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A Real-Time Energy Management of a PV/Battery/Grid-Connected System Under Uncertainties

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ABSTRACT

Building up grid-connected Hybrid Renewable Energy Systems (HRES) is one of the major challenges of developing countries. This relies on the feasibility study and moreover on the optimization of the system built. This paper aims to provide a good framework for Energy Management Systems (EMS) strategies. It consists of PV/Battery/loads connected to the power grid. Hence, the Hybrid Micro Grid System (HMGS) obtained is subject to meteorological uncertainties due to shadowing of the solar panels. Two approaches have been applied in this work: heuristic method using State Machine Logic (State Flow Method) and Linear Programming. These methods have been implemented using MATLAB R2018a. A thorough discussion describes the results of the simulations using both methods for two meteorological conditions: clear and cloudy periods. Four scenarios are presented in accordance to the specifications above-mentioned. A real-time analysis is performed for a specific case study on a daily basis.

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

I. INTRODUCTION

Electrification represents one of the major challenges in the world. Having access to a safe and reliable electricity is vital for every country. This will be helpful in every human activity nowadays (Alzard et al. 2019). One solution is the use of renewable energy sources (RES) to build up Hybrid Renewable Energy Systems (HRES). Generally, several energy sources are put together to constitute Hybrid Micro Grid System (HMGS). Nevertheless, due to the irregularity of RES, it is essential to stabilize the demand-supply balance within the system (Alvarez et al. 2017). Hence, reliability appears as one primordial criteria to assess a HMGS. Among all, integrating a storage system into HMGS is an alternative to better use the RES. Indeed, this will help into performing good Energy Management System (EMS) strategies to guarantee an efficient functionality of the HMGS. This relies on a reliable, safe and sustainable power generation and distribution, even under meteorological uncertainties.

For decades, numerous scholars have contributed into developing various approaches to improve EMS strategies. Many techniques have been proposed to obtain optimal and efficient HMGS. (Barakat et al. 2020) has performed a EMS in a multi sources environment using meta heuristic techniques. In the same line, (Tiwari et al. 2016) proposed an EMS based on other meta-heuristic approaches. (Elsied et al. 2016) developed a multi-objective EMS based on swarm and genetic optimization Furthermore, (Sukumar et al. 2017) proposed an EMS based on nonlinear and linear programming methods. (Iten et al. 2018) proposed a EMS based on a cosimulation using a fuzzy logic program and Hybrid Optimization Model for Electric Renewable (HOMER). (Khan et al. 2022) carried out a comparative analysis of EMS in terms of HRES research and technical tools used for assessment. Considering the uncertainties that can influence the HMGS, (Liu et al. 2017) proposed EMS based on other artificial intelligent methods. (Ghasemi et al. 2018) proposed an EMS based on stochastic and robust programming approaches.

In this paper, a grid-connected HMGS is considered for the study. It comprises of solar panels, batteries for energy storage, and two types of loads : variable and fixed load. Due to the sporadic nature of solar irradiance, two considerations are possible : clear and cloudy day. In these conditions, it is crucial to optimize the performance of the HMGS. Due to the double irregularities (sporadic nature of the radiation and variability of the demand), when the there is surplus of energy, the excess will be stored into batteries. When there is a deficiency, the difference of energy will be covered by the batteries. Furthermore, the control strategy employed in this work implies that the HMGS is not entirely dependent on the power delivered by the main grid, and the power supplied by the solar power generation and storage are sufficient at most of times. This paper is focused on two approaches : Heuristic approach using State Machine Logic (State flow method) and optimization approach using linear programming method. The modelling and simulations of the HMGS are performed using MATLAB R2018a.

The purpose of this study is to simulate and assess a microgrid that is powered in part by solar photovoltaics (PV) and batteries with a capacity of 10 MW. Integrated microgrid management EMS based on both the conventional heuristic approach and the more modern linear programming optimization approach have been developed and compared. Therefore, a proposed EMS seeks to keep the energy balance between solar-based generation and the variable load sides at a reasonable cost. The suggested EMS is based on linear

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programming optimization with the major goals of maximizing solar power output and increasing the lifetime of the energy storage system, assuring reliable power supply and maintaining environmental equilibrium. Since efficient, optimized energy management systems may be tested in a real-time setting, the proposed renewable-based integrated microgrid system is a viable option. The remaining paper is structured as follow : The stochastic modelling of the HMGS is discussed in Section 2. The formulation of EMS in the presence of solar and battery is discussed in Section 3. Likewise, a summary of the two approaches is presented in Section 4. The analysis and discussion of the four scenarios are presented in Section 5, followed by concluding remarks in Section 6.

II. SYSTEM MODELLING

A. Solar Modelling

Many categories of solar cell materials are being used worldwide but nowadays, silicon is ascendant material used in solar cells because of its impetus, adaptability and absorption of light efficacious. In this paper, we use a mono-crystalline PV array for its better performance in dry climates (Baghel et al. 2022). This PV array has a total of 24 modules per array comprised of 2 modules per string connected in parallel and 12 strings in series. The 72 Photovoltaic cells are connected in series to get 535kW solar panel. The power output of the PV is function of the solar radiation penetrating the area of the cells, the temperature, and the geolocation (Yang et al. 2009). (Herman DT et al. 2021) proposes a formula to compute the hourly output power of the PV 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.

A real-time Maximum Power Point Tracker (MPPT) is applied to the output power of the PV. A DC-DC converter is integrated into the HMGS. Depending on the daily conditions, the Maximum Power Point (MPP) is variable. In Incremental Conductance (INC) algorithm, the decided gradual change of the solar panel conduction is measured and then differentiate the instant conductance, which is well-known as the ratio of I/V. After being compared, in reference to the MPP, the position of the current (I) and voltage (V) changes (Alvarez et al. 2017).

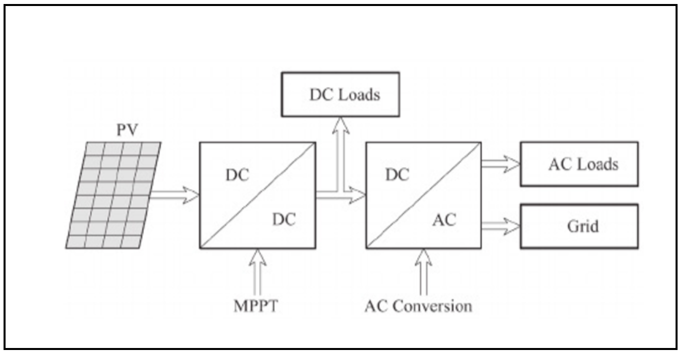

Fig. 1. Block diagram of the solar panel

B. Batteries Modelling

In the system modeling, the batteries are the elements that store the energy produced by the HRES when the energy produced is greater than the load requirements and at the same time transfer the stored energy to the system when the energy produced is not sufficient for the system. The energy stored by the batteries and the energy transferred to the system is AC voltage type. The state of charge of a battery in the discharge and the charge settings could be determined by Eqs. (3) and (4), respectively (Mohamed et al. 2019) :

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

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

Where P_l (t) and P_g (t) are the energy demand and generated power respectively. η_{BD} and η_{BC} represent the discharge and charge efficiencies of the battery. Parameter σ is the self-discharge of the battery, which is set to be zero in this study (Guasch et al. 2003). η_{cnv} is the efficiency of the converter.

Here, distributed battery with capacity of 3000kWh model is established based on the MATLAB. The instantaneous available energy $E_{avail}(t)$ to supply can be calculated by Eq. (5):

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

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

In this work, the rated power of ESS is 400 kW and capacity are 3000 kWh.

C. Load Modelling

In this work, two types of loads are considered : variable load and fixed load. The fixed load is a resistant with an active power of 350kW. Whereas the variable load has an active power of 200kW and a reactive power of 458.831kW. Furthermore, a dynamic load flow control is applied to generate specific active and reactive powers of the variable load every second of the day.

D. Uncertainties Modelling

During the day, the solar radiarion is not constant. Two considerations are done in this work : clear and cloud day. This will have an impact on the solar panels. Hence, the PV output power will fluctuate depending on the instantaneous radiation.

E. Power Grid Modelling

In this paper, a triphase AC source has been used with the following specifications : phase-to-phase voltage of 13833volts (RMS), frequency of 60Hz. A step-down transformer is used downstream of the AC source with the following characteristics : primary voltage :13833 volts (RMS), secondary voltage : 5000 volts (RMS). It has star-star connection

Figure 2 shows the block diagram of the HMGS.

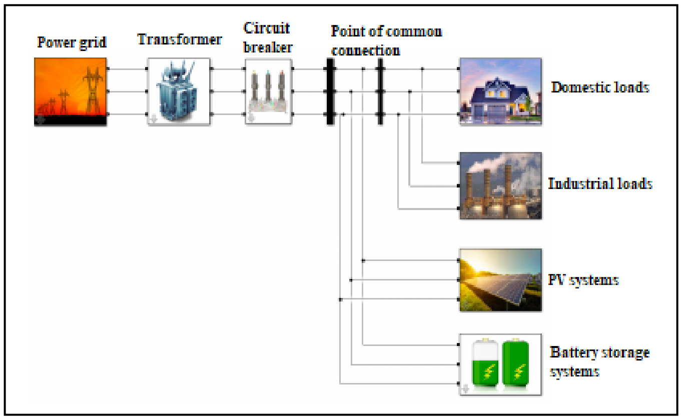

Fig. 2. Block diagram of the HMGS

III. PROBLEM FORMULATION

In this paper, the HMGS is made up of somar panels, batteries, loads and power grid. Hence, to assess its reliability, it is important to define objective and constraints functions.

A. Objective Function

The main objective is to maximize the power supplied to the PV. This will also contributes into maximizing the energy stored into the batteries. Let us consider negligible the losses during transmission of the energy transfered from the PV to the batteries. Hence, the instantaneous energy available in the batteries $E_{avail}(t)$ can be expressed as in 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) :

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

B. Constraints Function

To ensure a better operation of the battery storage system, the SOC needs to satisfy the Eq. (8):

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

Where SOC_{min} and SOC_{max} describe the respectively the lower and upper bounds of the state of charge of the batteries. In addition, this is a guarantee to have the battery always operating within its safe conditions at every time of the optimization.

IV. PROPOSED STRATEGIES

In this work, two approaches have been employed to proceed to the real-time analysis : Heuristic approach using State Machine Logic (State flow method) and optimization approach using linear programming method.

A. Heuristic Approach:

The State Machine Logic consists of finite number of states. Based on the current state and a given input, the machine performs state transitions and produces outputs. A state is a situation of a system depending on previous inputs and causes reactions on following inputs. A state transition defines for which input a state is changed from one to another. Figure 3 shows an example of door control.

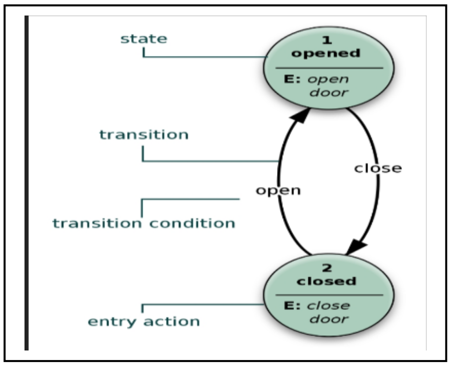

Fig. 3. Example of machine state logic:door control

Figure 4 depicts the state flow chart of the conventional heuristic approach, wherein distinct states are denoted by separate boxes. The heuristic Energy Management System (EMS) first assesses the overall state of the microgrid's operation and subsequently acquires the energy-related information. The outcome is contingent upon variables such as the time of day and the state of charge (SOC) of the battery. Upon execution of the heuristic algorithm, the decision logic will present a sequential analysis of the state flow chart.

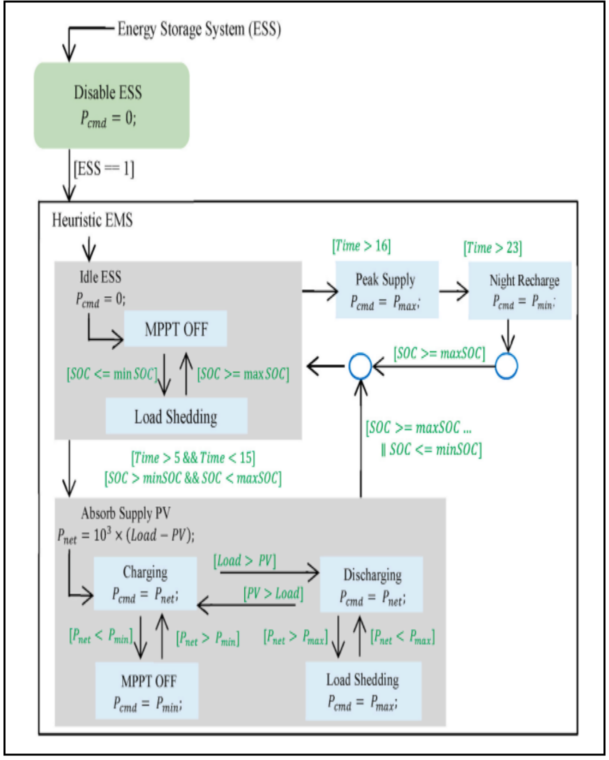

Fig. 4. State flowchart of traditional heuristic method.

B. Linear Programming:

The Linear Programming is a mathematical modelling technique in which a linear function is optimized (maximized or minimized) when subjected to various constraints. The solution of a linear programming problem reduces to finding the optimum value (largest or smallest, depending on the problem) of the linear expression (called 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):

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

The microgrid EMS utilises coordination controls that operate in two steps to ensure stable operation. The control logic of the solar power generators relies on the EMS to determine the different operation modes based on the measurement of the system net power (Pnet) and the charging/discharging rate of the battery system, while taking into account the energy constraints. Figure 5 depicts the microgrid control flowchart for the linear optimization Energy Management System (EMS).

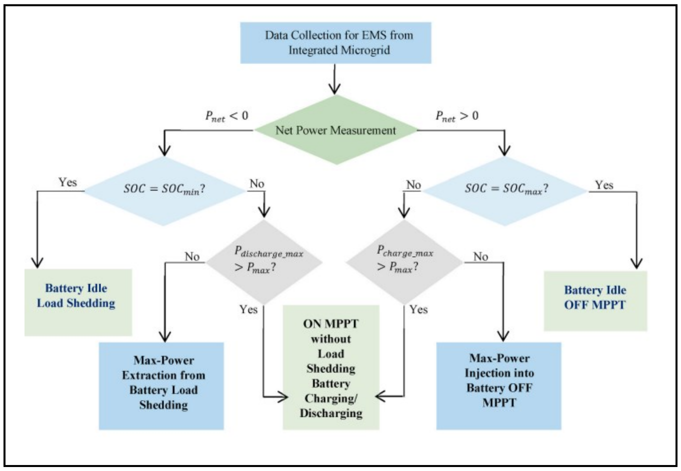

Fig. 5. A flowchart depicting the control of a microgrid using linear optimization Energy Management System (EMS).

V. SIMULATIONS RESULTS AND DISCUSSIONS

A HMGS is made of three essential parts : production, distribution and consumption. As shown in Figure 2, the test system is presented. Modelling and simulations have been performed with MATLAB R2018a. In this system, we are using two different conditions : clear day and cloudy day. Furthermore, two approaches are employed in this paper : Heuristic method and Linear Programming. Using these different conditions, we optimize the power supplied to the PV. Four scenarios will be presented in the below sections :

A. Heuristic Approach during clear day

The first scenario of the simulations is obtained using heuristic approach during clear day. Two waveforms are depicted in Figure 6. The first one represents the power of Photovoltaic (PV), grid, battery and load. The next displays the SOC of the batteries every second during one day. A real-time analysis shows that from 0 to 2 *10^4 seconds, the load demand is less than 500kW. During that period, the SOC is at its initial capacity which value is 50%. From 2 to 4 *10^4 seconds, we observed a increase of the demand up to 500 kW. At the same time, we have simultaneously an increase of the PV power and a decreease of the battery power. When the PV power starts to be greater than the load demand, the excess power generated is stored in the battery. This means the battery slowly starts to charge. In the interval of 4 to 6 *10^4 seconds, while the load remains constant, the SOC starts increasing, justifying that the battery is on charging mode. But while the load fluctuate slightly, the SOC continues increasing upto 80%. Likewise, the PV power gets reduced and the battery slowly starts to supply the power which means the battery starts discharging. In the interval of 6 to 8 *10^4 seconds, the load is increased up to 500kW but still the power from the battery though the PV power goes on decreasing. At an instant the battery gets fully discharged and the PV power is negligible, then comes the grid power.

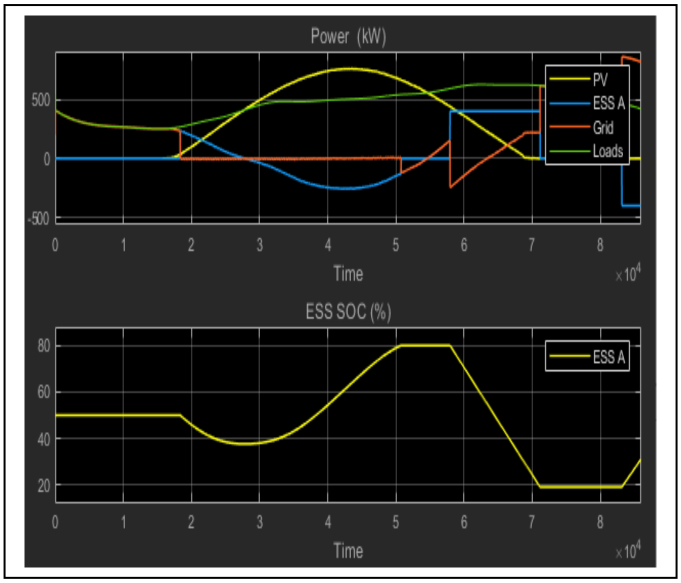

Fig. 6. Simulation result for a clear day using heuristic method.

B. Linear Programming during clear day

Linear Programming during a clear day has been simulated and results presented in the Figure 5. During the optimization process, from 0 to 2 *10^4 seconds, the demand is less than 500kW. Thus, only the grid will generate the sufficient energy to cover the deamand. The PV will be supplied and the battery will be on charging mode. The SOC will reach 80%. At a certain time when load is increasing, the grid supply will decrease due to PV and battery contributions. Simultaneously, the battery gets discharged. Within the interval from 2 to 4 *10^4 seconds, the load is slightly increasing up to 500kW. The PV power is on a positive slope showing it is increasing. Simultaneously, battery power and SOC are decreasing. Here, PV supply more power and the grid power decreases which means the battery does not supply. From 4 to 6 *10^4 seconds, the demand increases slightly. Both grid and PW power will increase to cover the demand. The battery remains at minimum SOC as the demand goes beyond 500kW. In the interval of 6 to 8 *10^4 seconds, the load remains constant for a while and will later on decreases slightly. The grid will continue to supply the load and the PW power continues decreasing. The grid will remain the only energy supplier to cover the demand and the battery remains at minimum SOC.

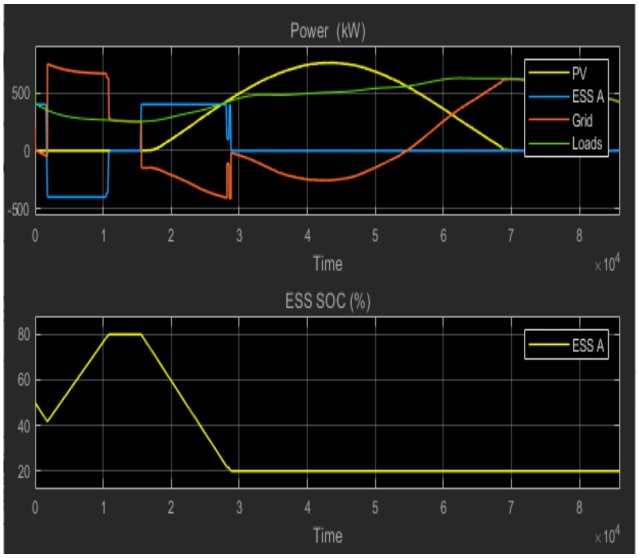

Fig. 7. Simulation result for a clear day using optimization approach

C. Heuristic Approach during cloudy day

In this section, we consider a cloudy day while the solar radiation is not so efficient to ensure a sufficient power delivered by the PV. The State Flow Method employed leads to the waveforms displayed on Figure 6. During interval 0 to 2 *10^4 seconds, the load demand is less than 500kW. The battery SOC is at initial value which is 50%. From 2 to 4 *10^4 seconds, the load starts increasing and reach 500kW. Nonetheless, the solar radiation is fluctuating. What will have an effect on the power delivered by the PV. Simultaneously, the battery and the grid will contribute complementarily into covering the gap. Hence, the SOC of the baterry will decrease, showing the effect on the battery which is discharging. During the interval 4 to 6 *10^4 seconds, the demand will increase slightly and we have the same behavior as in the interval 2 to 4 *10^4 seconds. SOC will reach the minimum value of 20%. From interval 6 to 8 *10^4 seconds, the demand is more than 500kW. The grid will be the only contributor to cover th demand and the battery will continue remain at minimum value.

D. Linear Programming during cloudy day

While proceeding to the optimization of the HMGS during cloudy day, Figure 7 depicts the waveforms of powers of the system and SOC of the battery in particular. From 0 to 2 *10^4 seconds, the demand is less than 500kW. The battery moves from an initial SOC of 50% to 40% due to the decreasing power of the grid. Few seconds later, the power grid increases to cover the demand, while the battery will start charging. The SOC will increase and reach 80%. From 2 to 4 *10^4 seconds, the load will increase but remains less than 500kW. But due to the irregularity of solar radiation, the PV output power fluctuates. Likewise, the battery will continue decreasing down to the minimum value of 20%. During the same interval, both grid and PV will contribute complementarily in power to cover the demand. From 4 to 6 *10^4 seconds, the load will remain constant, and both power grid and PV will have the same behavior as the same interval 2 to 4 *10^4 seconds. The battery will remain at the same value as earlier, meaning 20%. From 6 to 8 *10^4 seconds, the demand will decrease slightly. Simultaneously, the grid power will increase and the PV power will decrease. The battery will remain at the minimum value of 20%.

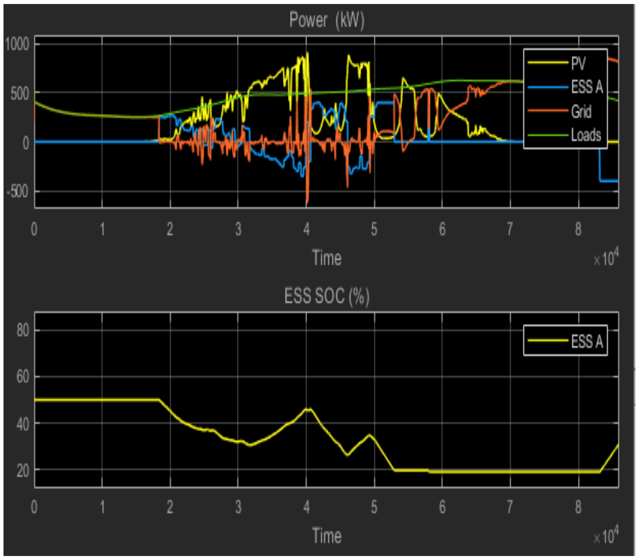

Fig. 8. Simulation result for a cloudy day using heuristic method

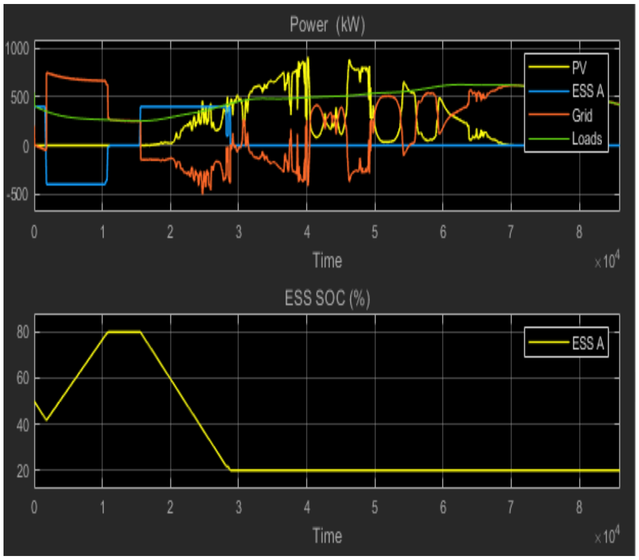

Fig. 9. Simulation result for a cloudy day using optimization approach

VI. CONCLUSION

In this paper, a Hybrid Micro Grid System (HMGS) constitutes of power grid, solar panels, batteries and loads is described. To assess the reliabitity of the system, a thorough methodology is applied. An integrated Energy Management System (EMS) strategy is employed to ensure a safe and reliable energy balance. To build up a robust HMGS, uncertainties due to meteorological condition have been taken into consideration. Indeed, considering the sporadic nature of solar radiation, this will have an impact on the energy within the system. In this work, the main objective is to maximize the power out of the PV that will be used to cover the demand and supply the batteries. The modelling is performed using MATLAB R2018a. to fulfill our objective, two approaches have been employed : Heuristic approach using State Machine Logic (State flow method) and optimization approach using linear programming. Considering the littérature review, many scholars have provided valuable and useful results in the domain. These methods are chosen based on their practicality, reliability, and resource availability in the microgrid environment. In this paper, the simulations present a good comparison of both methods considering both uncertainties.

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