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Optimal Power Scheduling for an Islanded Hybrid Microgrid

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***Abstract*—A microgrid is a system that integrates energy generation, energy storage, and loads and it is able to operate either in interconnected or islanded mode. Energy resources should be scheduled to supply the load properly in order to coordinate optimally the power exchange within the microgrid according to a defined objective function. In this paper, an optimal power scheduling for generation and demand side is presented to manage an islanded hybrid PV-wind-battery microgrid implemented in Shanghai-China. The optimization is addressed through a Mixed-Integer Linear Programming (MILP) mathematical model, wherein the disconnection of the load and not charging the battery when there is surplus of energy are penalized while physical constraints and requirements for a feasible deployment in the real system are considered. The proposed scheduling scheme is tested using a real-time control platform (dSPACE1006) in which a scaled down model of this microgrid is emulated.**

***Index Terms*—Power scheduling, Energy management, Integer programming, Islanded Microgrid.**

I. Introduction

The current trend in microgrids (MG) is the integration of distributed generators (DG) based on renewable energy sources (RESs), such as Photovoltaic (PV) and Wind Turbine (WT) generators. The MG can be complemented with Energy Storage Systems (ESSs) which provide energy support under times of low generation and additionally allows store energy during times of high generation. A MG can operate in islanded mode or connected to the main grid [1].

Particularly, under islanded mode the ESS plays an important role in the operation of the MG since it assumes the grid-forming responsibility [2], [3]. Meanwhile, the other distributed energy resources are current controlled units which follow the voltage reference imposed by the grid-forming unit. The operation of the ESS should be coordinated with the operation of the RESs and loads in order to avoid excessive charge or discharge which may affect the life-span and performance of the ESS. Therefore, the management of the MG in islanded mode implies additional challenges for ensuring the power balance between consumption and generation when the ESS is not able to store or supply the power unbalance. Because of this, under specific conditions the power generation should be curtailed or the load should be deferred or even disconnected to achieve the power balance in the MG [4]. Therefore, an Energy Management System (EMS) with global perception about the operational conditions of the microgrid, can define proper operational conditions for the DG and loads, looking for an optimal dispatch and commitment between distributed units which ensures reliable operation of the MG regarding specific objectives and generation capacity [5], [6].

A full-scale demonstrative, research-oriented real microgrid has been installed in Shanghai, China for evaluating the performance of the EMS under several conditions [7]. The availability of PV generation in the MG is high compared to WT generation and load consumption. It is due to the subsides in China promote the deployment of this kind of energy technology. Grid-connected generation-side optimization has been previously addressed in [8] but still the scheduling of devices where the system is not connected to the grid has not been considered.

This paper particularly considers the operation of this microgrid in islanded operation. The EMS aims to optimize the operation of the microgrid by scheduling the power of the distributed energy resources [9], [10]. Apart from that, the proposed EMS minimizes the disconnection of the load while ensuring periods of full charge of the ESS, within cycles of discharge based on a 24-h ahead optimal scheduling. This is particularly important for ESS based on batteries in order to preserve the life-span and health of batteries. In this proposal, a Mixed Integer Linear Programming (MILP) model is used that can be deployed easily in real microgrid sites since it is linear, simple and can be synthesized in commercial optimization software such as GAMS. This fact is a remarkable advantage compared to others optimization strategies [5], [11].

II. Operation of the Microgrid

The real site system under test is a 200 kW islanded PV-wind-battery microgrid as shown in Fig. 1. This system has been scaled to a laboratory prototype of 20 kW at the Microgrid Laboratory of Aalborg University [12], [13]. As

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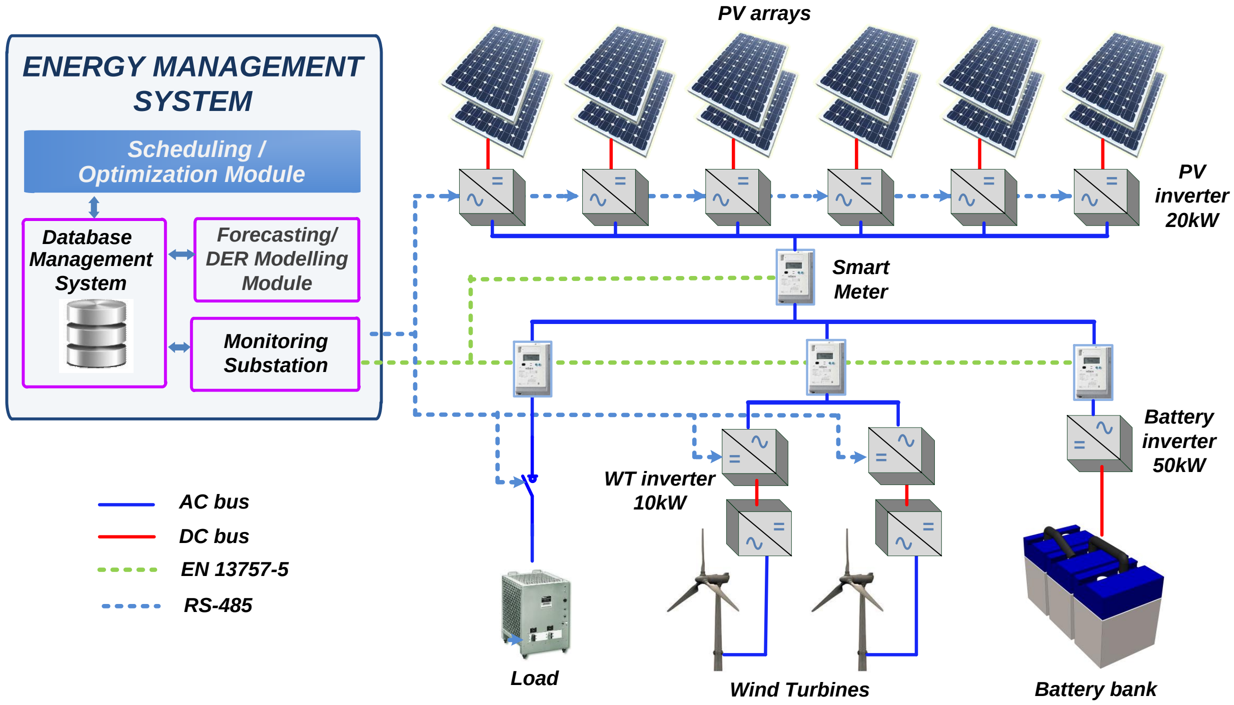

Fig. 1. General scheme of the microgrid in Shanghai in islanded mode.

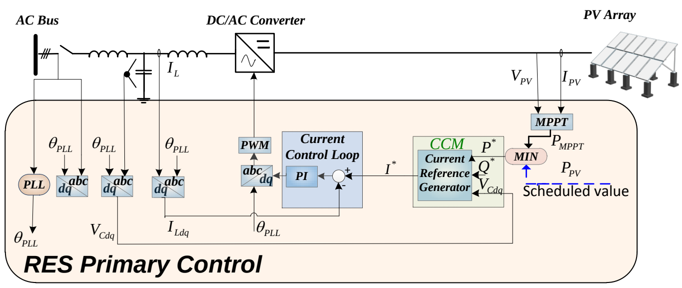

Fig. 2. General scheme of primary control for RES.

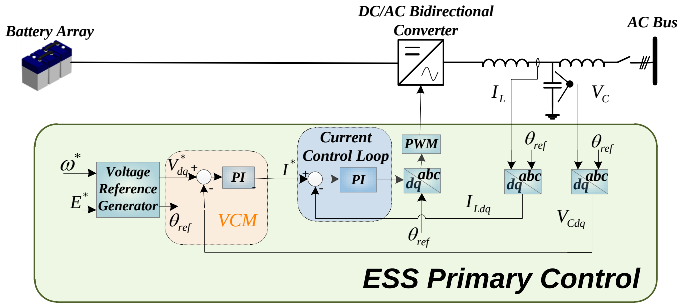

Fig. 3. General scheme of primary control for the ESS.

case study, the microgrid is supplying a resistive load which can be disconnected to ensure a safe operation range of ESS.

In this microgrid, the inverters of RESs allow the units to operate as constant power sources by providing the power reference given by a maximum power point tracking (MPPT) algorithm or derived from an optimization procedure. However, due to unpredicted variations on weather conditions the scheduled power reference for RESs can be higher than the current maximum available power. Therefore, the primary level control of these units have been modelled as current control mode (CCM) inner loops [14] where the power reference corresponds to the minimum value between the reference given by the scheduling process and by the MPPT algorithm as is shown in Fig. 2 [9]. The RES unit is synchronized to the common bus by means of conventional synchronous reference frame phase-locked loop (SRF-PLL) [15].

On the other hand, the ESS is responsible of voltage bus regulation by charging or discharging based on the power unbalance between the generated and consumed power. It operates under voltage control mode (VCM)where the primary controller is composed by a inner current control loop and an outer voltage control loop as can be seen in Fig. 3 [14]. In this case, no other distributed generator inside the microgrid can assume the regulation of the common bus because of technical restrictions. The proposed control scheme does not consider any additional control loop in the primary level in order to avoid battery overcharge or deep discharge. Because of that, the operation of the other distributed resources is scheduled to avoid those undesired conditions in the ESS.

Moreover, the voltage per cell in the battery should hold below a threshold value (V_r), known as the regulation voltage (typically 2.45 ± 0.05 volts/cell) to avoid battery overcharge. Additionally, high values of Depth of Discharge (DoD) can reduce life-span of the battery [16]. These conditions can be managed by means of curtailment of the surplus of RES energy

TABLE I
PARAMETERS OF THE MODEL

Name	Description	Value
T	Time horizon	24 [h]
Δt	Duration of interval	1 [h]
n_i	Number of PVs	6
n_j	Number of WTs	2
$P_{PV_{max}}(i,t)$	Max. Power for PV1 to PV4	0.4 [p.u.]
	Power max for PV5 to PV6	0.32 [p.u.]
$P_{WT_{max}}(j,t)$	Max. Power for WT	0.4 [p.u.]
$P_L(t)$	Resistive Load	0.1 [p.u.]
P_{losses}	Power losses	100 [W]
$SoC_{max}(k)$	Max. State of Charge	100 [%]
$SoC_{min}(k)$	Min. State of Charge	50 [%]
$SoC(k_0)$	Initial Condition	70 [%]
$\varphi_{bat}(k)$	SOC coefficient	1 [%/p.u.]
ξ_{load}	penalty costs for RES	0.1 [EU/p.u.]
$\xi_{storage}$	penalty costs for ESS	0.01 [EU/p.u.]
P_{losses}	Average losses	0.033 [p.u.]

and by disconnecting the load which is defined by the EMS.

On top of the controllers, an EMS is implemented to provide the references of the RESs and the disconnection of the load. The EMS is composed of several modules as can be seen in Fig. 1, that are connected by means of a database management system in order to avoid bottleneck due to processing times. This paper is focused on the mathematical model included in the scheduling module since it is the core of the EMS.

III. PROPOSED OPTIMIZATION MODEL

This problem has been developed as a mixed integer linear programming (MILP) problem to minimize the disconnection of loads in an islanded RES based microgrid. The scheduling will be performed for T hours in intervals of $\Delta t = 1$ hour. The index t is the elementary unit of time, $t = 1, 2, 3. \ldots T$. Moreover, the indexes i and j are used to represent the n_i PVs and the n_j WTs.

Besides, the output variables used in the model are the ON/OFF commands for the load, $x_{load}(t)$, defined as a binary variable, and the set points for the PV and the wind turbines, $P_{pv}(i,t)$ and $P_{wt}(j,t)$, respectively. The parameters used in this case are presented in Table I and will be presented along the mathematical formulation. The values are presented in per unit (p.u.), with a base of 50 kW.

A. Objective Function

The objective of the scheduling is to minimize the disconnection of the load and can be defined as,

$$\text{COST} = \sum_{t=1}^{T} P_L \Delta t \left(1 - x_{load}(t)\right) * \xi_{load} \tag{1}$$

where P_L is the power of the resistive load, ξ_{load} corresponds to the penalty cost of disconnecting the load. This function corresponds to the penalty for disconnecting the load which is 0 where the load is connected ($x_{load}(t) = 1$) and is equal to $P_L \Delta t * \xi_{load}$ when the load is disconnected.

Additionally, it is proposed to include a term in (1) in order to penalize not charging the battery when there is surplus of RES energy, defined as,

$$\sum_{t=1}^{T} \frac{(SoC_{max} - SoC(t))}{100\%} * \xi_{storage} \tag{2}$$

where SoC_{max} is the maximum state of charge, $SoC(t)$ is the state of charge of the ESS at each t and $\xi_{storage}$ corresponds to the penalty elementary cost for not charging the battery. This function cost should be lower than the cost associated to the disconnection of the load at each time in order to prioritize the load supply. In this way, the battery stores the surplus of RES energy, which avoiding deep discharge and consequently, degradation of the ESS.

B. Constraints

The optimization problem should also contain some constraints to define the feasible region where the optimal solution can be found.

a) Energy balance: The first condition that the model has to include is the energy balance between generation, storage systems and demand in the microgrid. This constraint can be written as,

$$\sum_{i=1}^{n_i} P_{pv}(i,t) * \Delta t + \sum_{j=1}^{n_j} P_{wt}(j,t) * \Delta t + \tag{3}$$
$$P_{bat}(t) * \Delta t = P_L(t) * x_{load}(t) * \Delta t + P_{losses}$$

where $P_{bat}(t)$ is a variable that corresponds to the power of the battery at each time slot t. Noted that, $P_{bat}(t)$ is positive when the battery is being discharged and negative when is being charged. P_{losses} is a parameter that represents the average losses in the microgrid for the operation range of power.

b) Energy Storage System: Regarding the ESS, it is required to estimate the among of the available energy at each t which is done by means of the state of charge ($SoC(t)$) that represents the ratio of its current capacity (in [Wh]) and the nominal capacity as a percentage [17]. In terms of the energy of the battery $P_{bat}(t)\Delta t$, the SoC can be defined as,

$$SoC(t) = \begin{cases} SoC_0 & t = 0 \\ SoC(t-1) - \varphi_{bat} * [P_{bat}(t)\Delta t] & t > 0 \end{cases} \tag{4}$$

where SoC_0 is the initial condition of $SoC(t)$ and φ_{bat} is an energy storage coefficient. In the case of batteries, this parameter can be defined as,

$$\varphi_{bat} = \frac{\eta_c}{C_{bat} * V_{bat_{nom}}}$$

where η_c, C_{bat} and $V_{bat_{nom}}$ are the charge/discharge efficiency, nominal capacity and nominal voltage of the battery, respectively.

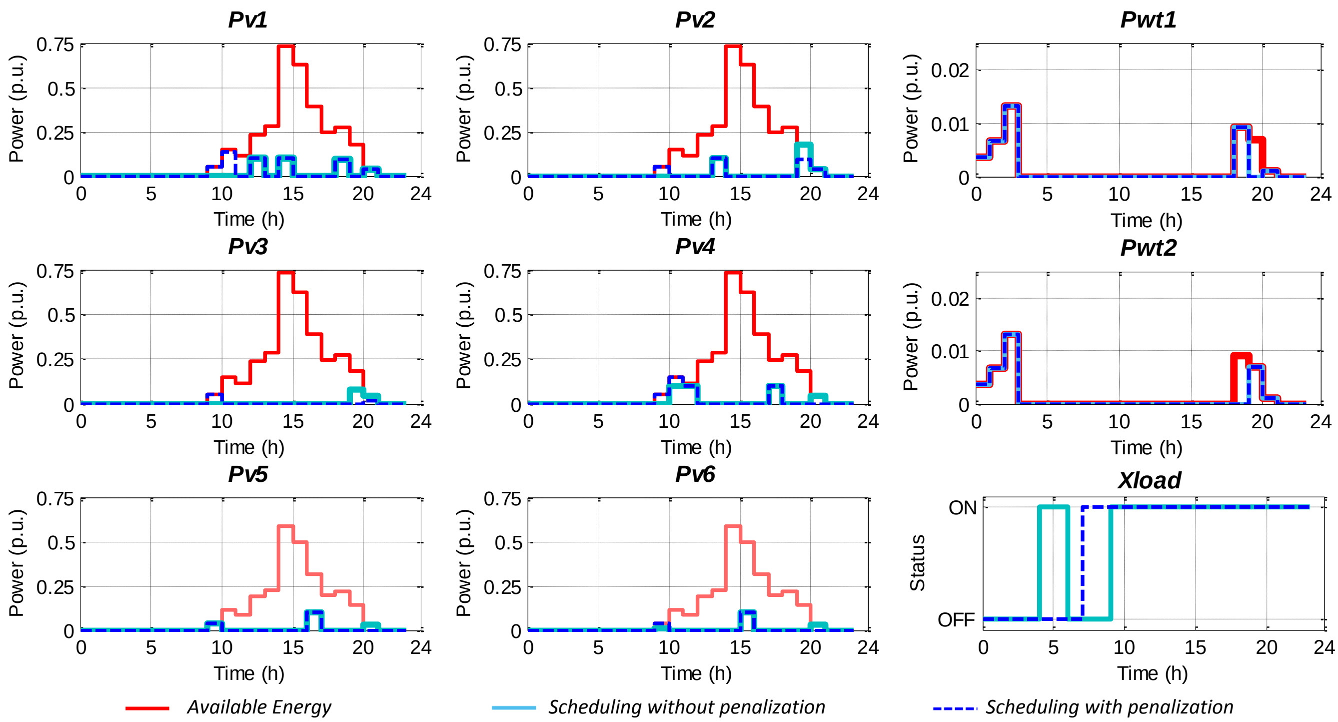

Fig. 4. Scheduling results for a summer day (dark blue with penalization and light blue line without penalization) and available RES generation profiles (red lines) . First two columns are related to PV arrays. First two frames in last column correspond to WT. Last frame in last column is the scheduling of the load connection.

c) Variable Boundaries: Additionally, each of the variables of the optimization problem must be bounded.

1) Firstly, the variables related to the generation are positive variables limited as,

$$0 \leq \quad P_{PV}(i,t) \quad \leq P_{PV_{max}}(i,t) \tag{5}$$
$$0 \leq \quad P_{WT}(j,t) \quad \leq P_{WT_{max}}(j,t) \tag{6}$$

where $P_{PV_{max}}(i,t)$ and $P_{WT_{max}}(i,t)$ are dataset that correspond to the maximum power provided by RESs at each t.

2) Regarding the storage system, the SoC is a positive variable whereas the power can get negative and positive values both within defined ranges. These boundaries can be written as,

$$P_{bat_{min}} \leq \quad P_{bat}(t) \quad \leq P_{bat_{max}} \tag{7}$$
$$SoC_{min} \leq \quad SoC(t) \quad \leq SoC_{max} \tag{8}$$

where $P_{bat_{min}}$, $P_{bat_{max}}$, SoC_{min} and SoC_{max} are the maximum and minimum values that the power and the SoC of the battery can get.

3) Along with, the demand is managed by switching thus the scheduled variable is binary, $x_{load}(t) = \{0, 1\}$.

IV. Results

The proposed optimization model is solved by using a commercial algebraic model language called GAMS, where the solver CPLEX has been set in order to compute the power references obtained for the proposed MILP. The scheduling is performed with an initial condition of SoC as 70%.

Afterward, the scheduled power references are included in a detailed Simulink model of the MG. This model is implemented in a dSPACE real-time control and monitoring platform, used to perform real time simulations, in one of the setups in the Microgrid Research Laboratory at Aalborg University [12].

A. Scheduling Results

The optimization problem is solved with and without the penalization presented in (2) (dark blue line and light blue line in Fig. 4, respectively) in order to show the effectiveness of including this term in the objective function. The parameters presented in Table I are used in the model as well as the generation profiles of a summer day with high PV generation and low wind generation (red line in Fig. 4).

The scheduling results for the PV arrays (*Pv1* to *Pv6*), wind turbines (*Pwt1* to *Pwt2*) and the commands for the load (*Xload*) are shown in Fig 4. As can be seen, there is no big differences with and without penalization related to the load. In both cases, the load is disconnected for six hours at the beginning of the day when there is not enough RES energy to supply the load ($P_L = 0.1p.u.$). During this low generation condition, the battery can supply the load during two hours (4th to 5th hour in the first case, and 7th to 8th in the second case). After that, the energy generated by the RESs are so high that even it has to be curtailed.

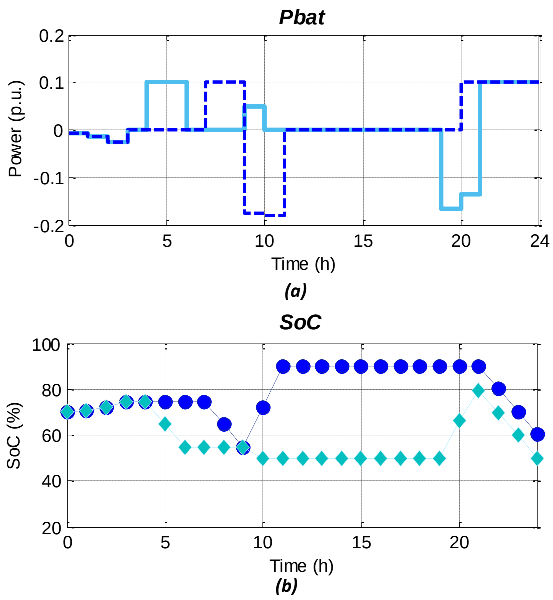

Fig. 5. Scheduled variables related to the battery with (dark blue line) and without (ligth blue line) penalization: (a) power and (b) SoC.

With respect to the battery, the SoC (Fig. 5b) is expected to be inside the predefined safe range (50% to 90%) in both cases but the results obtained for the model with the penalization avoid the battery to have deep discharge. The charge of the battery is privileged between discharge cycles, which is highly recommended by the battery manufacturers in order to enhance the performance of the battery. Additionally, the final SoC is higher than in the case without penalization.

B. Real Time Simulation Results

In order to test the proposed optimization model with the penalization, real time simulation of the microgrid is performed for a autumn day with an average generation of PV and WT and the initial condition of the SoC is set as 70%.

Figures 6 and 7 present the available energy and the scheduled profiles for PV and WT, respectively. Likewise, the power of the load is shown in 8.

As can be seen, the load is disconnected for three hours during the day (from 3 to 6 hours) when the available power of the RESs is low. During the next 4 hours, this low-generation condition remains but the battery supplies the load. After that, the energy generated by the RESs is high enough to feed the load. There is even surplus energy during the day that has to be curtailed.

With the previous references, the battery regulates the changes and the consequent power results to be as shown in Fig. 9. Under these conditions, the obtained SoC is shown in Fig. 10(b). To compare, the expected SoC by the scheduling process is presented in Fig. 10(a).

The simulation results have the behavior expected by the scheduling. The difference between them is due to power losses in the real system which have not been considered in the optimization model.

Regarding the voltage of the battery (Fig. 11), it can be seen that its value is kept under the threshold voltage, which

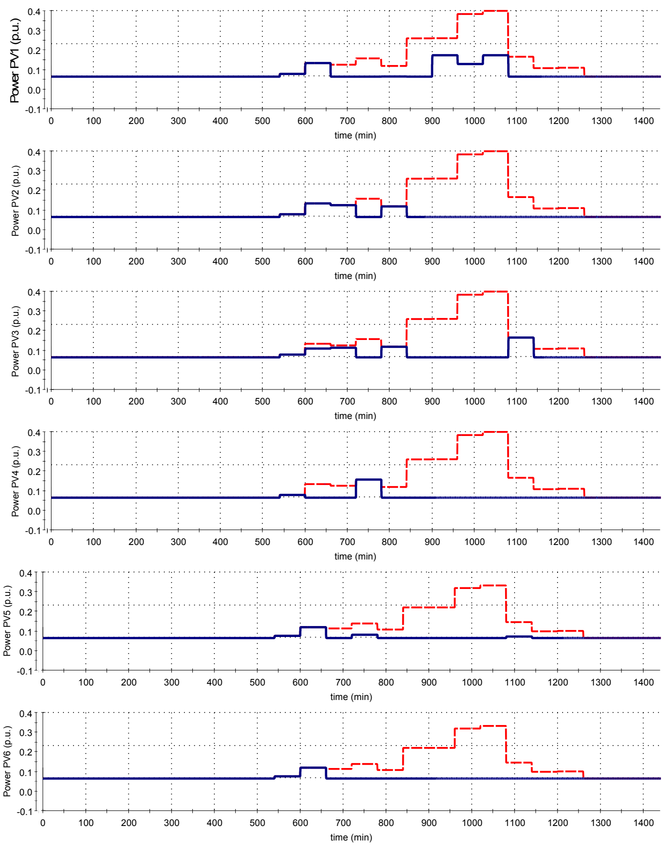

Fig. 6. Available (red line) and scheduled (blue line) PV energy obtained for simulation of the microgrid. Top to bottom: PV1 to PV6 data.

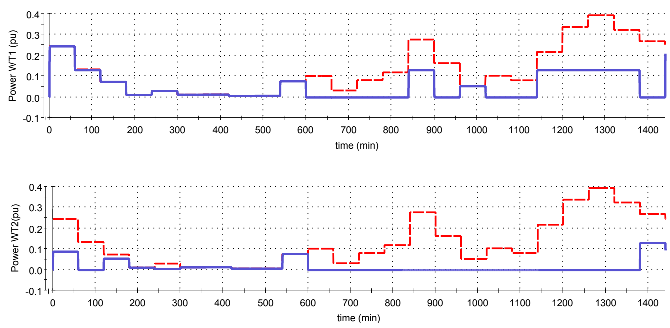

Fig. 7. Available (red line) and scheduled (blue line) WT energy obtained for simulation of the microgrid. Top to bottom: WT1 and WT2 data.

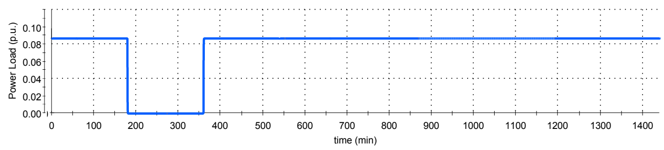

Fig. 8. Power of the load in simulation of the microgrid

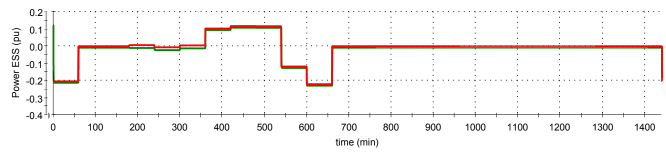

Fig. 9. Power of the battery obtained in simulation of the microgrid

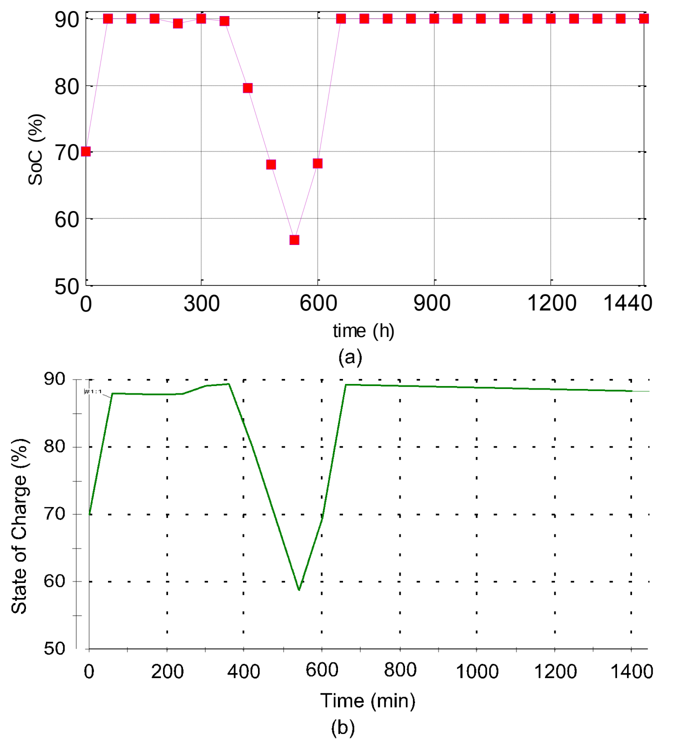

Fig. 10. Results of the SoC: (a) obtained from the optimization model. (b) obtained in simulation of the MG

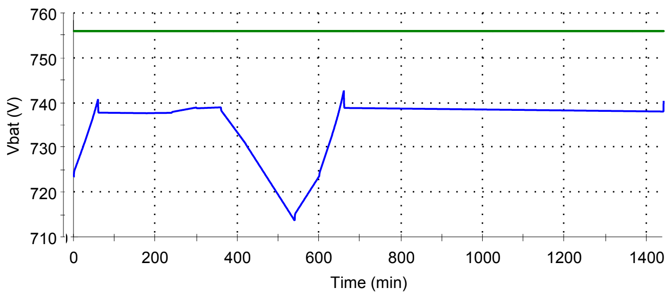

Fig. 11. Voltage of the battery (blue line) obtained in real time simulation of the microgrid. Green line: threshold voltage

is convenient for voltage-limiting devices such as lithium ion and lead acid based batteries to avoid overvoltage and damage of the ESS.

V. Conclusions and Future Work

An optimal scheduling is defined for a real site RES-based islanded microgrid by considering physical restrictions imposes by the devices and the whole system. The proposed optimization problem is defined as a MILP model for a time horizon of 24 hour that achieves a minimum times of disconnection of the load and allows a good performance of the battery. As a future work, the power losses can be included in the model to include their influence. Additionally, the proposal should be implemented in rolling horizon strategy in order to deal with the variability of the RES and mismatches of the battery model.

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