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Global optimization of hybrid AC/DC microgrid using HOMER and CPLEX

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ABSTRACT

This work presents an idea about to design, simulation, and analysis of an operational control system in order to control and supervise the operations of a hybrid AC/DC microgrid (HMG) in the different operating modes (connected and islanded). The main task of this paper is concerned with the development and the implementation of a global optimization method for solving the problems of the energy crisis of HMG with an adequate control algorithm. The supervision system was developed in such a way that it coordinates when power should be generated by sources renewable energy sources (RES) such as PV array or wind turbine and when it should be produced by grid power in on-grid operation or with diesel generator (DG) in off-grid operation. This system is intended to maximize the use of the RES while limiting the use of the other emergency sources of energy (the utility grid and DG). The control simulation proves that the management system reduces the total cost of HMG thereby reducing the total cost of the RES. From the simulation results, the developed supervision system reduces the global operational hours of the HMG and the proposed algorithm respects the optimization in real-time operation under different constraints.

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1. INTRODUCTION

The largest percentage increase in emissions of carbon dioxide (CO_2), fuel availability, and others are related to the centralized power production, the requirement for the development and designing an off-grid or on-grid hybrid microgrid system also growing. Therefore, hybrid ac/dc microgrids have become an optimal approach as they combine the main advantages of ac and dc microgrids. This work proposes a supervision control system for energy and power management in on-grid/off-grid hybrid AC/DC microgrid. The storage unit (SU) and diesel generator (DG) are used for the backup systems to replace the instability of energy production of renewable energy sources (RES). Moreover, the respect of constraints have an important role in minimizing and optimizing energy costs [1].

The role of the studied optimization is to maintain the perfect power distribution among the RES, so to minimize the total cost of energy, regulate the utility grid power peak and load consumption in on-grid mode, reduce the DG use in order to avoid load shedding of the solar collectors in both operating modes. Although the constraints are not too different between the two operating modes on-grid and off-grid, the resolution of the optimization problem will be reformulated separately. The optimal functioning of the studied system is ensured by the respect of the given operating conditions and constraints. The optimization gives an optimal solution within given constraints and operation condition [2].

2. STRUCTURE OF THE PROPOSED HYBRID AC/DC MICROGRID

The objective of the work will be accomplished through the following. First, hybrid AC/DC multi-source system output will be found out based on the design cited in [3]. This will be shown through simulation results from hybrid AC/DC microgrid (HMG) design using hybrid optimization model for multiple energy resources (HOMER) Pro software. A hybrid AC/DC microgrid installed in Avenue Agdal Rabat, Morocco (33.99761”, 6.85357”) is taken as the reference for this work. Secondly, total cost estimation and minimization of the aspects of the power system such as power management and supervision have an impact will be analyzed using a specified optimization algorithm [4], [5].

For the analytical aspect, we consider three main types of energy sources, namely PV array, wind turbine, and diesel generator. The hourly information about the solar and wind is exported from the national renewable energy laboratory (NREL) site. Solar energy availability is provided by HOMER Pro. Based on the location of our reference hybrid system, the annual average solar radiation is 5.43 $kWh/m^2/day$. The insolation increases between April and August and reduces in the winter season. The monthly average of wind speed taken is 4.13 m/s [6].

3. SUPERVISION SYSTEM DESIGN

The supervision system was developed through a multi-layer system including the global optimization methodology. The global role is the reduce energy cost respecting all constraints and the performance of the control system. The supervision system as described in [7] contains four layers, which are: i) client layer which is the interface that facilitates the users to select the criteria suitable to their need; ii) prediction layer wish predicts RESs production and load consumption; iii) energy management layer wish to optimize the power flow; and iv) local layer wish is used to transfer the upper-level strategies guidelines to the lower level.

4. FORMULATION OF THE OPTIMIZATION PROBLEM

4.1. Expression of cost and constraints

An optimization problem is usually characterized by an ”objective function”, a set of constraints and a set of variables that can take any real values to give an optimal solution and a set of stated data called optimization parameters”. In this part, these different components will be described to solve the problem of energy management of HMG. In the present study, we are concerned only in the energy management layer (EML), described in [7], and it has the objective of resolving an optimization hassle to determine the hourly power output of each disposable RESs for the next day, by considering the power generation and consumption. EML is mainly focused on economics, considering factors like capital costs, maintenance and energy costs, lifetimes [8].

4.1.1. Constraints of RES

Initially, the proposal of energy management which can guarantee optimal control of the hybrid energy system with respect to the imposed constraints is necessary. Then, in accordance with the organization of the supervision system, we develop an operating strategy in order to describe the global functioning methodology of the hybrid power system operation. The goal is to determine a perfect power management strategy that guarantees a suitable power balancing system [9], [10]. Finally, the PV panels are connected to the DC bus, so the wind turbine is connected to the AC bus. To ensure the proper functioning of the system, the power produced must be kept within suitable limits. Therefore, the output powers of RES should be limited. However, they should not induce negative power to avoid damage and maximize the life of the devices:

$$P_{PV}(t) \geq 0, P_{WT}^{AC}(t) \geq 0 \quad (1)$$

where P_{PV} and P_{WT}^{AC} are the maximum powers limits of PV array and wind turbine, respectively.

4.1.2. Constraints of storage units

The importance of the need for SU has related especially to the system operating mode (on-grid or off-grid). The battery is charged/discharged according to the chosen strategy. Whenever the total power produced by RES and DG exceeds the charge demand, the battery will be charged. On the other hand, if the available output is less than the consumption, the battery will discharge to cover the deficit. The battery capacity is related to the state of charge (SOC) and the operation of the system in a period between t-1 to t. In fact, the state of charge must be limited by constraints:

$$SOC^{max}(t) \leq SOC(t) \leq SOC^{min}(t), P_{B_D}^{min}(t) \leq P_B(t) \leq P_{B_C}^{max}(t) \tag{2}$$

where $SOC^{max}(t)$ and $SOC^{min}(t)$ are the maximum state of charge and the minimum state of charge respectively. Moreover, P_B,$P_{B_C}^{max}$ and $P_{B_D}^{min}$ are the battery bank power, the charging and discharging power limits of SU. $t \in [t_0, t_0+1, ..., t_0+n\delta\tau]$, with $\delta\tau$ is the time step.

4.1.3. Constraints of load

The variability of the daily load curve is a major problem in residential buildings, marked by significant increases and decreases in consumption, directly influences the stability of the hybrid AC / DC micro-grid. In addition, the integration of decentralized production systems requires the establishment of effective management strategies in order to maintain the balance between supply and demand. This balance requires adjusting, as much as possible, the daily consumption profile to production. The objective is therefore to modulate the load by shifting certain consumption in order to limit the risk of overloading the generated energy or the mismatch between local production and consumption [11].

The power consumption due to the load profile is expressed by the following formula:

$$P_L^{min}(t) \leq P_L(t) \leq P_L^{max}(t), P_L(t) = P_L^{AC}(t) + P_L^{DC}(t) \tag{3}$$

P_L^{AC} are P_L^{DC} the AC and DC load power respectively. P_L, P_L^{min} and P_L^{max} are respectively the power produced by the load, the maximum value of the load output power and the minimum output load power P_L, P_L^{min} et P_L^{max}.

4.1.4. Constraints of the utility grid

The standard microgrid has the advantage of purchasing electricity and selling it again to the grid network. Moreover, the purchase and sale costs of power are decided in real-time from loads demand variation during the day. Finally, the control of power demand depends on a rate parameter, denoted as in $/kWh$, which varies periodically with wholesale market prices. P_G is the utility grid power, so,this power is imported from the grid when $P_G(t) \geq 0$ and it's exported to the grid when $P_G(t) < 0$. To reliably operate the utility grid, the power exchanged should be limited by the following limits:

$$P_G^{min}(t) \leq P_G(t) \leq P_G^{max}(t) \tag{4}$$

4.1.5. Cost function

The objective function has been defined to minimize the total energy system operating cost. Costs include, RES costs (C_{pv} and C_{wt}), load cost (C_l) (DC and AC load), SU cost (C_b), DG cost (C_{dg}) and C_{gb} and C_{gs} are the costs for the purchasing power from the utility grid and the sold energy to the network (i.e., applicable in on-grid case). The objective function is mathematically expressed by the following (5) [12], [13].

$$C_{st}(t) = C_{pv}(t) + C_{wt}(t) + C_b(t) + C_l(t) + C_{dg}(t) \tag{5}$$

4.2. Resolution of the optimization problem for the different operating modes

An overview of power flow in different functioning mode is shown in Figure 1. The main goals of the proposed hybrid AC/DC microgrid are: minimizing power demand peak consumption, stability of grid power injection, reducing the total cost of the power system and maximizing the lifetime of the HMG with a smooth exchange of energy between the power system and the grid. In this case, the development of an algorithm to improve the performance index in order to obtain an optimal control strategy for the power system is needed in different functioning modes.

4.2.1. On-grid mode

Figure 1(a) gives a schematic of the power flow in on-grid operating mode. The PV panels, the wind turbine, the batteries, and the utility grid are connected to the DC or AC bus via their dedicated converters whose conversion efficiencies η_{PV},η_{WT}^{AC},η_B and η_G are respectively. The load consumes power directly from the DC or AC bus [14]. In physics, all the powers have a positive value, also for the proper functioning of the system, the power balancing must be respected for all tools connected to the DC bus taking into account the conversion efficiency, all this is described by [15].

$$MR^{DC} : P^*(t) \times \eta_* + P_L^{DC}(t) = (P_{PV}(t) \times \eta_{PV} + P_{WT}^{AC}(t) \times \eta_{WT}^{AC} - P_B(t) \times \eta_B \tag{6}$$

$$MR^{AC} : \eta_G \times P_G(t) = P_L^{AC}(t) + P^*(t) \times \eta_* \tag{7}$$

Where P^* is the power exchanged between two sides of the HMG (AC and DC buses) and is determined explicitly by equation from the other powers values, which makes P^* as the only unknown component andη_* its corresponding efficiency (interlinking converter). The system takes into consideration three situations: i) the energy generated by RES (PV panels and wind turbine) meets the specified load demand, ii) the total energy power generated by HMG (RES and batteries) is not sufficient to meet the power consumed by the loads, and iii) the energy generated is more than the need for power consumed by the HMG.

In the present work, $P_P(t)$ is the total power produced by the RES:

$$P_P(t) \times \eta_{INV} = P_{PV}(t) \times \eta_{PV} + P_{WT}^{AC}(t) \times \eta_{WT}^{AC} \tag{8}$$

in the first case, when the power produced by RES meets the required load demand, the electricity generated via the RESs is identical to the total energy demand ($P_P(t) = P_L(t)/\eta_{INV}$). Then, the power system will not inject any power into the grid (P_G^{sell}) or purchase power (P_G^{buy}) from the network and the battery bank keeps a stable value during this operation [16], so:

$$P_G^{sell}(t) = P_G^{buy}(t) = 0, P_B(t) = P_B(t+1) \tag{9}$$

in that case, the produced energy of the RESs is more than what's demanded (($P_P(t) > P_L(t)/\ eta_{INV}$)):

The surplus power available for charging the batteries:

$$P_B(t) = P_B(t_0) + \int_{t_0}^{t} [P_P(t) - P_L(t)/\eta_{INV}] \times \eta_{B_C}\, \mathrm{d}t \tag{10}$$

$$P_G^{buy}(t) = 0 \tag{11}$$

η_{B_C} is the battery efficiency in charging mode. η_{INV} is the DC/AC efficiency, and in this study, its default value as 90%, if the excess energy of the RES after the batteries being charged, this power may be sold to the grid:

$$P_G^{sell} = \frac{\eta_G}{720 \times \eta_{B_D}} \int_{t_0}^{t} [P_B(t+1) - P_B^{max}] \times \eta_B\, \mathrm{d}t \tag{12}$$

η_g and η_{B_D} are respectively the grid utility and the battery in discharging mode efficiency. Is the maximum of power reached by the storage system.

When the energy produced is less than the need of power by the HMG ($P_P(t) < P_L(t)/\eta_{INV}$). So, there are two cases:

a. The total energy provided by RESs and batteries can satisfy the need of power ($P_P(t) + \frac{\eta_{B_D}}{720} \int_{t_0}^{t} [P_B(t+1) - P_B^{min}] > P_L(t)/\eta_{INV}$).

$$P_B(t) = P_B(t_0) + \int_{t_0}^{t} [P_L(t)/\eta_{INV} - P_P(t)] \times 1/\eta_{B_D}\, \mathrm{d}t \tag{13}$$

$$P_G^{buy}(t) = P_G^{sell}(t) = 0 \tag{14}$$

b. The power stored within the batteries and the energy generated by the RESs can't meet the demand. Hence, the batteries are completely discharged and the overall produced electricity (PV panels + wind turbine + batteries) can't satisfy the devices power requirements, accordingly, the required power P_G^{buy} will be bought from the grid ($P_P(t) + \frac{\eta_{B_D}}{720} \int_{t_0}^{t} [P_B(t+1) - P_B^{min}] < P_L(t)/\eta_{INV}$):

$$P_G^{buy}(t) = P_B(t_0) + \int_{t_0}^{t} [P_L(t)/\eta_{INV} - P_P(t) - (P_B(t) - P_B^{min})] \times 1/\eta_{B_D} \times \eta_G \, dt \quad (15)$$

4.2.2. Off-grid mode

Figure 1(b) indicated the power flow in the off-grid mode, their respective natures and the components of the hybrid power system [17]. There are four operating modes to meet the needs of different off-line planning states:

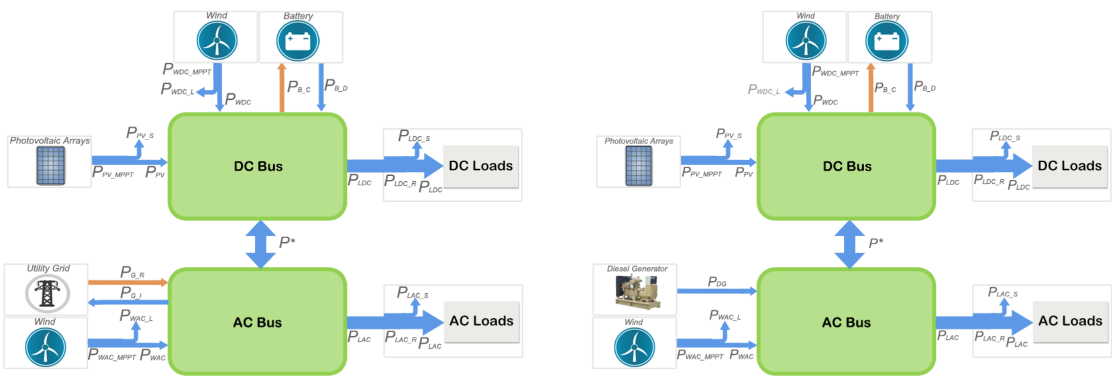
a. In the first case, the total energy produced by the RES is used to satisfy the consumption, during the operating of this state, the weather conditions are suitable for the photovoltaic panels and the wind turbine to produce a maximum power that can satisfy the load energy demand.
b. For the second state of hybrid system functioning, the energy produced by the RES can supply the load. However, if the HMG cannot operate correctly during this mode, and the energy produced by the PV panels or the wind turbine only cannot meet the consumption, in that case, the photovoltaic or the wind turbine can produce the need for energy. and any excess of power should be used to charge the SU.
c. The system operates in this mode when the energy produced by all RES is almost equal to the load demand. Therefore, if the energy generated by RES cannot meet the consumption and therefore the HMG must use additional power to satisfy the lack of power and the DG must be turned ON.
d. During emergency mode, the system will be able to automatically choose which has priority (DG or batteries) to meet the load demand based on the following decisions:

– If the SOC is greater than the minimum quantity, then the SU will be used to satisfy the energy requirement of consumption.
– If the SOC is at its minimum value, then the SU cannot be used to provide the necessary power deficit. Therefore, the DG will be activated.

The power should be balanced in off-grid mode considering conversion efficiency:

$$P_{PV}(t) \times \eta_{PV} + P_{WT}^{AC}(t) \times \eta_{WT}^{AC} + P_{DG}(t) \times \eta_{DG} = P^*(t) \times \eta_* + P_L^{DC}(t) + P_B(t) \times \eta_B \quad (16)$$

the CPLEX solver based on the linear and dynamic programming technique is used to solve energy optimization problems [18].



(a) (b)

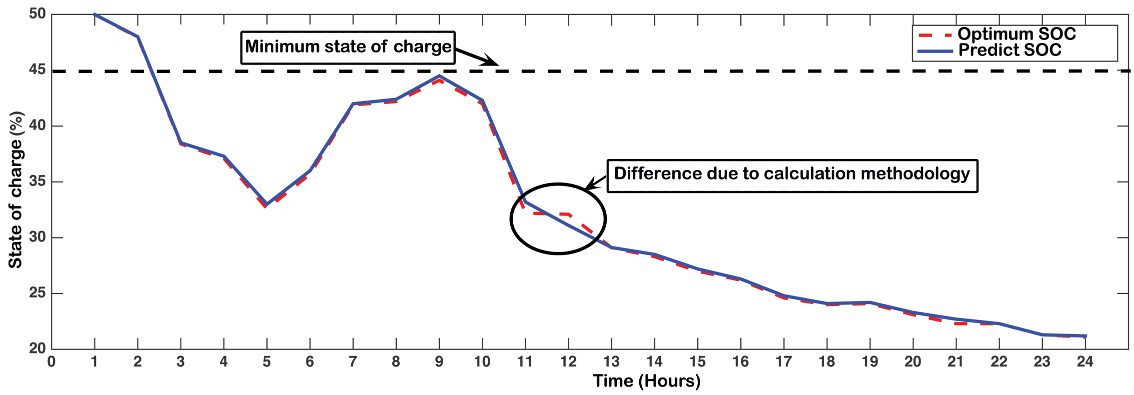
Figure 1. Power flow of hybrid AC/DC microgrid, (a) grid-connected mode and (b) off-line mode

5. SIMULATION RESULTS

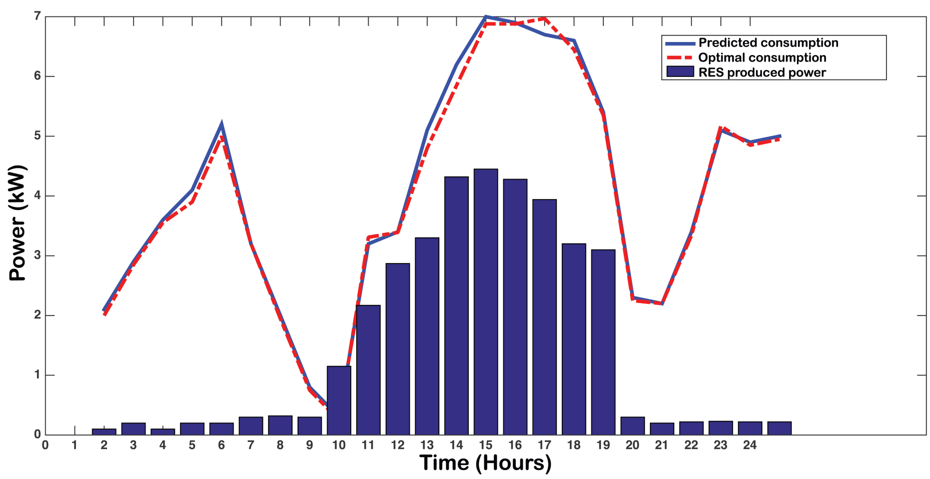
5.1. Grid-connected mode

We consider January 12, 2019, as a reference day for the sampling of the measurements used during the experimental study. Figure 2 gives a comparison of the forecast and optimized state of charge and load profiles both. The time of the modifications due to the methodology of the calculation of the prediction solution at the time between 11h00 and 12h00 in the morning as shown in Figure 2(a). The cost of the strategy is the same if the batteries are charged at 5 a.m. or 11 a.m. The forecasting strategy is provided directly by HOMER, while the optimized strategy is based on a complex calculation and optimization. It is, therefore, necessary to be careful to not confuse this difference between the optimization and the real measurement [19], [20].

Figure 2(b) shows that the energy management strategy only works perfectly during the critical period (12h00 a.m. and 17h00 p.m.) and that the real produced power is applied without optimization for almost the rest of the day. Through optimization, the optimum PV power does not exceed the limit most of the simulation time. Therefore, Homer's optimization strategy ensures constraints are met but does not ensure optimization in accordance with actual conditions. It follows that the basic optimization provided by Homer is not a satisfactory solution for day-to-day management. This method is considered to be a safety system that ensures compliance with constraints but which does not guarantee the best state of charge of batteries at the end of the day. Hence the goal of using an optimal management algorithm based on CPLEX [21].



(a)

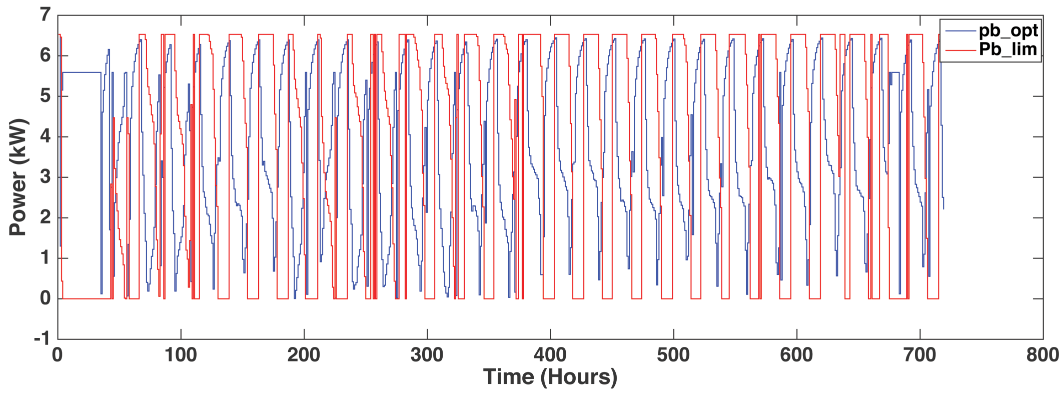


(b)

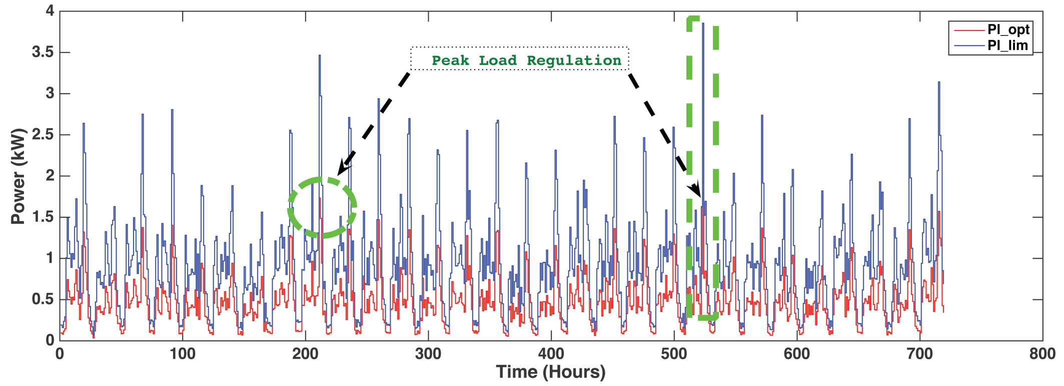
Figure 2. Comparison curve of loads and batteries in grid-connected case, (a) state of charge before and after optimization and (b) the power profile of the predicted and optimized consumption

5.2. Grid-tied mode

According to the forecasting information provided by HOMER, Figure 3 shows the role of the supervision system to provide the optimized power budget according to the resolution of the optimization equations calculated by the CPLEX solver. In Figure 3(a), the constraints imposed for the storage units ($0 \leq P_B(t) \leq 8kw$) in order to minimize the cost of a lifetime and good capacity of batteries have been respected [22]. We also notice that the battery charges when the power produced by the RES is sufficient during the day [23]. The load profile is shown in Figure 3(b). For the experimental simulations, the choice of an arbitrary load profile is favorable to clearly test the different events and cases used in the energy management strategy. As illustrated in Figure 3(b), peak load is decreased and shifted to other hours because of an optimal local power flow that gives a perfect security factor for unexpected events by regulating peak consumption [24], [25].



(a)



(b)

Figure 3. Optimization methodology in autonomous case, (a) the power profile of the predicted and optimized consumption and (b) experimental result of the predicted and optimized load power

6. CONCLUSION

For developing a stable hybrid AC/DC microgrid model with a local supervision control system for the given specific location, one of the most important deciding parameters is its technical and economic feasibility. For this purpose, the system consists of PV/wind, unit storage, and loads for the hybrid AC/DC microgrid were considered and the HMG can exchange power with the utility grid. The suitable size for all of the hybrid power system tools was considered. Then, the validation of energy management strategy under the different constraints imposed by the studied system for the two operating modes has been verified and simulated. Moreover, the proposed control strategy which assures us of an optimal energy management strategy has been technically verified. Even with the prediction conditions, the experimental result of the total cost can be controlled to a value close to the desired real values, which proves the reliability and the validation of the proposed management solution. The energy management simultaneously respects the various constraints such as peak hours of the load and the grid utility, the mentioned limits of renewable energy sources and of the storage unit too. With the same constraints, the optimized methodology is is more efficient and perfect. The HMG that was used in this study has high reliability since diesel generators were utilized as a backup for the RES and SU, especially in off-grid mode. The results tests showed the performance of supervision system ensuring optimal power balancing, reducing the total cost system, and avoiding undesirable peak load consumption. The simulation result validate perfectly the total cost reduction of the HMG.

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