Real-Time Energy Management System for a Hybrid AC/DC Residential Microgrid

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Real-Time Energy Management System for a Hybrid AC/DC Residential Microgrid

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***Abstract*—This paper proposes real-time Energy Management System (EMS) for a residential hybrid ac/dc microgrid. The residential microgrid is organized in two different distribution systems. A dc distribution bus which interconnect the renewable energy sources (RES), energy storage systems (ESS) and the building's common facilities; while the apartments are supplied by an ac distribution system connected to the grid. This architecture avoids any modifications in the electrical installation that supplies energy to the apartments. A pure dc voltage supply is not yet a feasible approach for residential buildings. This architecture increases the overall efficiency of the distribution by interconnecting the RES and ESS thorough a dc distribution bus, and therefore avoiding unnecessary dc/ac conversion stages. The real-time EMS performs an 24 hours ahead optimization in order to schedule the charge/discharge of the ESS, and the energy injection/consumption from the grid. The EMS estimates the RES generation based on the weather forecasting, together with stochastic consumption modelling of the building. The EMS architecture and the residential microgrid have been implemented and tested in a laboratory scale setup. The results shown how the operational costs of the system are effectively decreased by 28%, even with non-accurate estimation of the RES generation or building parameters.**

***Keywords*—Residential microgrid, energy management, decentralize control, DC Microgrid, hybrid ac/dc microgrid, mixed integer programming.**

I. INTRODUCTION

Microgrids effectively ease the integration of renewable energy sources (RES) and energy storage systems (ESS) at consumption level, which generally aims to increase the efficiency of the electrical system, and reduce the dependency of the electrical supply from fossil fuels. Microgrids intrinsically increase the efficiency of the electrical system by integrating the RES at the consumption level, which avoid most of the transmission losses [1]–[4].

In addition, the use of dc distribution systems has the potential to further increase the energy efficiency, and potentially reduce the cost of the system, especially when the penetration of RES and ESS is significant. DC distribution systems inherently reduces the losses in the transmission, because the majority of RES, such as photo-voltaic (PV) panels and fuel cells (FCs), ESS, such as batteries, and loads, such as (TVs, LED lights, phones, computers etc.), in residential building are dc-based elements. Therefore, the interconnection of dc-based generators, energy storage systems and loads, avoids dc-ac and ac-dc conversion stages in the power converters, which unnecessarily bring higher losses to the distribution system [4]–[9]. Moreover, even not dc-based elements, such as small-scale wind turbines, can benefit from dc distributions systems, since it stills allows a reduction of the power conversion stages in the interface converter [8]. In addition, the more than expected future integration of electric vehicles (EVs) into the electrical power system of the residential building, is going to further increase the potential efficiency improvement of dc distributions systems for residential applications. Therefore a dc distribution system is a more natural interface between mostly dc devices, which allows an elimination of a significant amount of power conversion stages, as well as simplicity and potential cost reduction, in the power converter units [8].

Even though, dc distribution systems offer significant advantages, their fully-implementation on residential buildings is not yet feasible. There is not an standardized voltage level for distributions in dc residential grids [3], [8], protection systems and devices are inherently more challenging [10], and the typical loads in residential buildings are not yet compatible with dc voltages. Therefore, hybrid ac/dc distribution systems appear as an intermediate solution for the integration of RES and ESS in residential grids [11]–[16].

In [11], a management system for hybrid ac/dc microgrid is shown, where a higher efficiency is achieved by reducing the conversion stages in the power converters. Also, it is pointed out that even though is theoretically possible to feed the loads in dc, the needed re-design, to adapt existing ac load to be supplied with dc voltages, is not feasible. The microgrid remain stable for both grid-connected and isolated mode, however, real-time power measurements, of the different elements in the system, are needed for the management. A similar approach is also follow in [14] where the RES and ESS and interlinked by a dc distribution system, while the loads remain fed from the ac grid. The proposed coordinated power flow control method requires real-time information from the consumption and generation units, which in general is unwanted since it needs a fast and reliable communication system. Alternatively, decentralize control schemes are shown in [12], [16] in order to regulate the power flow between microgrids; however, no high level optimization scheme can be implemented, due to the lack of a communication system. An optimal control for a residential ac microgrid, is proposed in [17], where the power injection by the thermal and electrical ESSs are scheduled in order to minimize the operational cost of the system. The work presented in this paper follows a similar strategy, where a high level EMS, including an optimization algorithm, schedules the power injection into the ac grid

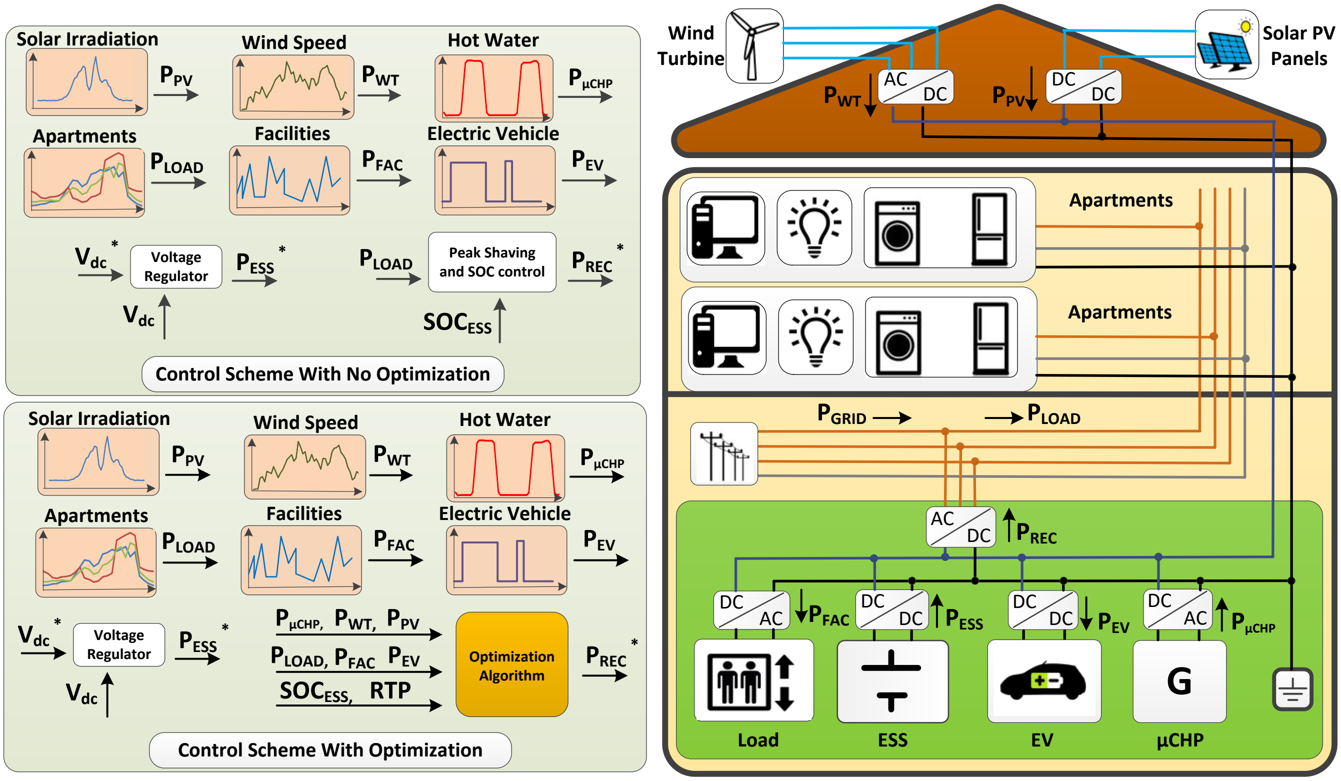


Figure 1: EMS for a Hybrid ac/dc microgrid

in order to minimize the operational costs. However in this work the microgrid is composed by two different distributions systems, and the scheduling is not performed directly on the electrical ESS, rather than on the power flow between the ac and dc part of the microgrid. Furthermore, the scheme in [17] relies on historical data for obtaining the generation and consumption profiles, while by using the approach proposed in this work, the EMS estimates the generation based on the weather forecasting, and the consumption with stochastic models. In addition, the smart metering infrastructure of the building can be integrated into the EMS architecture [18], in order to provide measured data to improve the estimation of the energy consumption.

II. Architecture of the Residential AC/DC Microgrid

The architecture of the system is shown in Figure 1. The local RESs (solar PV Panels, wind turbine and μCHP), common building facilities (loads and EVs chargers), and the ESS, are interconnected by a dc distribution system; whereas, the individual consumers (apartments) are fed from the ac grid. A 3-ph inverter interconnects the dc distribution bus with the ac grid. This architecture aims to decrease the conversion stages to a minimum [8], while maintaining the ac voltage supply to the apartments, in order to avoid any modifications in the existing installation (loads, protection devices..) to make them dc voltage compatible.

This architecture also allows to realize peak shaving strategies in a simpler manner, since the 3-ph inverter only needs to compensate the aggregated consumption from the apartments, in order to decrease the consumption peaks from the grid. However, if all the RES, ESS and loads were connected to the same ac distributions system, the compensation becomes more challenging, because the aggregated building consumption would be directly affected the extra elements, while the compensation effort would still be provided by the same ESS.

A. Control Schemes of Power Converter Units

Figure 1 shows the different power converter units (PCUs) needed to control the power flow in both parts of the microgrid. The PV and wind turbine (WT) power converters are controlled by maximum power point tracking algorithms, which are independent of the EMS. Therefore, in normal conditions, the power generated can be easily estimated by the solar irradiation and wind speed profiles for that particular location.

The μCHP unit works independently from the EMS. The power generated, only depends on the thermal consumption of the building. The ESS is the unit that regulates the dc bus, the control scheme and the selection of the control parameter have been obtained following the design guidelines in [19]. The 3-ph inverter is the only PCU that receives commands from the higher level EMS. The power control scheme is equivalent to a current control scheme, since the voltage

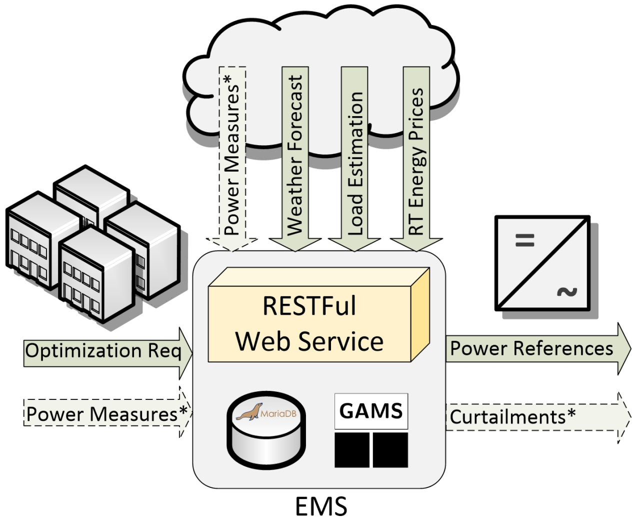


Figure 2: Concept of the implementation of the proposed distributed EMS

variations on either of distribution buses are expected to be minor. The specific current control scheme, control parameters, and stability analysis are shown in [20]. Furthermore, the common loads connected to the dc bus, are fed by PCUs which adapt the supply voltage level to the one required by the specific load (EVs, ligthing, lifts..).

III. Energy Management

The EMS is the cornerstone of the proposed architecture being responsible for the bi-directional power flow control between the dc and the ac distribution systems. Hence, two main tasks must be performed by this system. On one hand, it should directly or indirectly interact with the PCU by means of available communication standards. On the other hand, the optimization procedure is to be carried by the EMS in a transparent way to the user. Both perspectives are addressed in the following sections.

A. Structure and Implementation

As far as the communication implementation is concerned, the flexibility, ease of use and transparency to the end user were a priority. In this way, a distributed implementation was chosen, where the EMS was not attached to any specific building, but deployed in an accessible server running a web service which allowed the intercommunication through the HTTP protocol and a RESTful philosophy. Therefore, the system was concurrent, easy to debug and update, and flexible so new optimization algorithm could be implemented or modified on demand. The conceptual communication scheme is illustrated in Figure 2. As it can be seen each building controller sends an optimization request to the EMS using the RESTful service, accessible to all subscribers. This request has to use either in an XML or JSON format and contains basic information that identifies the building and the optimization options. Moreover, it might also include powers and battery SOCs in the case no advanced metering infrastructures (AMI) are accessible to the EMS using a third-party service.

Using the received information, the EMS queries an attached database which stores key parameters regarding the building such as the location, the installed DER, the dwellings' characteristics and the electricity tariff. By means of the location, the EMS requested the weather forecast to an external service and, subsequently, using the DER characteristics and estimation of the PV and WT power production is performed.

Likewise, the consumption estimation is requested to a previously developed service which implements a stochastic modeling methodology [21]. This method takes into account the unpredictable and chaotic behavior of the users and predicts the average aggregated consumption for the building employing the dwellings' characteristic and the weather conditions. What is more, since the model is based on a high temporal resolution occupancy model, the consumptions of the common areas due to lighting and other services such as the elevator can also be accounted.

In addition, for those users whose tariff varies along the day having a so-called real-time price (RTP), another service was implemented which aims to request the daily rate profile so it can be used in the optimization process. Once all these data are available, the web service initializes the optimization routine according to the method selected in the request packet. As a result of this process, the power references for the 3-phase inverter PCU are given, which are then sent as a response to the building controller, including for some optimization processes additional information about the curtailment strategies to be taken en the end users loads.

This structure allows having low computational tasks at the user side where even a low-cost embedded system might be used for the references exchange with the converter, whereas the high computational demanding processes are carried out by the central web service which is accessible by means of a widely spread standard such as HTTP. This boost the scalability, maintenance, and development times of the central system, whilst keeping the building controllers simpler.

B. Optimization Algorithm

The optimal operation management problem for the considered building-level microgrid is formulated as a mixed-integer programming (MIP) and set up as follows:

$$Min\{TOC = \sum_{t=1}^{T} (\rho_{GRID}(t) \cdot P_{GRID}(t) + \rho_{GAS}(t) \cdot P_{\mu CHP}(t)\} \quad (1)$$

so that,

$$P_{G,i}^{min} \leq P_{G,i} \leq P_{G,i}^{max}; \quad \forall\ i \in N_G,\ t \in T \quad (2)$$

$$P_{GRID}(t) + \sum_{N_G}^{i=1} P_{G,i}^{e}(t) = P_{LOAD}^{e}(t) + TPL^{e}(t); \quad \forall\ t \in T \quad (3)$$

$$\sum_{N_G}^{i=1} P_{G,i}^{th}(t) = P_{LOAD}^{th}(t) + TPL^{th}(t); \quad \forall\ t \in T \quad (4)$$

$$SoC_{ESS}(t) = SoC_{ESS}(t-1) + \\ + \frac{[P_{ESS,ch}(t) \cdot \eta_{ch} - [P_{ESS,dch}(t)/\eta_{dch}]] \cdot \Delta T}{E_{ESS}}; \quad \forall\ t \in T \quad (5)$$

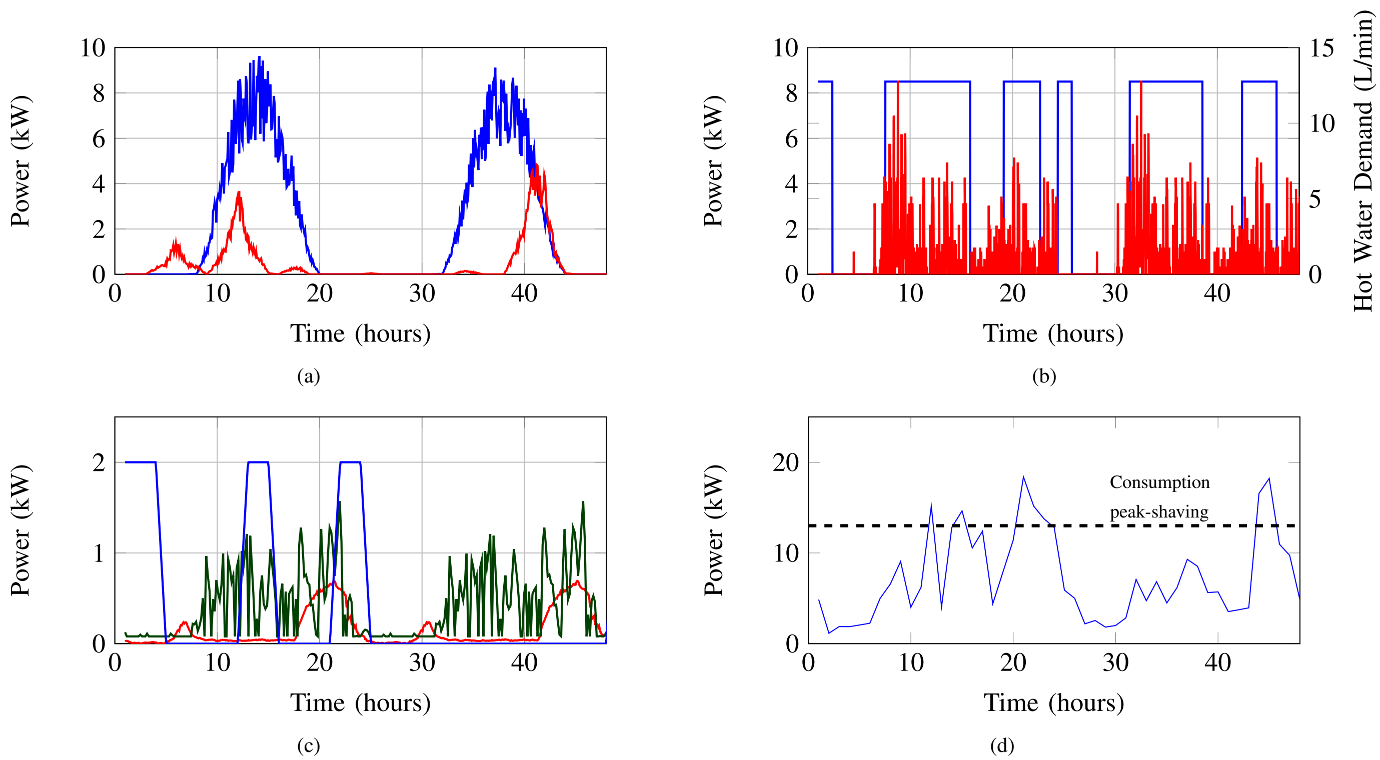


Figure 3: Consumption and generation profiles for the study case. a) PV (blue) and WT (red) generation. b) μCHP electrical generation (blue) and hot water consumption in the building (red). c) EV chargers (blue), lighting (red) and lifts (green) consumption. d) Hourly aggregated electrical consumption of the 16 apartments.

where, TOC is the total operating cost of the residential microgrid, $grid(t)$ and $Pgrid(t)$ are the real-time electricity price and the amount of power exchanged with the grid at time t, respectively. PG denotes the set of dispersed generations (DG) units. Also, $P_(G,i)^e$ ($P_(G,i)^{th}$) is the electric (thermal if applicable) output power of the i-th DG unit, P_load^e (P_load^{th}) is the electric (thermal) demand and TPL^e (TPL^{th}) is the electric (thermal) losses of the system, respectively. Finally, (4) represents the energy balance equation for a given ESS with a charging (discharging) power of $P_{ESS,ch}$ ($P_{ESS,dch}$) and a charging (discharging) efficiency of η_{ch} (η_{dch}).

In this paper, the General Algebraic Modelling System (GAMS) with Cplex and Dicopt solvers is used as the optimization engine, mainly due to its high-level modelling capabilities for solving linear and non-linear MIP problems, a similar approach have been successfully used in previous works [22].

IV. Study Case and Methodology

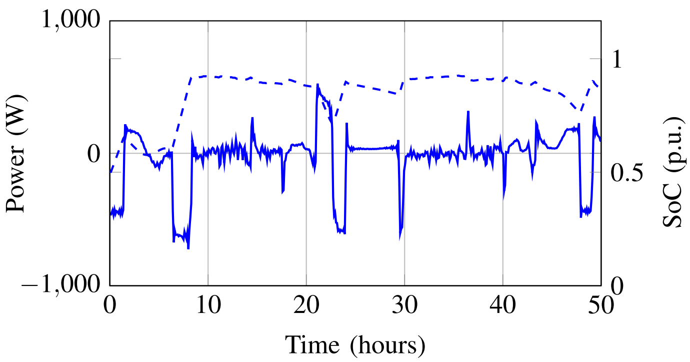
For the study case a 16-apartment building has been considered, which contains a 8 kWp PV installation, 5 kWp wind turbine, 8.5 kWp μCHP, 2 kW EV chargers, and a 80 kWh 30 kW battery pack as ESS. As shown in Figure 1, a 700V dc distribution bus interconnects the RESs, ESSs, EV chargers, and common load of the building. It has been found that the 700Vdc is as a good compromise between potential efficiency improvement, safety and compatibility with the ac grid [8].

The objective of the paper is to assess whether the EMS with the proposed optimization scheme effectively reduces the operational cost of the system, as well as, the feasibility of using purely estimated consumption and generation profiles for the real-time management. For the assessment of the proposed scheme a comparison has been made, with a more conventional peak-shaving strategy, which does not involve a higher level EMS with an optimization scheme.

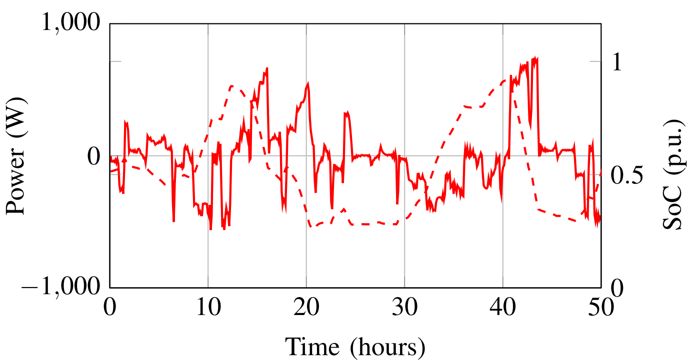
In order to make a fair comparison the same input data has been used for both experiments. The consumption profiles, are generated off-line from the stochastic models, and then used in both experiments. The same approach is followed with the weather information, rather than using real-time weather information, data recorded, by a weather station, in the Energy Technology Department at Aalborg University, has been used. The estimated generation and consumption profiles used in the experiment are shown in Figure 3.

The power consumption of the EV charger, when the vehicle is plugged in, has been approximated by the rated power of the EV charger. The power consumed by the EV charger mostly depends on the current SoC of the battery [23], however, the power variations from the rated value are not significant, therefore is more convenient for the analysis to approximate the EV charger power consumption.

In order to emulate the differences between the real RES generation and loads consumption profiles, and the estimations made by the EMS; the power profiles passed to the setup have been modified by adding random noise, on a 5 minutes



(a)



(b)

Figure 4: ESS power consumption (solid) and SoC (dashed). a) with the peak-shaving strategy. b) with optimization scheme.

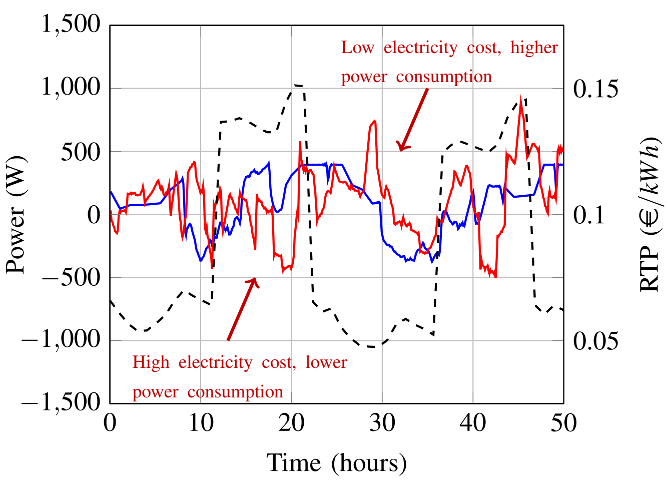


Figure 5: Grid power consumption with the peak-shaving strategy (blue), the optimization scheme (red) and real-time price of electricity (dashed black)

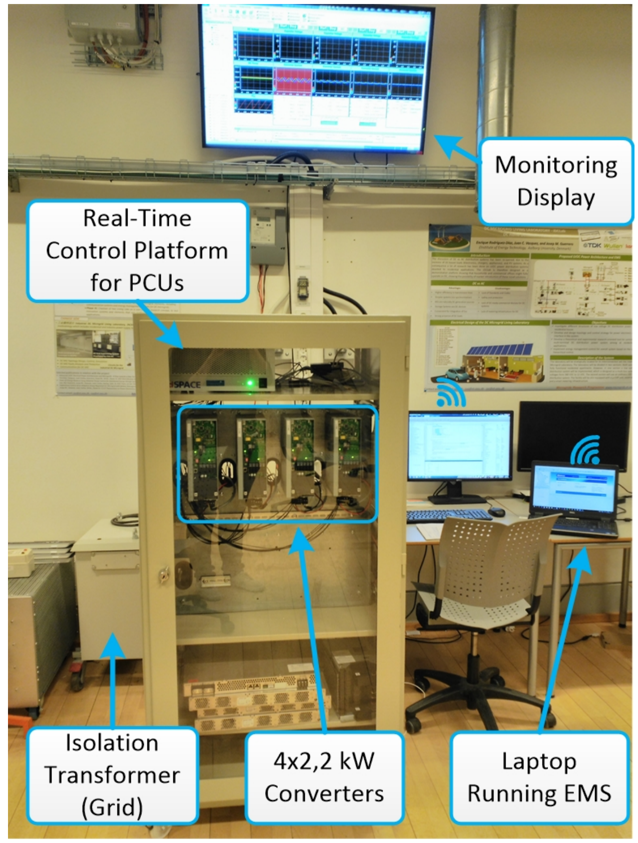


Figure 6: Experimental test-bed

interval, with values within ± 30% of the average power in the associated period.

The experimental test-bed, shown in Figure 6, has been used to test the management schemes. Four 2.2 kW 3-ph inverters, connected to the same dc distribution bus, are used to emulate the dc part of the microgrid. The electrical generation (PV + WT + μCHP) has been emulated together in one inverter, as well as the consumption (EV + lighting + lifts), while the ESS and the grid connected inverter have been implemented in the remaining units. The same structure has been used for both experiments, since the only difference, as shown in Figure 1, is how the power reference for the grid connected inverter (P_{REC}) is obtained.

Due to the hardware limitations, the consumption and generation profiles have been scaled down, in order to obtain feasible operating points for the power converters. The lower level control structures, for each power converter, which regulate the voltage and power flow in the microgrid setup, have been implemented in a real-time control platform. Furthermore, the architecture of the EMS, described in section III, has been implemented in a separate system (see laptop in Figure 6) and communicates with the grid rectifier by means of a local wireless network in the laboratory.

V. Experimental Results

The system depicted in Fig. 1, has been tested in the laboratory scale experimental setup shown in Figure 6. The power converters, used in the experimental setup, have a reduced power rating in comparison with the residential building used in the study case, therefore, the input power profiles of the units, shown in Figure 3, has been decreased by a factor of 40.

The same input information, solar irradiation, wind speed, hot water, and consumption profiles have been used, for testing the two systems. On one hand, the emulated system with a peak shaving strategy compensates the aggregated consumption of the building, to maintain the power consumed from the grid below a given limit. In the experiment this limit has been set for 14 kW (350W in Figure 5). On the other hand, the proposed EMS architecture schedules the P_{REC} to minimize the operational costs, which in this case account for the cost of electricity, since the μCHP profile is common in both experiments.

Figures 4 and 5 show the ESS power profiles and associated SOC, and the power exchange between the microgrid building and the grid. From the experimental results some conclusions that can be drawn; first, as seen in Figure 4(a), the local dc microgrid has a great excess of generation in comparison with the local consumption, since the ESS, remains fully charged during most of the experiments, which in practise would allow for a reduction of the ESS rated capacity, or a lower limit for the maximum power consumed from the grid. Second, from Figure 5, a trend can be seen where the EMS, reduces the power consumption from the grid for the periods where cost of electricity is high, and vice versa.

The operational cost of the system have been calculated, as stated in (1), and accounting for the differences in the stored energy in the ESS. The proposed EMS architecture reduces the operational cost by 28%.

VI. Conclusion

This paper contributes with a general decentralize EMS architecture for residential microgrids, with a local dc distribution system for the interconnection of the RESs, ESSs, and common building facilities. The hybrid ac/dc microgrid system, aims to reduce the distribution losses in order to ease the integration of local RESs and ESSs at consumption level. The proposed EMS uses open available weather forecast and real-time electricity pricing services, together with stochastic consumption models, to perform and optimization for the microgrid resources for the reduction of the operational costs. Furthermore, alternatively to similar EMS available in the literature, the EMS proposed in this work, only requires real-time information of the SoC, which does not suffer from sudden variations; therefore, significantly reducing the requirements of the communication system. The EMS architecture and an emulated ac/dc residential microgrid, have been implemented in a laboratory scale test-bed. The results show that the proposed EMS effectively reduces the operational cost of the residential microgrid, even with a non-perfect estimation of the local generation an consumption profiles.

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