Energy Management System for Islanded Microgrids Comprising PV Systems, Diesel Generators, Energy Storage Systems: Validation in a Laboratory Environment

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***Abstract*—The aim of the paper is to validate experimentally in an emulated platform an algorithm for ensuring optimal operation of isolated microgrids. The microgrid under analysis is based on different controllable distributed systems that supply different loads in an isolated distribution network. The proposed algorithm operates the AC microgrid, which includes a photovoltaic power plant, several diesel generators (based on synchronous electrical machines), a battery energy storage system and loads. The optimization algorithm (based on linear programming) can be implemented with different objective functions. It can maximize renewable power generation, minimize diesel consumption and ensure an appropriate management of the batteries without compromising the frequency stability of the system. The energy management system generates a day-ahead schedule and set-points for the distributed generation units and the energy storage system. The proposed algorithm is validated in a laboratory environment. The system is based on emulators of different characteristics. The validation includes testing of different generation and load scenarios. An emulation platform allows to transform software computed variables to real physical magnitudes such as voltages, currents or powers. This way, real equipment can be connected to the emulator to check its behaviour. The paper describes the validation of the entire system under a gicen scenario, considering different generation and load patterns.**

I. Introduction

Operation and control is one of the main challenges faced by microgrid development [1], [2], [3]. A number of different units need to be coordinated and communicated to supply a number of services which are essential for the correct operation of a power system. A microgrid must be capable to perform isolated operation [4], facing challenges in terms of active power balance to maintain the frequency within an acceptable range. To reduce frequency excursions produced by non-expected photovoltaic (PV) power variations, the curtailment of PV generation can be performed. Another option to limit frequency deviations is to increase the grid inertia by connecting rotating machines (normally attached to a diesel motor). Nevertheless, these measures increase the operation cost and the environmental impact.

Some authors have proposed optimization algorithms for the operation of isolated microgrids [5], [6], [7] which are based on cost minimization. Most of these algorithms are deterministic or heuristic problems, which consider power balance without taking into account forecast errors. Hence, transient frequency deviations may appear. Particularly, in [6] it is described that the optimization problem does not consider the grid frequency as it is controlled by a lower control level. On PV-Battery-Diesel based microgrids, grid inertia, which stabilizes the frequency, is provided by the diesel generators ($\mathrm{G_{dies}}$). The connection of a $\mathrm{G_{dies}}$ increases the grid inertia but a minimum amount of power (P_{dies}^{min}) must be generated. Hence, a compromise between the frequency stability and the power dispatching arises. Without considering frequency limits in the optimization algorithms, its variation due to unexpected power unbalances can compromise the system operation.

This paper deals with the experimental validation in an emulated platform of a power dispatch optimization algorithm which was developed by CITCEA-UPC and presented in [8]. The paper summarizes the optimization algorithm and presents the emulation platform and the results obtained in a case study which was implemented and tested.

II. System under analysis

A. System description

As shown in Figure 1, the system is composed by an energy management system (EMS) which operates optimally the resources of the microgrid controlling the local controllers (LC), which are in charge to manage each resource separately.

The frequency is regulated by the diesel system and supported by the PV and storage systems that follow a power-frequency droop to avoid larger deviations. The solution proposed is able to track the battery power setpoint, the maximum PV power setpoint and the connection or disconnection of each diesel generator, taking into account that the frequency must remain inside the limits after an eventual power variation.

B. Optimization problem

The problem optimizes the photovoltaic energy use while ensuring the power balance between the demand and the generation, and that the minimum frequency (f_{min}) reached after a maximum consumption and P_{PV} variation is between the limits.

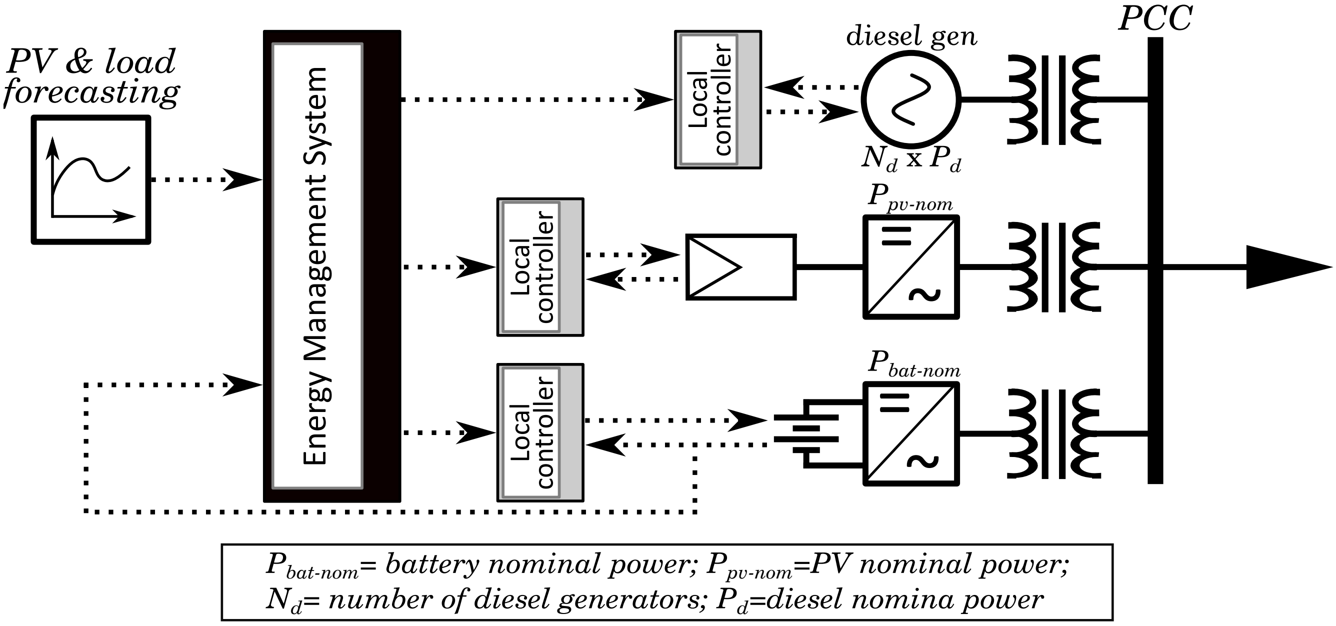

Figure 1: Simplified PV-Battery-Diesel-based microgrid scheme

The decision variables are the number of diesel generators connected D^*_{con}, the maximum photovoltaic power setpont P^*_{PV-max}, and the battery setpoint P^*_{bat} for the rest of the day. The system input parameters for each execution are the state of charge of the battery (SOC), and the consumption and the available P_{PV} forecast (mean and standard deviation).

According to Figure 2 three different time periods are defined, the forecast refresh period (T_{for}), the EMS period (T_{EMS}) and the intra period (T_{intra}). T_{for} is the time period between two forecast updates, T_{EMS} is the time period between two executions of the optimization problem, and T_{intra} is the time resolution that is taken for the optimization problem. In each execution the decision variables are calculated for the rest of the day, P^*_{bat} and P^*_{PV} are determined using T_{intra} resolution, and D^*_{con} using T_{EMS} resolution. As shown in Figure 2 decisions applied at period *t* must be calculated at period *t-1*.

C. Frequency restriction

The maximum increase in power demand and the maximum decrease in available PV power needs to be determined. This must be achieved analysing the microgrid historical operation and applying a security factor to the maximum values.

A set of scenarios varying (D_{con}) from nD_{max} to nD_{min}, the P_{PV} from P^{max}_{PV} to 0 and the P_{bat} from P^{max}_{bat} to P^{min}_{bat} are simulated. P_{PV} and P_{bat} determines the mix of the power supply to satisfy the demand and D_{con} determines the power per diesel generator and the grid inertia. Applying the maximum variations to the P_{PV} and P_{load} and storing the minimum frequency reached for each scenario, an analytical expression relating the minimum frequency reached after a power variation and the decision variables can be determined.

D. Execution Cycle

The optimization algorithm is designed to take advantage of the daily sun period, the execution cycle for day *d* is shown in Figure 2.

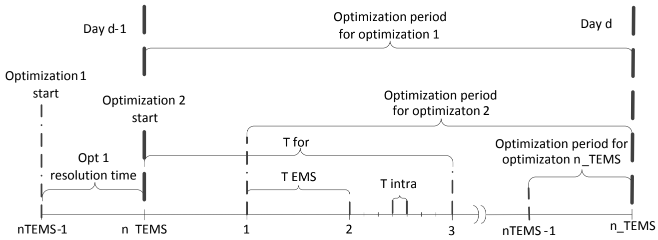

Figure 2: Temporal description of the daily execution cycle

Period *t* execution: At period *t* the $P^{bat}_{t,I}$ & $P^{PV_{max}}_{t,I}$ $\forall\ I \in \{1,..,nT_{intra}\}$ are sent to its respective converters, and the SOC at the beginning of period *t+1* is calculated using the current SOC, and the battery setpoints for the current execution period.

Using the calculated SOC and the previsions for the rest of the day *d*, the optimization problem is solved, and $P^{bat}_{T,I}$ & $P^{PV_{max}}_{T,I}$ $\forall\ I \in \{1,..,nT_{intra}\}$, $T \in \{t,..,nT_{EMS}\}$ and D^{con}_{T} $\forall\ T \in \{t,..,nT_{EMS}\}$ are calculated.

The solution must be reached before the beginning of the period *t+1*, otherwise, the setpoints calculated for the period *t+1* at the period *t-1* are sent to the respective converters.

III. Case study

The study case is based on a real microgrid. This microgrid has 9 diesel generator units of 1.2 MVA. The storage system is based on 2 batteries, where each one has a capacity of 560 kWh. These batteries are connected through 4 inverters with a total aggregated power of 2.2 MVA (550 kVA per inverter). Regarding the photovoltaic power plant, it consists of a bundle of PV arrays and inverters with

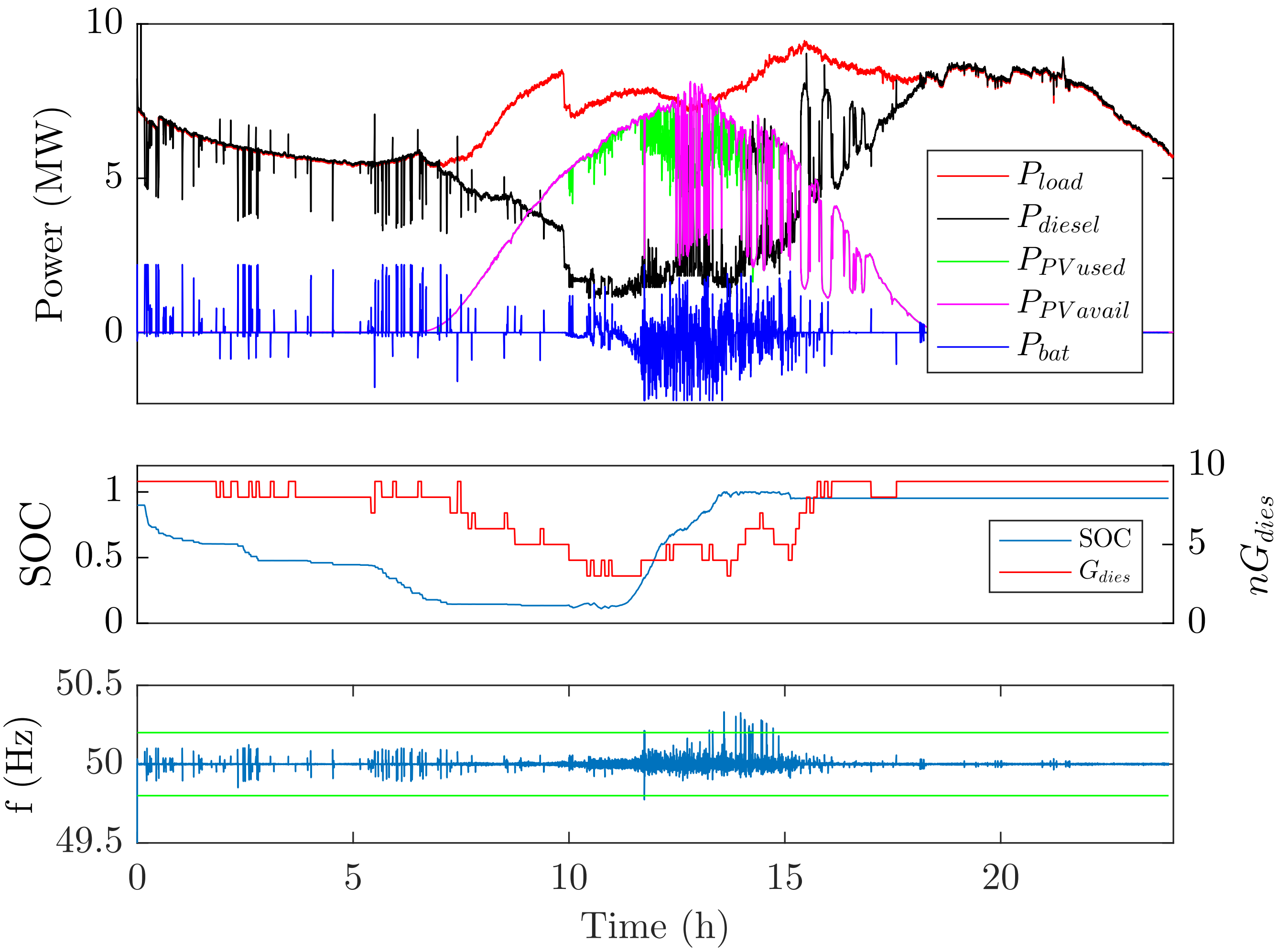

Figure 3: Simulation results for the scenario (high PV power variability after the midday)

an aggregated rated power of 10 MW. The optimization problem parameters are depicted in Table I and the minimum frequency considered is $f^{mn} = 49.0$ Hz.

Table I: Parameters for the EMS optimization problem

Parameter	Value	Parameter	Value	Parameter	Value
n_{TEMS}	288	Cap^{bat}	1120 kWh	P^{mnB}	-2200 kW
n_{Tintra}	10	SOC^{i}	0.9	P^{mnD}	0.3*1100 kW
N_d	9	η^{bat}	0.9	P^{mxD}	1100 kW
N_s	5	P^{mxB}	2200 kW	$marge_{dies}$	2000 kW

One example scenario has been simulated. The scenario has high PV variability after the midday. To simulate the whole system, the EMS is executed as described above and the corresponding setpoints are applied to a dynamic model of the microgrid. As mentioned before, this microgrid model consists of 9 diesel generators and simplified battery and PV models. After running the case study, the corresponding results are shown in Figure 3.

Results show in the top plot the active powers generated and consumed. In the middle plot, the SOC and the number of connected diesel generators are represented. Finally, the bottom plot shows the grid frequency, where the green lines represent the frequency deviation when the frequency droop control of the battery and PV plant is activated.

IV. Experimental validation

A. Platform description

The developed EMS has been tested with an emulator-based microgrid. An emulation platform allows to transform software computed variables to real physical magnitudes such as voltages, currents or powers [9]. This way, real equipment can be connected to the emulator to check its behaviour. So, the platform is adequate to test the system presented above.

The microgrid emulator scheme is shown in Figure 4, while Figure 5 shows a picture of it. The laboratory system consists of two subsystems where part of the devices are emulated, but the electrical power flowing in the system is real. The first subsystem is composed by the emulated systems such as diesel generators, photovoltaic generators, batteries and loads. These emulators mimic the behaviour of the corresponding real device and their configuration is performed through a central microgrid emulator configuration PC, which is interconnected with the emulators through an internal communication network. The real subsystem can be connected or disconnected from the external grid to emulate an isolated or grid connected microgrid. As this study considers the stand alone microgrid operation, the real subsystem is electrically isolated from the main grid. The real subsystem consists of hardware devices as the PV

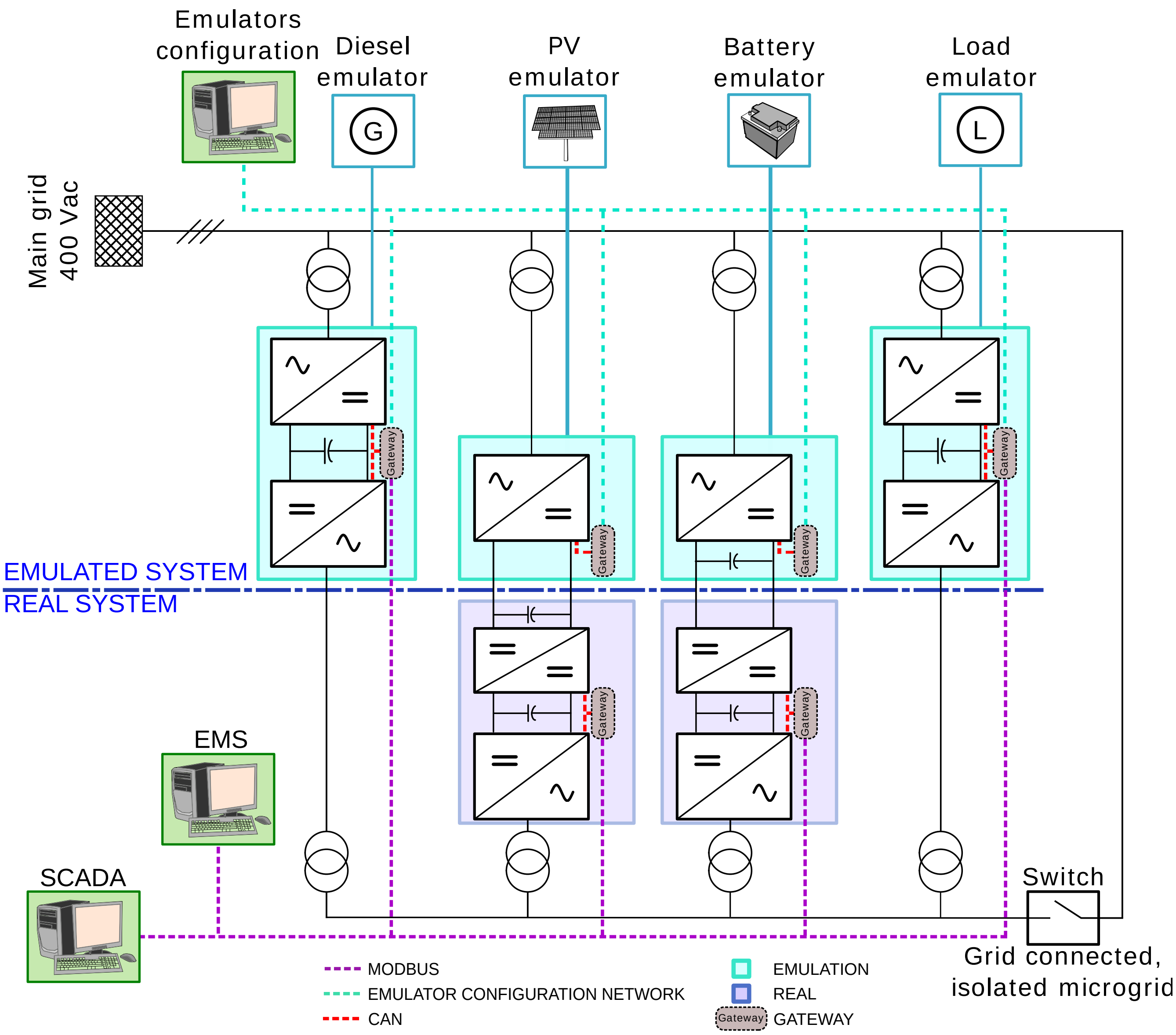

Figure 4: Microgrid emulator scheme

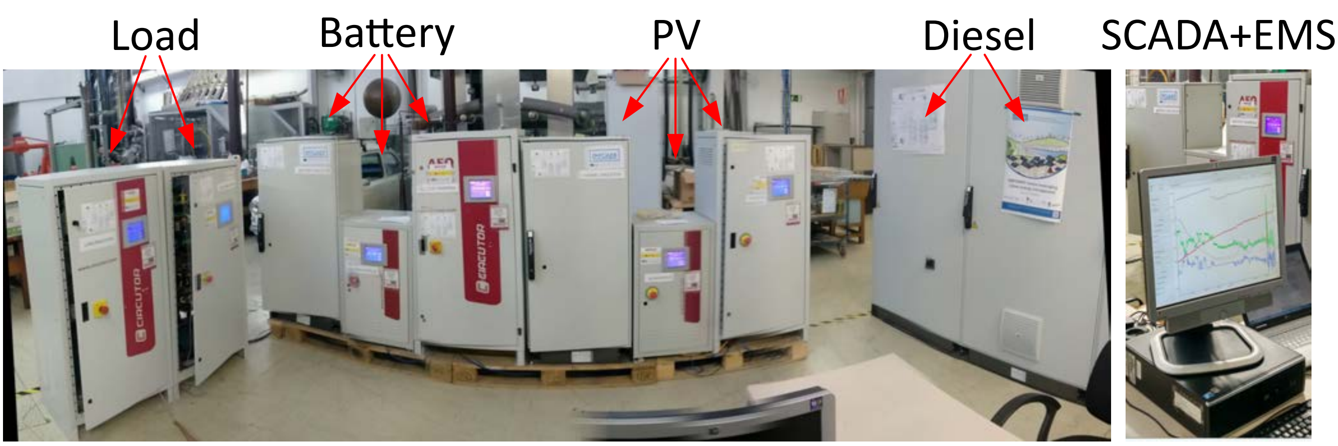

Figure 5: Microgrid photo

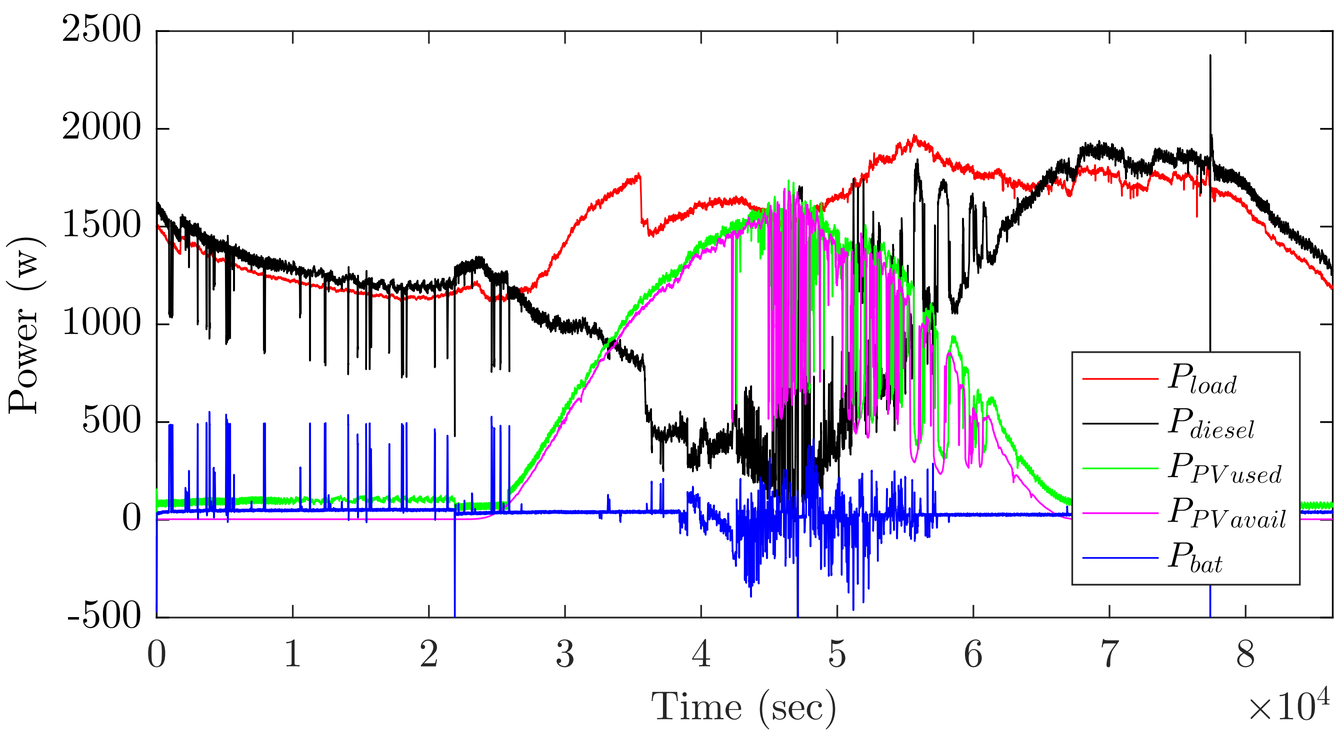

Figure 6: Laboratory emulation results for the scenario (high PV power variability after the midday

inverters, the battery inverters and the power transformers. Their operation is coordinated through the EMS (executed in a PC) and supervised by the SCADA with the corresponding communication network.

The real subsystem consists of hardware devices as the PV inverters, the battery inverters and the power transformers. Their operation is coordinated through the EMS (executed in PC) and supervised by the SCADA with their communication network with the microgrid.

B. Emulation results

The simulated day has been emulated using the previous described platform. Due to the fact that the platform has a nominal capacity lower than the real case, the presented results are scaled-down. The emulation is performed in real-time. The EMS is executed in a personal computer and each T_{EMS} period (each 5 minutes) the setpoints are sent to the emulators. The emulation results are shown in Figure 6. It can be observed how the system behave similar to the simulated case. The diesel generation decreases during the sunny hours and increases during the night time. On the other hand the battery is discharged and charged in same way than in the simulated case.

V. Conclusion

The paper has presented the experimentally validation in an emulated platform of an algorithm for ensuring optimal operation of isolated microgrids. The experimental platform has shown that the developed algorithm can be implemented in practical applications and it has been shown that a normal computer can be used to implement the algorithm and to communicate efficiently with the relevant power converters. Next steps will be focused on the application of the algorithm in a real microgrid project.

Aknowledgements

This work has been funded by the Spanish Ministry of Economy and Competitiveness under Project ENE2015-67048-C4-1-R. The authors would like to thank Luis Serrano and Carlos Pacheco from GreenPowerMonitor for their support in this work.

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