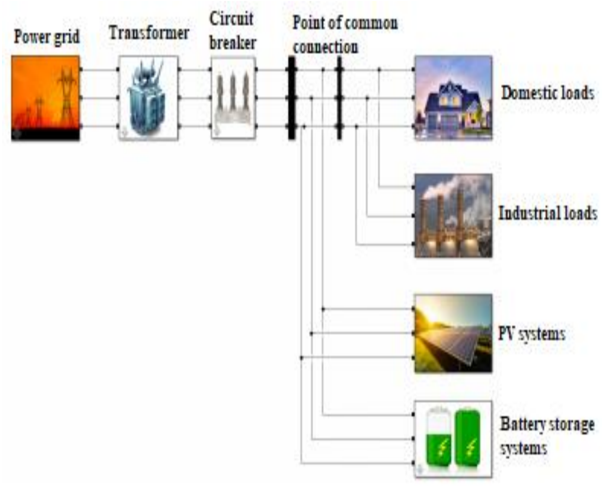

Fig. 2: Block diagram of the HMGS

3. Problem Formulation

This document describes the composition of the Hybrid Micro-Grid System (HMGS), which comprises photovoltaic modules, energy storage units, electrical loads, and a power distribution network. Therefore, in order to evaluate its dependability, it is crucial to establish objective and constraint functions

The primary goal is to optimize the power output of the photovoltaic system. This will also aid in the maximization of the energy stored in the batteries. Assuming minimal energy losses during the transmission process from the photovoltaic (PV) system to the batteries. Thus, the expression for the instantaneous energy available in the batteries, denoted as $E_{avail}(t)$, can be formulated as shown in the given statement. Eq. (6):

$$E_{avail}(t) = \left(\frac{P_g(t) - P_l(t)}{\eta_{cnv}}\right) * \Delta t \qquad (6)$$

The objective function will be defined as in Eq. (7):

$$\text{Obj} = \text{Max } E_{avail} \qquad (7)$$

In order to optimize the performance of the battery storage system, it is necessary to ensure that the State of Charge (SOC) meets the requirements specified in Eq. (8). [19]:

$$SOC_{min} \leq \text{SOC(t)} \leq SOC_{max} \qquad (8)$$

Where SOC_{min} and SOC_{max} describe respectively the lower and upper bounds of the state of charge of the batteries. Furthermore, this provides an assurance that the battery will consistently function within its designated safe parameters during all instances of optimization

4. Proposed Strategies

This study utilized two methodologies to conduct real-time analysis: a heuristic approach utilizing State Machine Logic (State flow method) and an optimization approach utilizing linear programming method.

4.1. Heuristic Approach

The State Machine Logic is comprised of a finite set of states. The machine undergoes state transitions and generates outputs based on the present state and an input provided. In the context of systems theory, a state refers to the current configuration of a system that is determined by its previous inputs and is capable of influencing its future responses to subsequent inputs. A state transition is a specification that determines the conditions under which a state is altered from one state to another in response to a given input. The diagram depicted in Figure 3 illustrates an instance of door control.

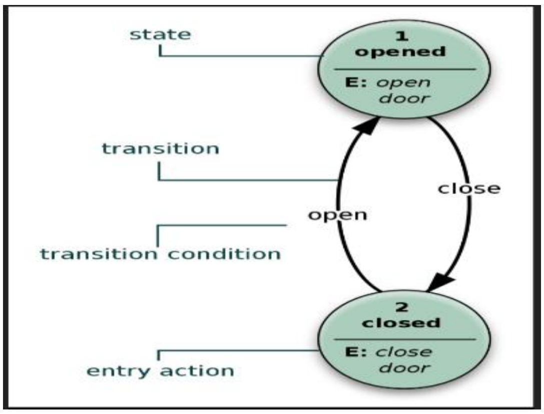

Fig. 3: Example of machine state logic for a door

4.2. Linear Programming

Linear Programming is a mathematical optimization method that involves maximizing or minimizing a linear objective function while adhering to a set of constraints. The resolution of a linear programming problem entails determining the optimal value, which can either be the largest or smallest depending on the problem, of the linear expression referred to as the objective function in Eq. (9):

$$F = \sum_{i=1}^{n}(c_i * x_i) \qquad (9)$$

Subject to a set of constraints expressed as inequalities in Eq. (10):

$$\begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \leq \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix} \tag{10}$$

The standard form of a linear programming problem is characterized by specific constraints and objectives that are linear in nature:

- The optimization problem is formulated as a minimization objective function.
- All constraints are of the type where the left-hand side is equal to the right-hand side.
- All decision variables adhere to the constraint of being greater than or equal to zero.

The aforementioned standard form can be altered based on the specifications of the optimization problem's objective function and variable constraints.

5. Simulations and Discussions

A HMGS comprises of three fundamental components, namely, production, distribution, and consumption. The test system is depicted in Figure 2. MATLAB R2018a was utilized to conduct modeling and simulations. This system employs two distinct conditions, namely clear and cloudy weather. Additionally, this paper utilizes two methodologies: a Heuristic approach and Linear Programming. By utilizing various parameters, we optimize the power output of the photovoltaic system. Four scenarios will be outlined in the following sections:

5.1. Heuristic Approach during Clear Day

The initial simulation scenario is derived through a heuristic methodology under conditions of clear atmospheric conditions. Figure 4 illustrates two distinct waveforms. The initial component denotes the electrical capacity of the Photovoltaic (PV) system, grid connection, battery storage, and electrical load. The following code snippet showcases the real-time monitoring of the State of Charge (SOC) of the batteries at an interval of one second for a duration of 24 hours. Based on a real-time analysis, it has been determined that the load demand remains below 500kW during the time frame of 0 to 2 *10^4 seconds. In that timeframe, the System-on-Chip (SOC) is operating at its initial capacity, which has a numerical value of 50%. During the time interval of 2 to 4 *10^4 seconds, there was an observed escalation in demand up to 500 kW. Concurrently, there is a rise in the photovoltaic (PV) power and a decline in the battery power. When the photovoltaic (PV) power output exceeds the load demand, the surplus energy is stored in the battery. This implies that the process of charging the battery initiates gradually. During the time period of 4 to 6 *10^4 seconds, with a constant load, the state of charge (SOC) experiences an increase, indicating that the battery is in a state of charging. However, despite slight load fluctuations, the state of charge (SOC) consistently increases up to 80%. Similarly, the photovoltaic power output decreases, causing the battery to gradually discharge as it begins to supply power. During the time frame of 6 to 8 *10^4 seconds, the load experiences a rise to 500kW. However, the power derived from the battery continues to decrease despite the PV power. In the event that the battery experiences complete discharge and the photovoltaic power output is insignificant, the electrical grid power source is activated.

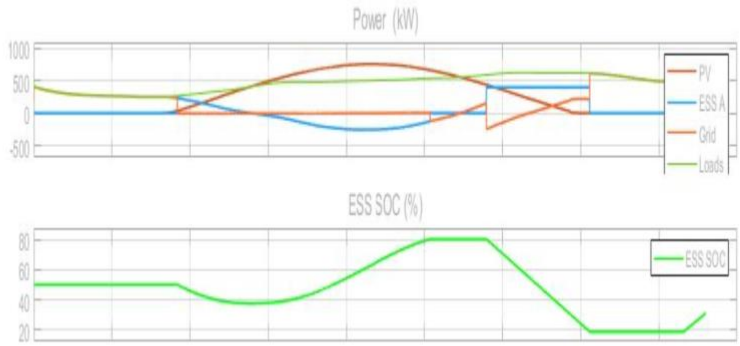

Fig. 4: Simulation result for a clear day using heuristic method

5.2. Linear Programming during Clear Day

A simulation of Linear Programming was conducted under clear weather conditions and the outcomes are illustrated in Figure 5. Within the optimization timeframe of 0 to 2 *10^4 seconds, the demand remains below 500 kilowatts. Therefore, only the power grid will produce the requisite amount of energy to meet the demand. The photovoltaic system will provide power to the battery, which will be in a state of charging. The System on Chip (SOC) is expected to attain a level of 80%. During a specific period of time, as the load rises, the grid supply will diminish as a result of the contributions made by PV and battery. Concurrently, the battery undergoes discharge. The load exhibits a slight increase up to 500kW within the time frame of 2 to 4 *10^4 seconds. The photovoltaic system's power output is exhibiting a positive rate of change, indicating an upward trend. Concurrently, the battery's electrical energy and state of charge (SOC) are diminishing. In this scenario, the photovoltaic (PV) system is providing a greater amount of power while the grid power is decreasing, resulting in the battery not being utilized for power supply. Between 40,000 to 60,000 seconds, there is a marginal increase in demand. The grid and photovoltaic (PV) power sources will be augmented to meet the rising demand. As the power demand exceeds 500kW, the state of charge (SOC) of the battery remains at its minimum level. Within the range of 6 to 8 x 10^4 seconds, the load exhibits a period of constancy followed by a gradual decrease. The power grid will sustain the electrical demand while the power output of the power wall gradually diminishes. The power grid will continue to be the sole energy provider to meet the energy requirements while the battery maintains a minimum state of charge (SOC).

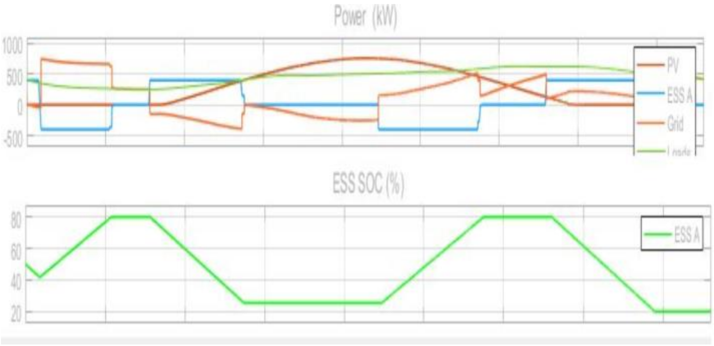

Fig. 5: Simulation result for a clear day using optimization approach

5.3. Heuristic Approach during Cloudy Day

In this section, we analyze a scenario where the sky is overcast and the solar radiation is insufficient to provide adequate power output from the photovoltaic system. The utilization of the State Flow Methodology results in the waveforms depicted in Figure 6. Within the time frame of 0 to 20,000 seconds, the load demand remains below 500 kilowatts. The state of charge (SOC) of the battery is currently at its initial value of 50%. Between 2 and 4 x 10^4 seconds, there is a gradual rise in load that culminates in a peak of 500 kilowatts. However, there are fluctuations in solar radiation. What factors will impact the power output of the photovoltaic system? Concurrently, the battery and the grid will provide supplementary support to bridge the disparity. Consequently, the State of Charge (SOC) of the battery will diminish, indicating the impact on the battery that is undergoing discharge. Within the time frame of 40,000 to 60,000 seconds, there will be a marginal rise in demand, exhibiting similar patterns as the time frame of 20,000 to 40,000 seconds. The System-on-a-Chip (SOC) is expected to attain the minimum threshold of 20%. During the time interval of 6 to 8 x 10^4 seconds, the power demand exceeds 500 kilowatts. The grid will be the sole source of power to meet the demand, while the battery will remain at a minimum level.

5.4. Linear Programming during Cloudy Day

During the optimization of the Hybrid Micro-Grid System (HMGS) under cloudy conditions, Figure 7 illustrates the power waveforms of the system and the State of Charge (SOC) of the battery. During the time interval of 0 to 2 *10^4 seconds, the power demand remains below 500 kilowatts. The state of charge (SOC) of the battery undergoes a reduction from 50% to 40% as a result of the declining power output of the grid. After a brief interval, the power grid experiences an upsurge to meet the demand, while the battery initiates the process of recharging. The System-on-Chip (SOC) is expected to experience an increase and attain a level of 80%. During the time interval of 2 to 4 *10^4 seconds, the load will experience an increment but will not exceed 500 kilowatts. The variability of solar radiation results in fluctuations in the output power of the photovoltaic system. Similarly, the battery will progressively deplete until it reaches the minimum threshold of 20%. During the identical time period, the grid and photovoltaic system will provide supplementary power to meet the energy requirements. During the time frame of 40,000 to 60,000 seconds, the load will maintain a consistent level, and both the power grid and PV system will exhibit identical behavior to the interval between 20,000 to 40,000 seconds. The battery's current state of charge will remain unchanged at 20%. During the time interval of 6 to 8 x 10^4 seconds, there will be a marginal reduction in demand. Concurrently, the electrical power supplied by the grid will augment while the photovoltaic power will diminish. The battery's minimum charge level will be maintained at 20%.

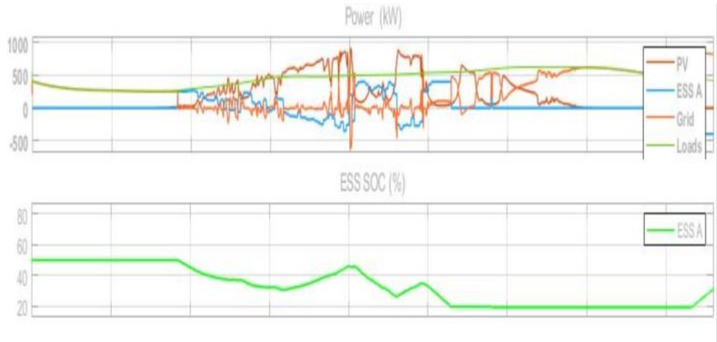

Fig. 6: Simulation result for a cloudy day using heuristic method

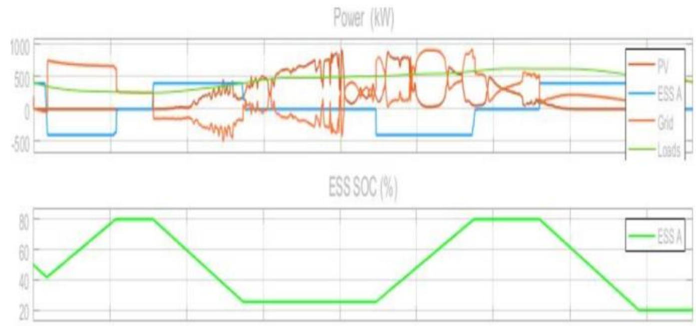

Fig. 7: Simulation result for a cloudy day using optimization approach

6. Conclusion

This paper presents a technical description of a Hybrid Micro Grid System (HMGS) that comprises a power grid, solar panels, batteries, and loads. A comprehensive methodology is employed to evaluate the dependability of the system. A strategy utilizing an integrated Energy Management System (EMS) is implemented to guarantee a secure and dependable equilibrium of energy. In order to construct a reliable Hydro-Meteorological Guidance System (HMGS), the potential impact of meteorological conditions on the system's accuracy has been accounted for. The intermittent nature of solar radiation will inevitably affect the energy levels of the system. The primary aim of this study is to optimize the power output of the photovoltaic system to meet the energy demand and charge the batteries. The process of creating a model has been executed through MATLAB R2018a. In order to achieve our desired outcome, two methodologies have been utilized: a heuristic approach utilizing State Machine Logic (State flow method) and an optimization approach utilizing linear programming. Based on the analysis of existing literature, numerous scholars have contributed significant and beneficial findings within the field. The selection of these techniques is based on their feasibility, dependability, and accessibility of resources in the microgrid setting. In this paper, the simulations present a good application of both methods considering both uncertainties.

Credit authorship contribution statement

Fendzi Mbasso Wulfran: Conception and design of study, Data acquisition, Analysis, and interpretation of data, Drafting the manuscript, Programming. **Molu Reagan Jean Jacques**: Data acquisition, Analysis, Drafting the manuscript. **Dzonde Serge Raoul Naoussi**: Methodology, Reviewing the manuscript, Approval of the version of the manuscript to be published. **Kenfack Saatong Tsobze**: Methodology, Reviewing the manuscript, Approval of the version of the manuscript to be published.

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Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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