

# Optimal Energy Management and Scheduling of a Microgrid in Grid-Connected and Islanded Modes

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**Abstract – Microgrids are becoming one of the main components of future smart grids. Ensuring their optimal and stable operation is of crucial importance and can be a challenging task. In this paper, two optimization algorithms are implemented for scheduling the microgrid operation in grid-connected and islanded modes, according to the priorities and objectives in each mode. For achieving an optimal operation at each mode, the proposed scheme is able to shed loads, define the generation level of the photovoltaics and regulate the charging/discharging level of the Energy Storage System (ESS). The effectiveness of the proposed scheduling is demonstrated through an analytical real-time simulation, where various transitions between the grid-connected and islanded modes are considered. The results indicate that the proposed scheme is able to regulate successfully the energy flows of the microgrid even under various transitions.**

**Keywords—Energy Management, Microgrid Scheduling, Optimization, Real-Time Simulations.**

## I. NOMENCLATURE

$P_g(t), P_{gen}^{max}, P_{gen}^{min}$	Diesel generator's output power and its maximum/minimum levels in kW
$P_b(t)$	Absorbed power from the grid in kW
$F(P_g(t))$	Piece-wise linear cost function of the generator in €/15-minute
$c_b(t)$	Cost of the absorbed power from the power grid in €/kWh
$c_s(t)$	Cost of the injected power to the power grid in €/kWh
$\hat{M}$	High value penalty cost
$\hat{b}(t)$	Binary variable for the storage charging
$SOC(t)$	State of charge in kWh
$IC$	Storage initial capacity
$P_{ch}(t), P_{dis}(t)$	Storage charging/discharging power and their respective maximum rates
$P_{ch}^{max}, P_{dis}^{max}$	
$L(t)$	Total load demand
$P_{pv}(t)$	Total power produced by the PVs
$J$	Total number of buildings
$K$	Total number of load categories

$\eta_c, \eta_d$	Storage charging/discharging coefficient
$b_{ch}(t), b_{dis}(t)$	Storage charging/discharging binary variables
$D_{j,k}(t)$	Load demand of building $j$ , category $k$
$w_{j,k}(t)$	Load binary variable
$M_k$	High value coefficient

## II. INTRODUCTION

### A. Motivation and Background

Increasing energy demand, energy market deregulation, power system decentralization and the increasing penetration of Renewable Energy Sources (RESs), are the main drivers responsible for the vast changes which the power system is currently experiencing. All these challenges had as a result to decrease the resiliency and stability of the power system. Amongst many solutions proposed for increasing the resiliency and reliability of the grid, the concept of implementing and introducing microgrids has prevailed [1].

Microgrids are defined as small-scale controllable electrical distribution systems, which have the important advantage of operating either autonomously (islanded) or interconnected to the main grid. Microgrids are usually composed of Distributed Energy Resources (DERs), Energy Storage Systems (ESSs) and controllable loads [2], [3]. The DERs are based on conventional and renewable primary resources, such as diesel generators and photovoltaics (PVs), respectively. For investigation purposes, university campuses are typically selected as pilot microgrids to serve as living laboratories [4]. The design and implementation of such a microgrid framework (enhanced by novel control schemes) in a university campus is the goal of the 3DMicroGrid project funded by ERANETMED.

The control of a microgrid is usually separated into three hierarchical levels. The primary and secondary control levels consider droop controls and coordination methods respectively [5]. Examples of novel secondary controller methodologies responsible for ensuring the stable operation and the smooth transition of the microgrid between the grid-connected and islanded modes are proposed in [6] and [7], respectively.

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Tertiary control level represents the microgrid's highest control level and it is responsible for managing its power flows in order to maintain an economically optimal operation of the system [8]. Therefore, microgrid scheduling also falls under the category of tertiary control applications, since it aims at coordinating all the components of the microgrid in a way such that the stability and reliability of the system will remain high while ensuring minimum operation cost [8].

The main objective of this paper is the development of a control strategy responsible for the energy management and scheduling of the microgrid operation. The microgrid scheduling considers historical data, energy production and load profile forecasting, having as a goal to manage the energy flows such that the microgrid's operational cost will be minimized while the operational and security constraints are fully satisfied. However, the main issue that this paper will address is the case where an emergency signal has arrived to the microgrid operator requesting the immediate islanding of the microgrid, cancelling that way the day-ahead scheduling of the grid-connected mode. To overcome this issue, a novel optimization approach is developed for deriving promptly an updated scheduling whenever the microgrid mode changes, keeping always as priority the fulfillment of the operational constraints while minimizing the microgrid's operational cost. Note that the proposed scheduling algorithm will be executed every time the microgrid changes mode (grid-connected or islanded) in order to identify the optimal energy management for the system. In the meantime, the method presented in [7] will ensure a smooth transition and it will keep the system stable until the proposed scheme applies all the necessary modifications.

### B. Relevant Literature

The small size of typical microgrids makes them ideal for implementing and applying optimization algorithms for controlling their operation, which could not be used in the case of the power system due to its large size and complexity. More specifically, their small scale and reduced complexity, provides affordable time to coordination/scheduling algorithms in order to estimate their control actions and apply them in real-time conditions. Optimization techniques have been widely used for the energy management of smart buildings and microgrids in order to maximize the profits of such systems by defining the optimal scheduling of the energy storage, renewable generation, controllable loads and the distributed generators. A Mixed Integer Linear Programming (MILP) model is presented in [9], to minimize the cost of the electricity bill by scheduling the battery energy in a non-residential building equipped with a PV and a battery system. The day-ahead scheduling of a microgrid battery storage system is optimized using linear programming in [10]-[11] while the forecasted load, PV generation and spot electricity prices are considered. Similarly, a dynamic programming method and a particle swarm optimization algorithm are presented in [12]-[13] for energy management in grid-connected microgrid with PV and battery storage. In [14], a MILP formulation is proposed for economic scheduling of a microgrid which is composed of the utility grid, distributed generators, storage system, PV generation and both critical and controllable loads. The methodology in [14] is enhanced in [15] using a model predictive control approach, in order to cope with inevitable disturbances and forecast errors. In the prior mention

works the scheduling have been performed considering the same operational mode for the whole day. The main novelty of this paper compared to the above works, is its ability to re-schedule the day-ahead planning at the event of sudden transition between the two operating modes (grid-connected and islanded), where certain control actions are followed in order to ensure the smooth operation of the microgrid.

### C. Contribution and Organization

In this paper a novel MILP optimization methodology will be developed for the microgrid's optimal scheduling in both grid-connected and islanded modes. The main contributions of this paper are the following:

1. Implementation of two optimization algorithms for the energy management of a microgrid in both grid-connected and islanded modes where each algorithm considers how the scheduling need to be revised in case the operational mode is changed. Also, there is a mechanism for a smooth transition between the two modes.
2. Evaluation of the proposed scheme's effectiveness in grid-connected and islanded modes using a *real-time* simulation framework combined with actual on-site measurements.

The rest of the paper is structured as follows. Section III presents the microgrid pilot configuration and components. The formulation of the proposed scheme for the microgrid's optimal scheduling is presented in Section IV. Section V presents the examined case study along with the outcome of the proposed scheduling and the real-time simulation results. In Section VI the main conclusions are drawn.

## III. MCAST MICROGRID CONFIGURATION

In this section, the main components of the future pilot microgrid are presented and discussed. The university campus considered in the 3DMicroGrid project for the implementation of a pilot microgrid is the Malta College of Arts, Science and Technology (MCAST) campus. The single line diagram of the pilot is presented in Fig. 1. As it can be noted, the components consisting the future microgrid can be separated into four parts: (i) the energy demand, (ii) the energy generation, (iii) the energy storage system, and (iv) the single Point of Common Coupling (PCC) for interconnecting with the main grid. More information for the MCAST microgrid can be found in [4].

### A. Energy Demand

The successful implementation and operation of a microgrid requires the capability of the operator to intentionally shed loads whenever needed (e.g. in islanding conditions) in order to keep the system stable. All the loads in the three buildings of the microgrid in Fig. 1 are considered to be controllable through remote-controlled circuit breakers.

As explained in [7], the benefit of having all the loads be controllable is that a load categorization can be applied. This is a necessary step for the implementation of optimization techniques, responsible for the smooth and economical operation of the microgrid. Therefore, the loads are categorized according to their priority level into essential (ESN), non-essential (NE) and air-conditioning (AC) loads. ESN loads have high priority and thus their shedding must be avoided. The NE loads are medium importance loads where curtailment can take place but

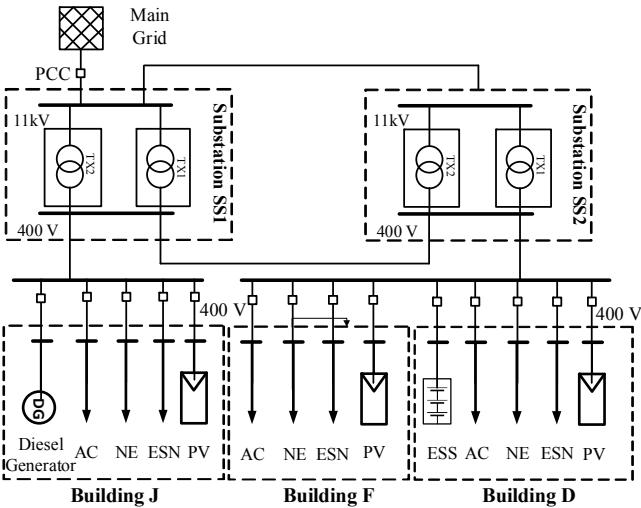


Fig. 1. MCAST microgrid single line diagram

if possible it should be avoided. Finally, AC loads represent the low priority loads, which can be taken out whenever need.

### B. Energy Generation Units

In order to achieve autonomy during islanding conditions, the inclusion of DERs into the microgrid is necessary. For this reason, the MCAST microgrid considers both conventional and renewable generation units. More specifically, a 100 kVA diesel generator ( $P_g^{max} = 100$  kW) is located in building J in order to accommodate the intermittent nature of the PVs and the loads. As RESs, PVs are located on the top of each building with a total rated power of 63 kW peak (21 kW peak in each building).

### C. Energy Storage System

A flexible microgrid requires the existence of flexible devices, which can absorb or provide energy on demand. Therefore, a 50 kW ESS is considered to be included in building D with a usable capacity of 100 kWh. Note that the adopted ESS solution is capable of charging and discharging according to set-points provided by the microgrid's central controller.

### D. Point of Common Coupling (PCC)

PCC represents the point that connects the microgrid to the remaining system. It is usually a controllable single point of interconnection and according to its breaker's status (on/off) the microgrid operates in a different mode (grid-connected/islanded). Islanding and resynchronization techniques, such as the ones presented in [7], aim to control the PCC in such a way so that a smooth and seamless transition will be achieved. It should be noted that a ring configuration is considered for satisfying the “N-1” criterion shown in Fig. 1.

## IV. PROBLEM FORMULATION

The single line diagram of the microgrid used for formulating the two optimization problems is illustrated in Fig. 1. As aforementioned, the microgrid model is composed of PVs, an ESS, a diesel generator, and the controllable loads of the three buildings which are further divided into ESN, NE, and AC loads. In this work, it is assumed that the diesel generator is always synchronized in both modes (grid-connected and islanded) in order to serve as the master of the microgrid, which preserves

the frequency in islanding and regulates the power exchange with the grid during grid-connection. Furthermore, in the grid-connected mode, it is assumed that the minimum state of charge of the ESS is 50% of its usable capacity in order to have enough stored energy in the case of a sudden transition to the islanded mode. Conversely, in the islanded mode, the ESS can be fully discharged in order to satisfy the load demand. Note that the ESS's minimum state of charge (SOC) (in the grid-connected mode) can be defined by the system operator. Therefore, the aforementioned minimum SOC is considered adequate here.

The two optimization problems are formulated as a MILP along an arbitrary time horizon  $T$ . In this work, the time horizon is set for 6, 11 and 24 hours with fifteen minute time intervals. Note that the time horizon for each scenario is explained in Section V.A. The quadratic cost function ( $C(P_g) = a + b \times P_g + c \times P_g^2 [\text{€}/15 - \text{minutes}]$ ) of the generator is approximated by a piece-wise linear function for enabling the MILP technique to solve the problems. Note that the accuracy of this approximation can be controlled by the number of the linear segments considered. In this study, deterministic forecasted data for: controllable loads, day-ahead electricity price, and PV generation are used (Fig. 2).

### A. Grid-connected mode

In the grid-connected mode, the microgrid can absorb power from the grid when the electricity price is low and inject power to the grid when the electricity price is high in order to maximize its operational profit. The objective function of the optimization algorithm for the grid-connected mode is presented in (1). It is important to mention here that this algorithm aims: 1) at minimizing the cost of buying power from the grid, 2) at maximizing the profit of selling power to the grid, 3) at minimizing the operational cost of the generator, and 4) at minimizing the penalty cost from the violation of the permissible state of charge range of the storage for the whole period of study. It must be noted that the allowed state of charge range of the ESS is violated during the transition from the islanded to the grid-connected mode due to the fact that the storage can be fully discharged in islanded mode. Then, the storage is forced to return quickly to its permissible SOC range due to the high penalty cost, in order to be prepared for another sudden transition. Note that the load and PV curtailment is not modeled in this mode, because the main grid can supply all the loads and it can absorb any extra power in case of high PV production.

$$\min \sum_{t=1}^T \left( \frac{c_b(t)}{4} \times P_b(t) - \frac{c_s(t)}{4} \times P_s(t) + F(P_g(t)) + \hat{M} \times \hat{b}(t) \right) \quad (1)$$

Note that  $\hat{b}(t)$  is set to one if the permissible state of charge range (50% - 100%) of the storage is violated, and is set to zero otherwise. Note that the cost parameters are divided by 4 due to the fifteen minute time slots in order to be associated for each fraction of time. Also, in order to avoid the simultaneous power absorption and injection with the grid (due to the same cost of buying and selling electricity), an infinitesimally small constant is added to the cost of buying.

The objective function of the grid-connected mode is subjected to several constraints such as the power balance (2), the energy storage (3)-(4), the system reserve (5), the charging

and discharging restrictions (6), and the power limitations (7). In (3), the  $SOC(t)$  of the ESS in time  $t$  is expressed as the  $IC$  of the storage minus the summation of the  $P_{dis}(t)$  plus the summation of the  $P_{ch}(t)$  for all the past and present time intervals. The charging and discharging power is divided by 4 due to the fifteen minute time slots, in order to be associated for each fraction of time. In (4), the  $SOC(t)$  must be less than the maximum SOC of the storage ( $SOC_{max}$ ) in kWh. Also, the minimum SOC ( $SOC_{min}$ ) is modeled as a soft constraint, which means that any violation is penalized. In (5), a system reserve of 10% of  $L(t)$  of the microgrid is satisfied by the diesel generator in order to keep running as the system's master. The simultaneous charging and discharging of the storage is restricted in (6). Note that  $b_{ch}(t)$  and  $b_{dis}(t)$  are set to one when the storage is charged and discharged respectively, and are set to zero otherwise.

$$\begin{aligned} P_b(t) + \eta_d \times P_{dis}(t) + P_{pv}(t) + P_g(t) \\ = P_s(t) + \frac{1}{\eta_c} \times P_{ch}(t) + L(t) \quad \forall t \end{aligned} \quad (2)$$

$$SOC(t) = IC - \sum_{j=1}^t \frac{1}{4} \times P_{dis}(j) + \sum_{j=1}^t \frac{1}{4} \times P_{ch}(j) \quad \forall t \quad (3)$$

$$SOC(t) \geq SOC_{min} \times (1 - \hat{b}(t)), \quad SOC(t) \leq SOC_{max} \quad \forall t \quad (4)$$

$$P_g(t) \leq P_g^{max} - L(t) \times 10\% \quad \forall t \quad (5)$$

$$\begin{aligned} b_{ch}(t) + b_{dis}(t) \leq 1, \quad P_{dis}(t) \leq P_{dis}^{max} \times b_{dis}(t), \quad P_{ch}(t) \\ \leq P_{ch}^{max} \times b_{ch}(t) \quad \forall t \end{aligned} \quad (6)$$

$$\begin{aligned} P_g^{min} \leq P_g(t) \leq P_g^{max}, \quad 0 \leq P_{dis}(t) \leq P_{dis}^{max}, \\ 0 \leq P_{ch}(t) \leq P_{ch}^{max} \quad \forall t \end{aligned} \quad (7)$$

### B. Islanded mode

The main goal during islanded mode is to satisfy the majority of the buildings' loads by scheduling the diesel generator's output power, the PV curtailment and the charging/discharging power of the ESS. The objective function of the optimization algorithm for the islanded mode in (8) minimizes the operational cost of the diesel generator and minimizes the penalty cost of the non-satisfied building loads. Note that the PV utilization is favored due to the high cost of the diesel generator.

$$\min \sum_{t=1}^T \left( F(P_g(t)) + \sum_{j=1}^J \sum_{k=1}^K M_k \times D_{j,k}(t) \times (1 - w_{j,k}(t)) \right) \quad (8)$$

Note that in this work, a priority is given to the ESN loads, then to the NE loads and lastly to the AC loads. In addition, the value of the power demand of each load is multiplied by the  $M_k$  coefficients in the objective function, in order to shed as less loads as possible, and to avoid the disconnection of a big load in the case of a small mismatch between generation and demand.

The objective function of the islanded mode is subjected to constraints given in (3), (5)-(7), and (9)-(11). The power balance constraint of the islanded mode is shown in (9), where the produced power from the diesel generator and the PVs plus the discharging power of the storage must be equal to the charging power of the storage plus the power demand from the connected loads. In the case where the PV production is higher than the

total load demand, and the storage is fully charged, then a PV curtailment is applied in (10) by the reduction of the PV produced power. In islanded mode, the storage can be fully discharged ( $SOC(t) = 0$ ) or fully charged ( $SOC(t) = SOC_{max}$ ) as shown in (11). Thus, in islanded mode, the algorithm is capable to utilize the full usable capacity of the storage.

$$\begin{aligned} \eta_d \times P_{dis}(t) + P_{pv}(t) + P_g(t) \\ = \frac{1}{\eta_c} \times P_{ch}(t) + \sum_{j=1}^J \sum_{k=1}^K D_{j,k}(t) \times w_{j,k}(t) \quad \forall t \end{aligned} \quad (9)$$

$$0 \leq P_{pv}(t) \leq P_{pv}^{max} \quad \forall t \quad (10)$$

$$0 \leq SOC(t) \leq SOC_{max} \quad \forall t \quad (11)$$

## V. SIMULATION RESULTS

This section presents the proposed algorithm's results for scheduling the MCAST microgrid, when the latter changes modes. For formulating and solving the two MILP problems, MATLAB and a commercial solver were used. The performance of the proposed scheme is validated in *real-time* conditions by considering a discrete-time Electromagnetic Transient (EMT) simulation model of the MCAST microgrid (Fig. 1), which is implemented using RT-Lab and MATLAB/Simulink and it runs in a dedicated real time simulator (OPAL-RT OP5700). Note that for the smooth and seamless transition between the grid-connected and islanded modes, the methodology presented in [7] has also been considered in this study.

### A. Proposed Methodology's Results

For the evaluation of the proposed algorithm's performance, a scenario which considers various transitions between the grid-connected and islanded modes has been considered. More specifically, at time  $t=00:00$  hours the model of the grid-connected mode is solved for a horizon of 24 hours (Fig. 3(a)), by utilizing deterministic forecasted data values for the controllable loads, the day ahead electricity pricing, and the PV generation (Fig. 2). Note that in the grid-connected mode, the

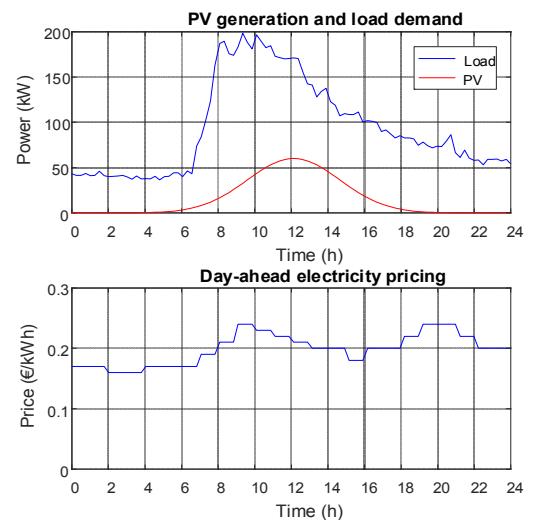
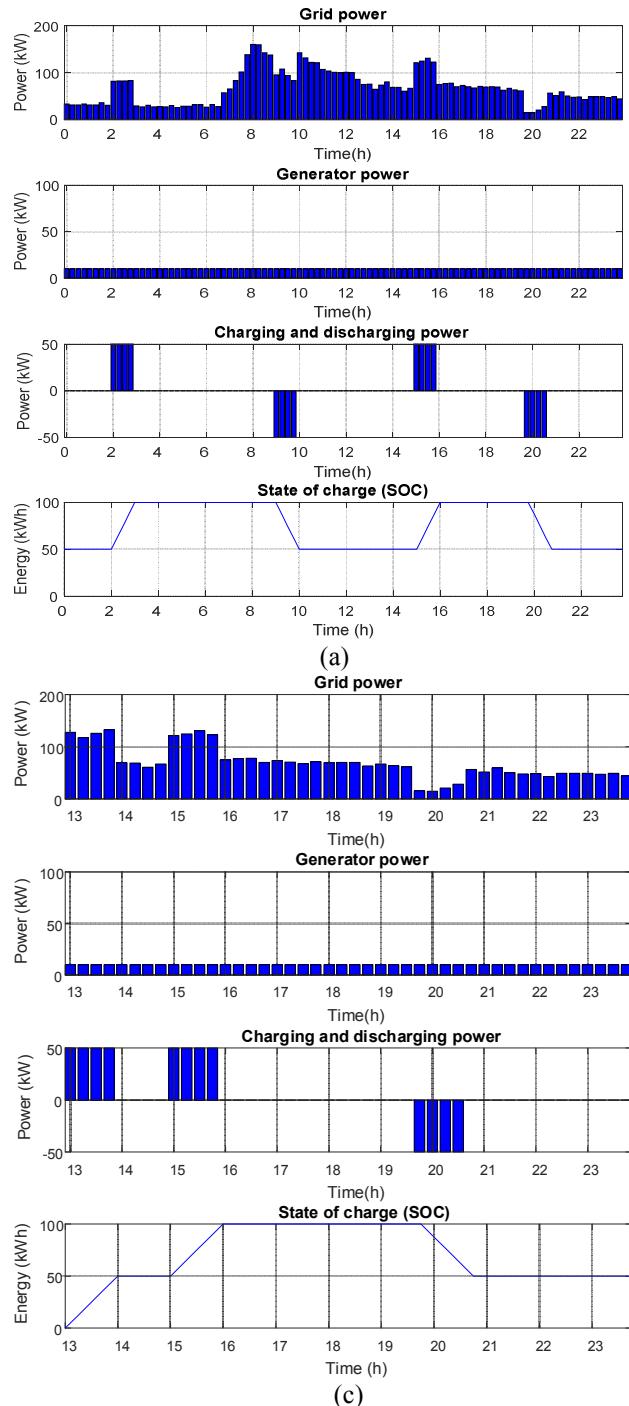


Fig. 2. Forecasted inputs for demand, PV production and electricity price.

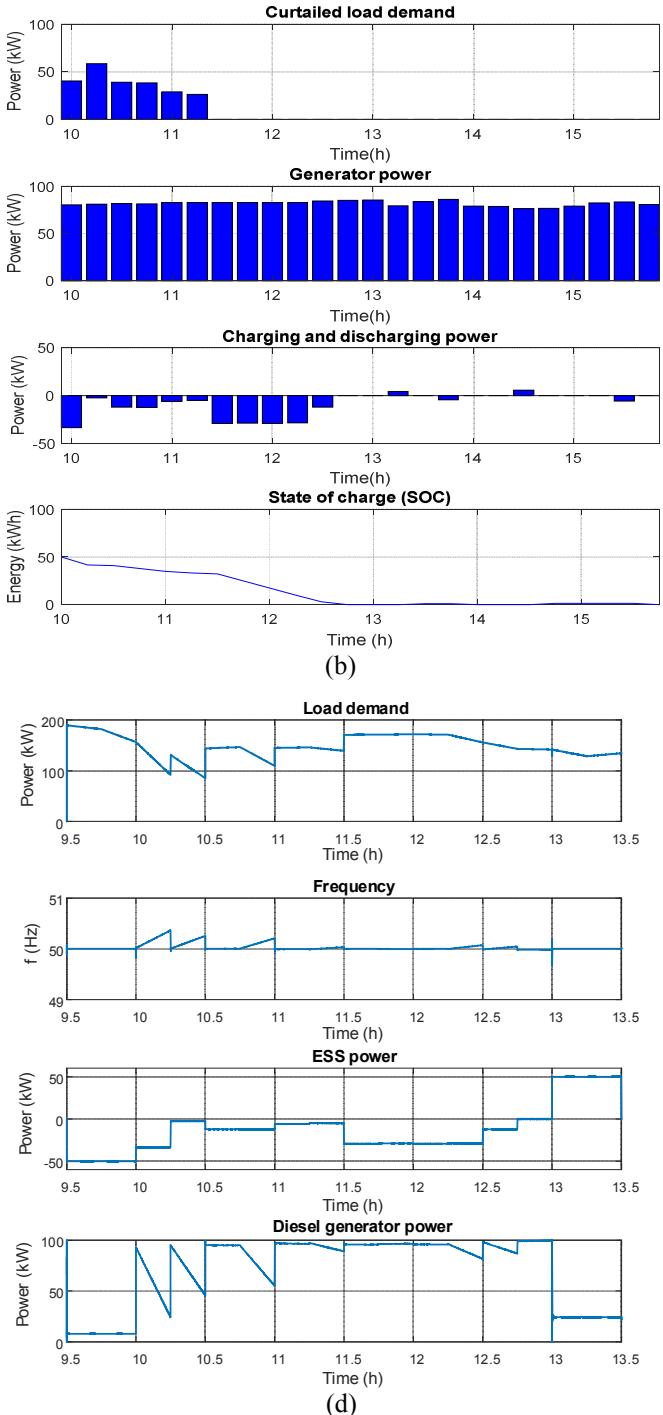
storage is restricted to operate between 50%-100% of its capacity, in order to have enough stored energy in the case of a transition to the islanded mode. Its SOC considered at  $t=00:00$  hours is 50%. As it can be seen in Fig. 3(a), the battery is charged and discharged during low and high electricity prices respectively, in order to minimize the total cost of buying electricity. It is worth mentioning that in this work, high value cost parameters are set for the cost function of the diesel generator ( $a=4.5$ ,  $b=3$ ,  $c=0.3$ ), in order to be more economical to buy power from the grid instead of producing it from the generator. As a result, the diesel generator operates at its minimum stable level during the grid-connected mode.



(c)

Fig. 3. (a)-(c) Proposed scheduling results before, during and after islanding; and (d) Real-time simulation results.

The microgrid follows this operation until an immediate islanding request is received at  $t=10:00$  hours, thus canceling the former scheduling. Then, after the smooth transition to the islanded mode, the model of the islanded mode is solved for a horizon of 6 hours which is assumed that it is the maximum period of time that the microgrid remains in the islanded mode (Fig. 3(b)). Here, the main aim of the algorithm is to satisfy the majority of the loads, while preserving the energy balance. Due to this change, Fig. 3(b) illustrates that during the first six time intervals, certain loads need to be shed. Note that the applied load prioritization has forced the algorithm to choose only AC loads for curtailment.



(d)

The microgrid operates in islanded mode for three hours, when a resynchronization request is received (at  $t=13:00$  hours), causing once again the re-scheduling of the microgrid's operation for a time horizon of 11 hours (until the end of the day). As shown in Fig. 3(c) at the beginning of the horizon, the state of charge of the storage returns quickly to the allowed range (50%-100%) due to the high penalty cost. Following that, the battery is charged and discharged according to the electricity prices in order to maximize the system profits.

### B. Real-Time Simulation Results

While the proposed algorithms have presented some promising results, their actual validation under realistic conditions is still a necessary step for illustrating their effectiveness. This is where a Real Time Simulator (RTS) comes in, for which a detailed EMT model of the MCAST microgrid has been developed for validating the proposed scheduling technique in a *real-time* framework. More specifically, the microgrid analytical model along with the proposed scheduling algorithm were executed in *real-time* for four hours, from  $t=09:30$  - 13:30 hours. Field measurements have been considered for replicating the load and the PV generation profiles of the microgrid. Further, for each component of the microgrid, the associated primary (local) controller has been properly modelled and the secondary controller of the microgrid has been considered within this study. The OPAL-RT OP5700 Real-Time Simulator has been utilized.

All the obtained *real-time* results from the operation of the microgrid are presented in Fig. 3(d). In particular, this figure illustrates the applied load shedding during the islanding, as this was set by the proposed scheme (Fig. 3(b)). It also presents the frequency ( $f$ ) of the microgrid which fluctuates in islanding conditions, but due to the operation of the master (diesel generator) it remains in acceptable limits. Furthermore, the power outputs of ESS and diesel generator are presented here as well. ESS follows accurately the obtained scheduling in both modes (grid-connected and islanded). However, one can note by comparing Fig. 3(b) and Fig. 3(d) that this is not the case for the diesel generator, where a different power output is observed. The reason behind this mismatch is because the forecasted data inputs considered for the scheduling (Fig. 2) differ from the actual conditions which are utilized into the simulation. This is done in order to acquire a more realistic scenario. Therefore, the diesel generator is needed for accommodating these discrepancies. Finally, the "sawtooth" behavior of the diesel generator's power output and frequency is due to the fact that actual on-site measurements are used for simulating the loads, the value of which change constantly and not every 15-minutes as a step-change, like the algorithm considers. This can be solved by including a proper secondary controller responsible for changing the reference power of the diesel generator.

## VI. CONCLUSION

This paper presents the formulation of a scheduling algorithm for the optimal operation of a microgrid and its *real-time* application. The proposed scheme consists of two MILP-based optimization problems (intended for grid-connected and islanded modes respectively), which take as inputs forecasted data. In the grid-connected mode, the objective of the proposed algorithm is the maximization of the operational profit, while in

the islanded mode this changes to the satisfaction of the majority of the building loads while preserving always the energy balance. Therefore, at each mode transitioning, the proposed scheduling identifies the loads to be shed, the state of the ESS and even the PV energy curtailment. For the evaluation of the proposed scheme a case study is utilized where transitions from grid-connected to islanded mode (and vice versa) are considered in order to illustrate its performance and effectiveness in cases where the scheduling needs to be recalculated. For more realistic conditions, the proposed method is applied to a *real-time* simulation environment, which considers a detailed model of the MCAST microgrid. The results indicate the effectiveness of the proposed scheduling in operating optimally and smoothly the adopted microgrid even in the case of various transitions between the grid-connected and islanded modes. Future work will focus on the implementation of a central controller enhanced with novel capabilities, which is also in line with the objective of the 3DMicroGrid project.

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