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Research Article

Control Strategy of Hybrid AC/DC Microgrid in Standalone Mode

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ABSTRACT. The fluctuation of production of renewable energy resources (RESs) is a big problem for its installation and integration in isolated residential buildings. A hybrid AC/DC microgrid facilitates the good operation of RESs with a storage system in standalone mode and the possibilities of smart energy management. In this paper optimization research of the hybrid ac/dc microgrid in isolated mode of operation is presented. The power system is supplied by various Renewable Energy Resources (RESs), Photovoltaic arrays (PVA), a Wind Turbine Generator (WTG), Diesel Generator (DG) and supported by Batteries Storage System (BSS) for short term storage. The main objective of this study is to optimize power flow within a hybrid ac/dc microgrid with regards to reliability in islanded mode. First a mathematical model optimized by mixed integer linear programming and solved by CPLEX solver with JAVA language is developed for an islanded RES system and then, based on the developed model, the power system control was simulated for different cases of off-grid mode. Simulation results have shown that the management strategy can maintain power balancing while performing optimized control and give a controllable loads and batteries charging/discharging powers, even with unpredictability of RESs powers outputs and arbitrary energy tariffs. Finally, the proposed algorithm respects the optimization in real-time operation under various constraints.

Keywords: Hybrid ac/dc microgrid, Isolated mode, Optimization, Control.

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1. Introduction

In the past few decades, after the increase use of the AC technology in electric power systems among DC power, the DC technology has come back as an increasingly big rival with the advance of technology in power generation, conversion, consumption and transmission. However, in spite of significant advantages in many energy tools, there are still a lot of obstacles to overcome, and the big challenge is the integration of the DC technology into the system through a smooth process. Micrograds, as a principle part of building block of future intelligent distribution systems as shown in figure 1, are one of the main areas where the DC technologies are expected to win (Planas et al. 2015). In particular, hybrid AC/DC Microgrids (HMG) may facilitate the integration process of DC technologies into the existing AC power systems. Moreover, Hybrid AC/DC systems are becoming attractive for the electrification in rural areas in all aspects like environmental concerns, sustainability, reliability and advances in renewable energy technology; especially for villages living far in areas where grid extension is difficult so the use of RESs like PVA and WTG to provide reliable power supply with more efficiency and a very low energy cost. The interest of current research is based on the quantification of energy efficiency improvement that hybrid AC/DC microgrid may introduce in isolated buildings or in very far away areas. In that case, the concept of hybrid AC/DC microgrid (figure 1) is proposed which combines the advantages of AC and DC power systems (Unamuno et al. 2015). The main feature of HMG is that its AC and DC microgrid are combined in the same distribution grid, facilitating the direct integration of both AC- and DC-based distributed sources including generation, storage and loads. The HMG can operate either as an autonomous system with no connection to the utility grid or in grid-connected mode. Typically, an HMG has two modes of operation: Isolated and connected mode. In this study, the power balancing control strategy in islanded-mode is developed, which takes into consideration several constraints as prediction data, storage ability, and energy cost. The management of the HMG is proposed as a hybrid control system (HCS) to ensure an optimal power control, as described in figure 2, based on information approximately the user's criteria request, weather forecasts, conditions concerning grid availability. The powers flow is optimized by mixed-integer linear programming (MILP) and solved by CPLEX solver with JAVA language (Xiong *et al.* 2011).

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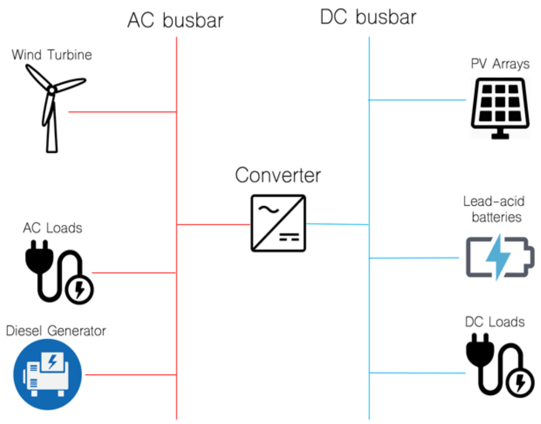

Fig. 1. Hybrid AC/DC Microgrid in isolated mode.

2. Intelligent hybrid ac/dc microgrid

Unlike conventional and typical power systems, smart hybrid ac/dc microgrid (SHM) use more communication with implements the role of end customers to ensure the control of power flow. In Figure 2, the SHM are defined as networks able of self-correcting and with dynamic optimization capabilities based on real-time measure-ements to minimize energy losses while increasing reliability and its performances. They are also able to react to unforeseen situations thus facilitating the integration of renewable energy sources while increasing the quality of energy (Qachchachi *et al.* 2016). The SHM have many capabilities that conventional microgrids do not have:

- The inclusion of the end users;
- Diversification of RESs;
- The possibility of developing a new electricity market with more tariffs;
- The assurance of a better quality of energy;
- Automatic detection of problems, faster decision-making and better adaptation in case of unforeseen events.

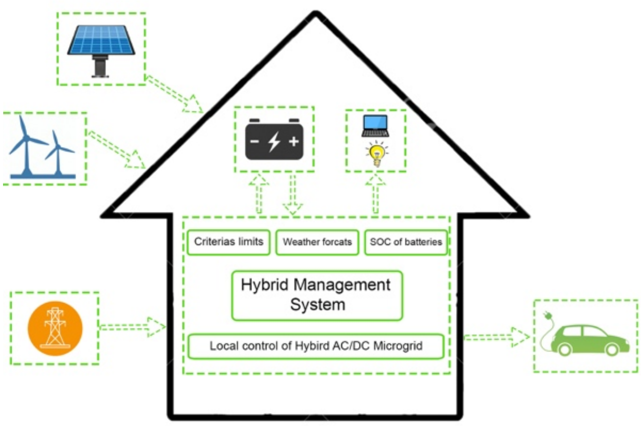

Fig. 2. Power management strategy in hybrid ac/dc microgrid

One of the major problems faced by the technology of integration of RESs in isolated areas are the high level cost or accessibility of energy. However, the stochastic nature of RESs is sometimes seen as a hindrance to their development, and to guarantee a constant access with stability and viability of energy, complex control algorithms are needed. In order to guarantee a certain competitiveness for this new type of network, certain goals must be achieved. The amount of fuel consumed by diesel generators should be minimized and the power extracted from RESs must be maximized. However, the DC and AC buses voltages must be regulated, the distribution of power must be properly done and finally the power sources must synchronize properly with the load demand. The main objective of this paper is to guarantee the proper functioning of the proposed hybrid ac/dc microgrid including the definition of the different modes of operation. Moreover, this study aims to ensure an optimal synchronization of the different RESs components with load demand with minimal fuel consumption of diesel generators (Nejabatkhah *et al.* 2019; Li *et al.* 2019).

3. Operating strategy for the HMG

When the RESs produce less power than what is requested (the wind speed and the solar radiation are low), the power needed by the loads should be supplied by the BSS. When the state of charge of BSS reaches its minimal level, in this study is 45% (Table 3), then the diesel generator functions. The achievement of a good operation of the HMG needs a wall control strategy of the interaction in the operation of the different components (Teimourzadeh *et al.* 2015; Wang *et al.* 2018).

3.1. Objective Function

During the study of HMG in isolated mode, the behavior of the DC and AC subsystems must be treated in the same way. On the other hand, the objective function will be different compared to a standard power system. In this case, the goal is to minimize the cost of investing a HMG by considering all the components of the studied system (Li *et al.* 2019):

$$Cs(t) = Cpv(t) + Cwt(t) + Cb(t) + Cl(t) + Cdg(t) \tag{1}$$

with Cs being the total energy cost, Cpv being the PV arrays energy cost giving by (2). Cwt being the wind turbine energy cost presented in (3), Cb being the batteries energy cost, following (4), Cl being the total load (DC & AC load) energy cost given by (5), and Cdg being the diesel generator energy cost, following (6).

$$C_{pv}(t) = \sum_{t=0}^{tf} [(P_{pv\_mppt}(ti) - P_{pv}(ti)) * T_{pv}(t_i)]\,\delta t \tag{2}$$

$$C_{wt}(t) = \sum_{t=0}^{tf} [(P_{wt\_mppt}(ti) - P_{wt}(ti)) * T_{wt}(t_i)]\,\delta t \tag{3}$$

$$C_b(t) = \sum_{t=0}^{tf} [(P_{bc}(ti) - P_{bd}(ti)) * T_b(t_i)]\,\delta t \tag{4}$$

$$C_l\,(t) = \sum_{t=0}^{tf}[\,P_l(ti) * T_l\,(t_i)]\ \delta t \quad (5)$$

$$C_{dg}\,(t) = \sum_{t=0}^{tf}[\,(P_{dg}(ti) * T_{dg}\,(t_i)]\delta t \quad (6)$$

Following the logic cost order, the tariffs are chosen in order to respect the power management strategy as given in the Table 1.

Table 1
Description of objective function parameters.

Parameters	Power tariff of:	Value
Tpv	PV Arrays	0.5$/kWh
Twt	Wind Turbine	0.5$/kWh
Tb	Battery	0.1$/kWh
Tl	Electricity loads	0.5$/kWh
Tdg	Diesel Generator	0.8$/kWh

The goal is the reduction of the total energy cost by using a specific optimization algorithm during a continuous operation time given in (14) of the HMG by calculating the energy cost of each RESs and loads of the system (Wang *et al.* 2017).

3.2. Constraints

System power balancing: the laws of physics imposing the balance of powers at every moment such as:

$$\eta_{DG}\times P_{DG}(t) + P_{PV}(t)\times\eta_{PV} + \eta_{WT}^{AC}\times P_{WT}^{AC}(t) = P^*(t)\times\eta^* + P_L(t) + P_B(t)\times\eta_B \quad (7)$$

$$P_L(t) = P_L^{AC}(t) + P_L^{DC}(t) \quad (8)$$

Where P_{PV} is the PV power, P_{WT}^{AC} is the wind power, P_L is the load power consumption, P_L^{AC} *and* P_L^{DC} are the AC and DC load power respectively, P_B is the batteries power, and P_{DG} is the diesel generator power. The exchange power $P^*(t)$ is determined explicitly by equation from the other powers values, which makes $P^*(t)$ as the only unknown component and η^* its corresponding efficiency(interlinking converter). $\eta_B, \eta_{DG}, \eta_{PV}$ *and* η_{WT}^{AC} are the battery, diesel generator, PV arrays and wind turbine efficiencies respectively, and in this study, these efficiencies are considered as constant value and shown in Table 2.

3.3. RESs power output constraints

A large number of RESs and other components are connected to the HMG, such as Wind, PV Arrays and batteries. Therefore, the power output of all HMG devices must not induce negative power, so it is constrained:

$$0 \le P_{PV}(t) \le P_{PV\_MAX} \quad (9)$$
$$0 \le P_{WT}^{AC}(t) \le P_{WT\_MAX}^{AC} \quad (10)$$

Where P_{PV_MAX} and $P_{WT\_MAX}^{AC}$ are the maximum powers limits of PV and Wind, respectively.

Table 2
Converter efficiencies for optimization.

Symbol	Description	Value
η_{PV}	PVA converter efficiency	90%
η_{WT}^{AC}	WTG converter efficiency	85%
η_B	BSS converter efficiency	90%
η_{DG}	DG converter efficiency	85%
η^*	Interlinking converter efficiency	90%

$$SOC_{MIN} \le SOC(t) \le SOC_{MAX} \quad (11)$$

$$0 \le P_B(t) \le P_{B\_MAX}\,,\ P_B(t) = P_{B\_C}(t) - P_{B\_D}(t) \quad (12)$$

$$SOC(t) = SOC(t_0) + \frac{1}{720} \times \frac{\eta_B}{C_N \times V_{BUS}} \times \int_{t_0}^{t}\left(P_{B_c}(t) - P_{Bd}(t)\right) dt \quad (13)$$

$$t \in \{t_0, t_0 + 1 \ldots, t_0 + n\Delta\tau\} \quad (14)$$

Where SOC is the state of charge of batteries, P_{B_MAX} is the maximum power of energy storage device, SOC_{MIN} and SOC_{MAX} are the lower and upper limits of SOC, respectively. V_{BUS} defined as DC bus voltage, C_N is the storage nominal capacity and η_B is battery charging efficiency. $\Delta\tau$ is the time step. Finally. P_{B_c} , P_{Bd} are the maximum charging and discharging power of batteries bank, respectively.

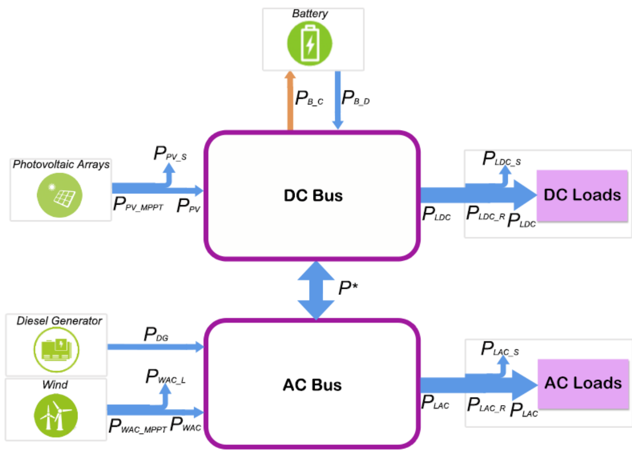

Fig. 3. Power flow in isolated mode.

Considering other elements constraints, the whole problem is formulated as:

$$\begin{cases} \min Cs(t) = Cpv(t) + Cwt(t) + Cb(t) + Cl(t) + Cdg(t) \\ \textit{with respect to}: \\ \eta_{DG}\times P_{DG}(t) + P_{PV}(t)\times\eta_{PV} + \eta_{WT}^{AC}\times P_{WT}^{AC}(t) = P^*(t)\times\eta^* + P_L(t) + P_B(t)\times\eta_B \end{cases}$$

State 1:

AC MG: $P_L^{AC}(t) \leq \eta_{WT}^{AC} \times P_{WT}^{AC}(t)$
DC MG: $P_L^{DC}(t) + P_B(t) \times \eta_B \leq P_{PV}(t) \times \eta_{PV}$

$P^*(t) = P_{DG}(t) = 0$,
$P_B(t) = P_B(t_0) + \int_{t_0}^{t}\left[\left(P_{PV}(t) \times \eta_{PV} + P_{WT}^{AC}(t) \times \eta_{WT}^{AC} - P_L^{DC}(t) \right)\right] \times \eta_B \, dt$

State 2:

AC MG: $P_L^{AC}(t) > \eta_{WT}^{AC} \times P_{WT}^{AC}(t)$
DC MG: $P_L^{DC}(t) < P_{PV}(t) \times \eta_{PV}$

$P^*(t) = \int_{t_0}^{t}[P_L^{AC}(t) - \eta_{WT}^{AC} \times P_{WT}^{AC}(t)] \times {}^{1}/_{\eta^*} \, dt,$
$P_B(t) = P_B(t_0) + \int_{t_0}^{t}\left[\left(P_{PV}(t) \times \eta_{PV} + P_{WT}^{AC}(t) \times \eta_{WT}^{AC} - P_L^{DC}(t) - P^*(t) \times \eta^* \right)\right] \times \eta_B \, dt$

State 3:

AC MG: $P_L^{AC}(t) < \eta_{WT}^{AC} \times P_{WT}^{AC}(t)$
DC MG: $P_L^{DC}(t) > P_{PV}(t) \times \eta_{PV}$

$$P^*(t) = \int_{t_0}^{t}[P_L^{DC}(t) - \eta_{WT}^{AC} \times P_{WT}^{AC}(t) + P_{PV}(t) \times \eta_{PV}] \times {}^{1}/_{\eta^*} \, dt \quad (15)$$
$P_B(t) = P_B(t_0) + \int_{t_0}^{t}\left[\left(\eta_{WT}^{AC} \times P_{WT}^{AC}(t) - P_L^{AC}(t) - P^*(t) \times \eta^* \right)\right] \times \eta_B \, dt$

State 4:

AC MG: $P_L^{AC}(t) \geq \eta_{WT}^{AC} \times P_{WT}^{AC}(t)$
DC MG: $P_L^{DC}(t) \geq P_{PV}(t) \times \eta_{PV}$

$P^*(t) = P_G(t) = 0$,
$P_B(t) = P_B(t_0) + \int_{t_0}^{t}\left[\left(P_L^{DC}(t) - P_{PV}(t) \times \eta_{PV} - P_{WT}^{AC}(t) \times \eta_{WT}^{AC} \right)\right] \times \eta_B \, dt$
$P_B(t+1) = P_B^{min}$
$SOC(t) = SOC(t_0) + \frac{1}{720} \times \frac{\eta_B}{C_N \times V_{BUS}} \times \int_{t_0}^{t}\left(P_{B_c}(t) - P_{B\_D}(t)\right) dt$

$SOC_{MIN} \leq SOC(t) \leq SOC_{MAX}$
$0 \leq P_{DG}(t) \leq P_{DG\_MAX}$, $0 \leq P_{WT}^{AC}(t) \leq P_{WT\_MAX}^{AC}$, $P_L(t) \geq 0$

$P_{DG}(t) > 0 \; If \; SOC(t) \leq SOC_{MIN}$
$P_{DG}(t) = 0 \; If \; SOC(t) \geq SOC_{MAX}$

4. Optimization problem formulation

Figure 3 shows the studied system introduced in section 2. In this figure are indicated the power flow cases , their respective sign conventions and the components of the system.

4.1. Optimization Model Solving Strategy

In the current work, the optimization of the control strategy of different kinds of distributed power resources to the HMG in stand-alone mode was carried out and solved. The mathematical model is a mixed integer programming problem of the devices composing the power system, the model is built as a Java program and is solved using the IBM ILOG CPLEX solver. For the study of PV/Wind/Diesel-Generator power generation system we use HOMER software. Firstly, the power produced by all RESs of the microgrid is calculated in each hour over the year and stored in a database. So, the powers values can be acceded easily in each time step (Zahboune *et al.* 2016).

4.2. Hybrid Control System

During the installation of a hybrid microgrid in isolated residential buildings, a control strategy must be installed in the same time. This way of control upgrade conditions for the proper functioning of the overall multisource system, such as the time required to turn mode on the diesel generator according to parameters such as the current state of charge of the batteries and the conditions of use of the loads during peak-hours. For this, the hybrid control system is based on 4 modes of use (Qachchachi *et al.* 2016; Kumar *et al.* 2013).

a) Mode 1

In the first mode we use the energy provided by the RESs to supply the loads, in this mode we consider that the weather conditions are good for the photovoltaic panels and the turbine to produce a maximum power to satisfy the load demands. As the PV panels and wind turbine are connected to the system, but not used to supply the load and the batteries charging, in this mode, we use a switcher to disconnect the renewables sources from the microgrid.

b) Mode2 (State 2 and 3)

In this mode we adopt that the energy produced by the PV panels plus the wind generator meet the load demand. When the system is in Mode 2, we consider that the energy available from wind turbine or PV Arrays can't satisfy the need to supply the load, in that case the PV or wind turbine produce the amount needed and any excess power from the PV arrays or wind turbine can be used to charge the batteries.

c) Mode 3

The system is in Mode 3 when the energy produced by all RESs is almost equal to load demand. Therefore, if the energy generated by the RESs can't meet the demand. So the HMG must use additional power and the diesel generator turned ON.

d) Emergency decision mode

During the emergency mode the system will be able to choose automatically who has the priority (diesel generator or batteries) to meet the load demand based on the following decisions :

- If the SOC of the battery is greater than the minimum amount and therefore the battery is able to supply power to the load. The battery will be used.
- If the battery is at its minimum SOC and therefore cannot be used to supply the deficit of power required. Then the diesel generator will be used.

5. Simulation Results

The HMG has been modeled by HOMER software to provide a practical load demand data and real weather data of a residential building located in Avenue Agdal, Rabat, Morocco. Simulation studies are carried out for power control during one month. For autonomous mode operation, the parameters quoted in table 3 are used for the implementation of the methodology followed for the energy management and the developed optimization. for the purpose of a similar and optimal system behavior, these parameters are chosen according to the energy configuration of the HMG (Zahboune *et al.* 2016; Shenai *et al.* 2011).

Table 3
Parameters for standalone operation.

Symbol	Value
P_{PV_MAX}	5000W
$P_{WT\_MAX}^{AC}$	18000W
P_{B_MAX}	5000W
P_B^{min}	1000W
P_{DG_MAX}	20000W
SOC_{MIN}	45%
SOC_{MAX}	55%
SOC_0(t=0)	50%
V_{BUS}	400V
C_N	100Ah
Load peak hour	13h00 – 15h00
Load shedding	22h00 – 23h00

According to the prediction data, the HCS solves the optimization problem by MILP optimization algorithm and provides a perfect supervision control solution, in Figure 4. The power flow optimization effect can be remarked.

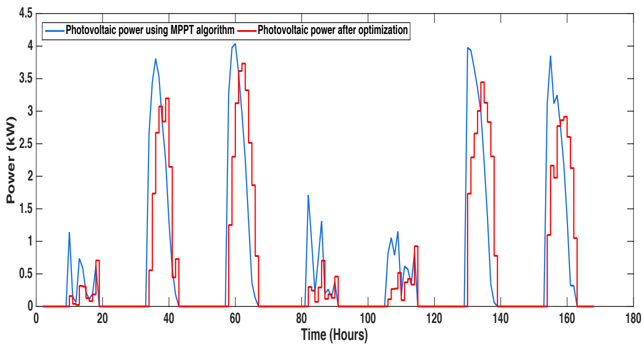

Fig. 4. Photovoltaic power reduction employing MILP optimization algorithm.

The management control for the islanded mode is simulated for same operating condition during January 2019 in Rabat, Morocco. For simulation validation, the photovoltaic power prediction data is calculated from the real measurement data in order to assign the day-ahead prediction data uncertainty error as random. The measured PV arrays powers is shown in Figure 4: the red curve shows the photovoltaic power reduction after optimization, while the blue one are the PV arrays power using MPPT algorithm (Riffonneau *et al.* 2011).

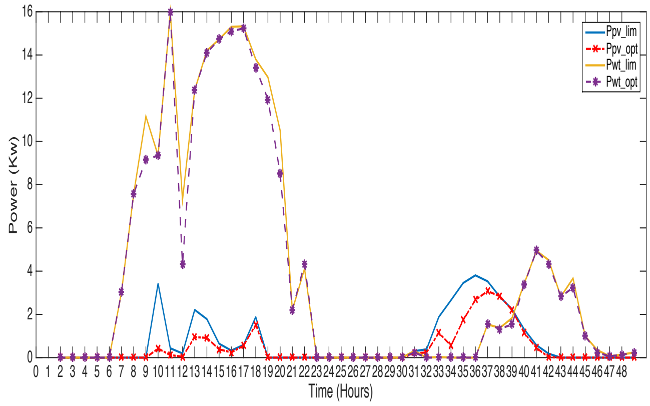

Fig. 5. Optimized power flow by HCS for off-grid mode.

Figure 5 shows the generation of RESs before and after optimization. The blue line indicates the maximum generation power of PV arrays is 3.9020 kW, the average power generation is 3.8475 kW, but the minimum generation power is 1.905 kW. Meanwhile, for the red line, the maximum of power produced is 2.5684 kW, the average power generation is 1.8559 kW, but the minimum production power is 0.9352 Kw; the simulation results in Figure 4 and 5 shows that the proposed algorithm can effectively reduce the increase of the generation power of RESs; then, ensuring the peak shaving and the valley filling and the reduction of the total economic cost of operation of the HMG.

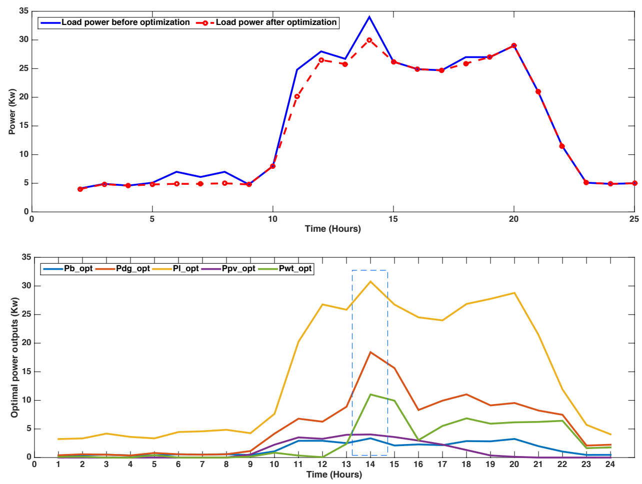

Fig. 6. HCS employing MILP optimization algorithm with Peak load case

Load data are supposed to be given by building control system, which implies additional uncertainties. A simple arbitrary load power evolution is considered. The difference of load power and load power prediction is shown in Figure 6-a. The generation of load power before and after optimization indicates the advantage of our proposed optimization algorithm. The peak load of HMG is reduced effectively and the peak load decreases by 2.94834 kW. Therefore, the peak day of winter 2019 was selected.

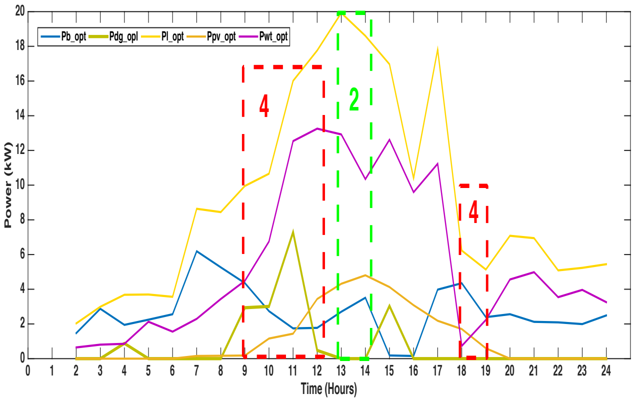

Fig. 7. HCS employing MILP optimization algorithm showing different operating mode.

Figure 6-b shows the peak hour (33.87634 kW) at the same time as figure 6-a (2:00 pm) after optimization. During the peak hour of loads, we remark the discharging of batteries. However, the power generated by RESs cannot meet the load demand at peak time so the diesel generator is turned ON. The HCS would not be functional in case peak does not appear. During this day operation, the RESs and BSS share the produced power with the diesel generator in case of emergency to satisfy the load demand. During the peak hours (13h00-15h00), the load is supplied by RESs, storage and DG which is mainly used to ensure power balance of the HMG. Between the period (22h00-23h00) a load shedding can be remarked when the BSS is almost empty.

Figure 7 shows the operation of the HMG under different operating modes presented by the HCS, we can remark in the figure that there are two types of modes. The zone 2 during the period (13h00-14h00) corresponds to mode 2 where the power consumed by loads has an average of 19.269859 kW while the total of power produced by the whole of the RESs is 21.495829 Kw, then the power in excess will be used to charge the battery. On the other hand, there is also the presence of the mode used in an emergency case (zone 4), we observed two areas of this mode, the first at the period (9h00-12:00) where all resources of power connected to the HMG do not meet the load demand then the diesel generator is turned ON. Moreover, the second area is presented in the period (18h00-19h00) and the HMG is still in emergency mode but the HCS system use the storage system only to balance the need of power. The general operating value of the HMG, taking into account the costs of produced power by the DG, is equal to $75,239.

6. Conclusion

In this paper, an optimal optimization study of isolated HMG incorporating a combination of alternative RESs with a BSS was presented. The RESs were based on the PV Arrays and wind turbine energy and a set of diesel generators was taken as a traditional emergency power source. A deterministic optimization algorithm was described to develop an optimal configuration of each HMG devices by minimizing the system total cost by taking into account the personal criteria of end-users as well as the forecast of the energy production of the HMG, the climatic criteria and also some specific constraints such as storage capacity, energy prices, and load peak hours. The objective of this study is to achieve several goals such as the investigation of the best design layout, best optimization of HMG components in standalone mode and reaching the lowest total system cost. To solve the optimization problems was CPLEX mixed integer optimizer with Java language was a perfect solution. Despite the lack of precision of the weather forecast and the random changes of the energy price on the market, the results of the simulation, taken as hypotheses in this study, indicate that the proposed HCS design can function effectively in autonomous mode and optimize the system performance in real-time, taking into account several constraints such as peak hours and the instability of power production of RESs. Finally. an intelligent hybrid AC/DC microgrid in standalone mode was developed and optimized in this paper. The results achieved show that the HMG with a hybrid control system can be considered as the optimal combination system and most cost-effective to meet the load power demand in isolated residential buildings.

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