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Published in:
Proceedings of the 2018 IEEE International Energy Conference, ENERGYCON 2018

DOI (link to publication from Publisher):
10.1109/ENERGYCON.2018.8398788

Publication date:
2018

Document Version
Accepted author manuscript, peer reviewed version

Real-time optimal scheduling for prosumers resilient to regulatory changes

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***Abstract*— The last decade marked an exponential increase in photovoltaic (PV) systems installed on the rooftop of domestic residences within Europe. This situation was basically favored by generous financial schemes such as Feed-in-Tariff and the market of green certificates. However, such governmental incentives drastically reduced, or they were already replaced with net-metering schemes which favor different scenarios, like those based on increase of self-consumption and decrease of grid-back injections. This unstable regulatory environment puts both new and old owners of PV systems under a regulatory financial risk. Recently, a regulatory resilient architecture, called UniRCon, was proposed, to overcome both financial and technical regulation uncertainties, where local battery energy storage system plays a key role. Here we propose a real-time energy management tool that could be used for the daily operation of such UniRCon architectures. The methodology is based on a mixed-integer linear programming energy management tool that considers possible arbitrage benefits due to price difference in the energy purchased from the grid, while explicitly considering the efficiency of the power electronic interfaces (converters) according to the operation point. We prove our approach using a lab-scale experimental setup of a DC residential microgrid. The results are analyzed under realistic operation scenarios derived from one-year load and PV power output measurements.**

Keywords*— *battery storage system; DCmicrogris; energy management system; mixed integer linear programming, resilient prosumer

I. INTRODUCTION

The widely adopted financial support for promoting local generation of renewable-based electricity, especially photovoltaic systems (PV) at domestic prosumers was Feed-In-Tariff (FiT) scheme. However, this scheme is already, or it will be soon abolished. The FiT rates (per kWh produced from PVs acting alone) reduced drastically, up to tens of times less than the prices offered at the beginning of applying such schemes. Currently, most of the countries in Europe plan to replace FiT with Net-Metering (NM) schemes [1], which are favorable to a different scenario: increase of self-consumption and decrease of grid back injection of the PV power production. There is, however, heterogeneity in the way NM is implemented and, furthermore, there is no actual provision of guarantees for how long this new scheme will last. Thus, a new investor in PV installations (either the energy user itself or a third party looking for a profit) faces high uncertainties regarding the internal return of investment streams. Besides the financial uncertainty of cash flows for the investment, technical regulations, the so-called Grid Codes [2], tend to be more and more restrictive, leading to often situations of PV curtailment [3], [4].

Microgrids, when integrated to the main grid, have embedded resiliency features, while intrinsically reducing energy transmission losses when most of the local power generation is locally consumed by microgrid installations [5]–[7]. In residential and office buildings, DC native or compatible loads are expanding their presence compared with the situation 20 years ago or more [8]. Thus, DC distribution systems for such microgrids inherently reduces losses in the electricity transfer because both RES generation side and load side are dominated by DC-based elements [9]–[11].

Storage technology is recognized recently with a high potential to be deployed at distribution level and by the energy end-users [12]. It also presents high value in case of disasters or other disruptive events [13]. Even though battery storage technology has a high potential to unlock several economic and technical barriers for low voltage prosumers, there is no homogeneity in terms of regulation in treating battery storage systems in hybrid configurations with PVs. National regulations consider it in a traditional way, either as load (in charging mode) or generator (in discharging mode). This requires from the storage systems to fulfil all demanding conditions for grid connection, reflected in the network codes [2], thus making the solutions more complex and expensive.

In [14] it was shown that efficiency in a DC microgrid could be improved by using an energy management system (EMS) that aims at reducing the conversion stages in power converters. However, similar to [15], the solution involves a coordinated power flow control and it needs a reliable communication network for collecting measurements in real time from the generators and the loads. Decentralized control schemes for the low-level power flow control were proposed in [16] but without an optimization strategy for the upper layer, the EMS. In [17] a real-time EMS for a hybrid AC/DC residential microgrid was proposed, making use of available forecasting weather data for predicting RES generation and using a simulator to estimate the consumption time-series. Within this architecture, however, only the battery energy storage system (BESS) was in charge for regulating the voltage level on the DC-link side where all RES and BESS are directly connected.

Recently, a novel architecture was proposed to enhance the resiliency of the prosumers against changing regulatory environment [18], [19]. In [20] it was proposed a methodology for calculating the capacity of the BESS for this architecture.

Note that the BESS plays an important role of migrating the prosumer back into "consumer-only" as seen by the utility. This architecture (as it is shown in Figure 1), labeled as "UniRCon", is in fact a building-level microgrid and it presents several technical and economic advantages:
(a) almost risk-free analysis on the internal rate of investment;
(b) increased self-consumption rate of the PV local generation, close to unity factor;
(c) increased resilience of the microgrid (MG) which is the network owned by the prosumer, in case of grid outages (smooth transition to islanding mode of operation);
(d) easy scaling-up potential at community level, while keeping a "plug-and-play" expansion plan.

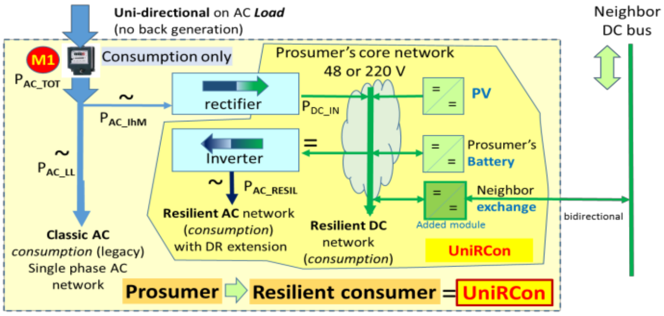

Figure 1: UniRCon Architecture **[18]**

This work is an expansion of [18], by proposing an actual EMS for the UniRCon Architecture making use of available historical information on both PV power produced locally and the energy demand of the microgrid in the past year. We rely our analysis on two case studies: (a) when the BESS is used to compensate the forecasting mismatches and thus keeping the DC bus voltage within the stability limits; and (b) the case when the grid is used to achieve the DC bus power balance. Note that in the latter case, we may allow back-generation into the main grid with no-payment or, in the case of penalty measures from the grid, we might accept short periods of RES self-curtailment. Thus, for the two cases, the BESS performs either the voltage stability of the DC bus where it is connected (case (a)) or it may perform a temporal arbitrage in an electricity market by charging with energy purchased at a low price, and discharging this stored energy when it can be sold at a higher price (case (b)). The profitability of this form of arbitrage depends not only on the price difference but also on the cost of the battery cycle aging caused by these charge/discharge cycles. The rest of the paper is structured as follows: Section II presents the general architecture of the proposed real-time EMS system as a three layer implementation for the operation of the UniRCon regulatory resilient architecture for prosumers; Section III mathematically describes the optimization model used at the second layer that provides the optimal setpoints for the physical layer of the system; Section IV describes the real-test bed system and the experimental setup and also analysis the results, while Section V concludes the work and gives future directions of research. The main contributions of the proposed work could be summarized as follows: (1) proposition of an architecture and EMS with two operation modes that could be interchanged at any given time with BESS used as voltage regulator or with the grid used as voltage regulator for the microgrid; (2) the EMS is based on a long-term strategy of the prosumer that ensures a safe investment even during regulatory changes, a feature not yet explored in the literature; (3) the proposed optimization model is an adaptive-real time strategy that takes into account the deviations from the forecasted values (generation and load) when re-evaluating the scheduling for the next time-horizon.

II. Energy Management System

A. *UniRCon Architecture as a DC Microgrid*

The motivation for the UniRCon Architecture and its EMS is given by the following business-as-usual scenario. Let's consider a roof-mounted PV installation (1 kW peak power) which can produce, with variation due to latitude and season, up to 4 kWh/day during summer time, and only 1 kWh/day during the winter period. This summarizes for a 10 kW installation (e.g. a typical Romanian residential PV installation 5 years ago) up to 40 kWh energy during a summer day, significantly higher than the average daily energy consumption of about 20 kWh. In this scenario, there is, by design, an excess of electricity produced locally on a major part of the year. This excess energy, if injected into the network, might lead to curtailment orders or penalties (in case of voltage limits and grid capacity violation, or even in case of stability constraints). This scenario also includes the case when subsidies for RES and priority on renewables dispatch are cancelled. Moreover, the scenario considers an increase of self-consumption, which becomes a viable approach enforced by the situation of reaching or approaching grid parity price in many European countries (e.g. already reached in countries like Cyprus and Greece), thus collecting FiT or Green Certificates being less and less profitable. Therefore, sizing the generation units becomes a techno-economic problem since the profitability and internal rate of return are decisive for choosing a solution.

In [18] it was analyzed the scenario of a complete self-consumption, when no locally generated electricity is injected back into the network. The proposed architecture (Figure 1), had as primary design objective to achieve an optimal self-consumption while avoiding curtailment, even during unfavourable regulatory situations like, for example, total lack of incentives for RES-based generation. In other words, the prosumer behaves as a pure consumer on the LV network side.

The UniRCon solution brings advantages to several energy actors, such as: Distribution System Operators (DSOs) and indirectly to the Transmission System Operators (TSOs) and, to a large extent, to the prosumer. DSOs and TSOs benefit from keeping the legacy power structure design (e.g. unidirectional power flow towards consumer), by not perceiving any disruptive operational changes beyond decreased load profile due to RES generation consumed locally, while on the prosumer side foreseen advantages are:

- resilience against network outages, due to the internal busbar which allows short to medium time operation;
- stability and predictability of the benefits brought by the RES and storage investment (resilience to regulatory changes);
- increased self-consumption and arbitrage opportunities brought by the storage system;
- higher efficiency brought twofold: consuming/storing the locally produced energy and by using the DC distribution design (both PV and storage are naturally functioning in DC and even many of today AC loads are also directly pluggable in appropriate DC local grids) [21], [22].

- lower costs of grid-connection if consumers have the historical right to access electrical energy.

B. *Energy Management System for the UniRCon architecture*

The UniRCon architecture tried to solve the following design challenge: given the current regulatory changing environment with respect to RES incentives what options an investor or owner of a small PV/wind system to keep his/her investment future proof? In the following, the design and proof of concept of the UniRCon is complemented with a proper EMS that gives the prosumers the opportunity to alternate two operational modes: (1) using the grid or (2) using the storage unit as energy exchange controller (and bus voltage regulator).

A three layer functional approach is used to formulate the optimization problem: (1) input and preprocessing data layer; (2) the scheduling layer (actual optimization model for the EMS), and (3) the physical layer, as they are illustrated in Figure 2.

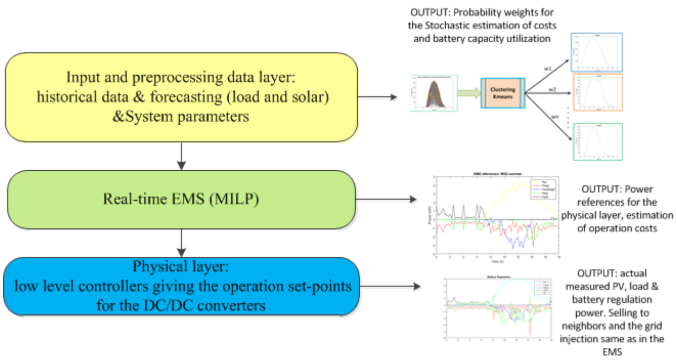

Figure 2: Structure of the real-time EMS for UniRCon prosumers

(1) *Input and preprocessing data layer:* consists of preprocessing of historical data collection for one year into three clusters for PV data and six clusters or data profiles for load consumption, respectively. They were determined applying a k-mean clustering method. The output are representative centroids (cluster groups) that will be used for calculating the expectation of the operation cost for the specific day in the off-line & real-time, implementation of the EMS, respectively. Operational conditions and load prediction data base are delivered from this layer to the scheduling layer.

(2) *Scheduling layer*: consists of the real-time EMS. It applies an adaptive mixed integer linear programming algorithm A-MILP. The optimization is performed to obtain the BESS scheduling profiles and/or grid power requirements for the next 24 hours, by combining the operating conditions and load prediction data with the battery characteristics & scheduling constraints (initial SoC, maximum/minimum allowed charging/discharging power, maximum/minimum allowed charge/discharge from the rated battery capacity, efficiency of power electronics converter & efficiency of charging/ discharging BESS, respectively). The scheduling layer transfers the optimized setpoints to the physical layer.

(3) *Physical layer*: Based on the scheduling result from the scheduling layer, the power conversion system (PCS) performs practical BESS charging and discharging, set the commands for power/energy exchange with neighboring similar microgrids, as well as the optimal estimated set-points for the power to be taken from the grid.

III. Optimization Models and Input Data of the EMS

A. *K-mean clustering unsupervised learning*

Within the preprocessing data layer, k-mean unsupervised clustering algorithm is applied to real data (power and energy measurements) of one year. The pseudo-code of the k-mean algorithm is given in Table 1. The real data is from a residential building in Cyprus with a PV installed power of 2kW. Therefore, the data was scaled such that to reflect the characteristics of a microgrid that would correspond to the design characteristics of a UniRCon architecture [18] (e.g. 4kW installed PV capacity for a maximum allowed loading of 5kW and a BESS of 7.5kWh capacity with a maximum charging power rating of 5kW and with 3kW discharging). The PV power production time series were available in recordings of averages over 10 minutes intervals. Thus, they were rescaled to 15 minutes intervals to be aligned with the load data recordings for the same year. The PV profiles were rearranged into a 144x365 matrix (columns store the daily PV power production) and fed as input to the k-mean algorithm.

The output of the k-mean algorithm gives the statistical relevance of the generation data: the probability weights of each centroid (cluster's characteristic PV daily profile). In other words, it indicates how many days per year correspond to the specific centroid. The number of clusters, *k,* is a pre-defined parameter for the k-mean algorithm. Through trial and error and applying a distance matrix it resulted that the optimal choice was *k*=3. The resulted centroids (characteristic daily profiles) reflect the profiles dominant for sunny days (mainly summer), partially cloudy days (spring and autumn) and cloudy days (especially in winter time), respectively. The output of the k-mean algorithm is then used to forecast the generation and load profiles used in the second layer of the EMS.

TABLE I. K-MEAN CLUSTERING ALGORITHM

Input:

$\boldsymbol{D}=\{\boldsymbol{x_1},\boldsymbol{x_2},..,\boldsymbol{x_n}\} \in \mathbb{R}^d$ - dataset matrix (PV/load time series)

$\boldsymbol{k}$ number of centroids/clusters (predefined parameter)

Output:

$\boldsymbol{\mu_1},\boldsymbol{\mu_2},..,\boldsymbol{\mu_k}; \forall\ \boldsymbol{\mu_k}=\{\mu_1^k,\mu_2^k,..,\mu_d^k\}$ vectors storing the Clustering groups or Centroids

Method:

1. *Initialize* cluster centroids $\boldsymbol{\mu_1},\boldsymbol{\mu_2},..,\boldsymbol{\mu_k} \in \mathbb{R}^d$ randomly as distinct selections of $\boldsymbol{x_1},\boldsymbol{x_2},..,\boldsymbol{x_n}$.
2. *Repeat until convergence:*

   {2.1. for each data vector $\boldsymbol{x_n}$ assign cluster membership:

   $\gamma_{ij}=\begin{cases}1, if\ j=argmin_j\|\boldsymbol{x_j}-\boldsymbol{\mu_j}\| \\ 0, otherwise\end{cases}$, where $\gamma \in \{0,1\}^{kxn}$ is the indicator matrix with $\gamma_{ij} \in \{0,1\}$, 1 if input $\boldsymbol{x_i}$ belongs to cluster j

   2.2. fix γ and update each $\boldsymbol{\mu_i}$ (to the average of all points assigned to cluster j): $n_j=\Sigma_{i=1..n}^{n}\gamma_{ij}$; $\mu_j=\frac{1}{n_j}\cdot\Sigma_{i=1..n}^{n}\gamma_{ij}\cdot\boldsymbol{x_i}$ }
3. *Return:* $\boldsymbol{\mu_1},\boldsymbol{\mu_2},..,\boldsymbol{\mu_k}$ and their corresponding $\omega_1,\omega_2,..,\omega_k$ (probabilistic weights or the percentages from all data corresponding to each centroid $\boldsymbol{\mu_j}$).

B. *A-MILP algorithm for the EMS of the UniRCon-MG*

The energy management system for the UniRCon microgrid architecture is formulated as an adaptive mixed integer linear programming economic scheduler (similar in some sense with a stochastic rolling-planning formulation [23]). Thus, at every time step in the scheduling process (every 15 minutes in a time horizon of 12 hours), the microgrid's EMS takes high level decisions about:

- when and how much energy should be purchased (from neighboring MGs or from the main utility grid) or to be sold to the neighboring MGs such that to meet its own load demand at a minimum cost and avoid as much as possible self-curtailment due to overproduction form RES (Economic Dispatch decision);
- when and how much energy is to be stored to/discharged from/ the BESS such that to consider arbitrage opportunities from grid and/or neighbors, prediction of self-RES power production and the overall cost of the system operation to be kept at minimum (commitment and dispatch decisions).

Details on the notations and description of parameters, input data forecast/estimations and the decision variables of the optimization problem are given in Table II.

TABLE II. DESCRIPTION OF PARAMETERS AND DECISION VARIABLES

Symbol	***Description***
E_{rated}^{bat}	Rated capacity of the EBSS (kWh)
E_{min}^{bat} / E_{max}^{bat}	Minimum/maximum operational capacity of the EBSS (% of the rated values)
P_{ch}^{bat} / P_{dch}^{bat}	Power ratings for changing/discharging (kW)
η_{ch}^{bat} / η_{dch}^{bat}/ η^{bat}	Battery efficiency at charging/discharging (0.95pu)
SoC_0	Initial state of charge of the EBSS (% from the rated capacity)
$\eta_{DC-DC}(x)$	Efficiency curve (4-point piecewise linear function) for the DC/DC converters, where x denotes here the operating power level (import or export)
$\eta_{AC-DC}(x)$	Efficiency curve (4-point piecewise linear function) for the AC/DC grid-side inverter
$c^{grid}(t)$	Time series for the time of Use tariffs of the energy purchased from the grid (€/kWh)
P_{max}^{grid}	Maximum power limit for the connection with the grid (kW)
P_{max}^{neigh}	Maximum power limit for the power exchange with the neighbors (kW)
P_{rated}^{PV}	Power rating of the PV system (kW)
P_{max}^{Load}	Maximum power rating for the cumulated loads connected to the DC bus (kW)
$\hat{P}_{load}(t)$	Estimated load demand for the next 24 hours with a time resolution of 15 minutes (kW)
$\hat{P}_{PV}(t)$	Estimated PV power production for the next 24 hours with a time resolution of 15 minutes (kW)
$\hat{c}^{sell}(t)$ / $\hat{c}^{buy}(t)$	Price for the energy to be sold/purchased to/from the neighbors for the next decision time horizon (€/kWh)
$P^{neigh}(t)$	Power exchange with the neighbors in each time interval (kW)
$P^{grid}(t)$	Power purchased from the grid in each time interval (kW)
$P^{bat}(t)$ / $P_{ch}^{bat}(t)$ / $P_{dch}^{bat}(t)$	Power/Energy exchange with the BESS at each time interval (sign convention being "-"for charging, i.e. $P^{bat}(t) = -P_{ch}^{bat}(t)$ and "+" for discharging, i.e. $P^{bat}(t) = P_{dch}^{bat}(t)$) (kW)
t δt	Index for the time step in the optimization process, including the input data time series; Time interval between two consecutive steps (hours)
T	Time horizon for the decision making (hours)
SoC(t)	Estimated SoC of the battery in each time interval (% from the nominal capacity of the BESS)

Note that within the decision-making process the forecasted information coming from layer one is taken as deterministic. Thus, the output of the scheduler is also a deterministic vector of power references or setpoints for the electronic interfaces controlling the power exchange between grid and the UniRCon-MG, between neighboring MGs and the UniRCon-MG, and the electronic interface controlling the BESS of the UniRCon-MG, respectively. The scheduler is called every 15 minutes to provide the updates for the next 24 hours, and it updates its previous forecasts with real-time measurements collected within the last 15 minutes interval. Thus, if deviations from the previous forecast were observed, a new forecast time-series is generated for the next scheduling, without going back to layer one. The updated procedure will be explained and exemplified later, within the formulation of the optimization problem.

The optimization problem to be solved within the second layer of the proposed EMS is mathematically formulated below.

Objective function:

$$\min OC = \sum_{t=0}^{T}\{c^{grid}(t) * P^{grid}(t) * \eta_{AC-DC}(P^{grid}(t)) - c^{sell}(t) * P^{neigh}(t) * \eta_{DC-DC}\left(P^{neigh}(t)\right)\} \quad (1)$$

Subject to (constraints),

$$\hat{P}^{PV}(t) + P^{grid}(t) * \eta_{AC-DC}(t) + P^{bat}(t) - P^{neigh}(t) * \eta_{DC-DC}(t) - \hat{P}^{load}(t) = 0, \forall t \in 0..T \quad (2)$$

$$0 \le P^{grid}(t) \le P_{max}^{grid}, \forall t \in 0..T \quad (3)$$

$$-P_{max}^{neigh} \le P^{neigh}(t) \le P_{max}^{neigh}, \forall t \in 0..T \quad (4)$$

$$-P_{ch}^{bat} \le P^{bat}(t) \le P_{dch}^{bat}, \forall t \in 0..T \quad (5)$$

$$SoC(t) = SoC(t-1) + \left[P_{ch}^{bat}(t) * \eta_{ch}^{bat} - \frac{P_{dch}^{bat}(t)}{\eta_{dch}^{bat}}\right] \cdot \frac{\delta t}{E_{rated}^{bat}} \quad (6)$$

where, (2) is the power balance of the system to be respected at all times; it also includes the conversion losses in the power electronic converters as functions of the power operating points; (3) and (4) denote the power supply limits from the grid (note that there is a restriction that there is no back-flow to the grid) and to/from the neighboring MGs; and (5) and (6) are the operating limits of the BESS. Note that for this implementation the price for buying/ importing energy from the neighbors is set the same as the grid, and thus it appears as ignored in the objective function (1). The reason was a lack of reliable information with respect to available power from the neighboring MGs. An extension of this work is planned to include also a negotiation phase between neighbors and a settlement time for the market must be decided before the EMS of each MG starts.

The above problem (1 -6) is then solved using a MILP solver from Gurobi called directly from Matlab (TM Mathworks). The output of the optimization are the setpoints of operation for the energy transfer (to be imported) from the grid, exported to the neighbors and the charging and discharging decisions (indirectly evident form the sign and values of the variable $P^{bat}(t)$) for the BESS. These results are then transmitted to the third layer where the physical control commands of the power electronic interfaces take place. Also, real time measurements are compared with the estimated $\hat{P}^{PV}$ and $\hat{P}^{load}$ and sent back to the second layer for adjustments/adaptive measures in the next time-rolling call for the EMS. Note that the EMS is called every 15 minutes and gives directions for set-points for the next 24hours. These adjustments occur only for the next 2 points, while the rest up to 96 are kept from the rolling forecasting coming every 15 minutes. Thus, the changes are as follows:

$$\hat{P}^{PV}(t+1) = (P^{PV}(t) + \hat{P}^{PV}(t+1)) \cdot 0.5 + \hat{P}^{PV}(t+1) \cdot 0.3 + \hat{P}^{PV}(t+2) \cdot 0.2 \quad (7)$$

$$\hat{P}^{load}(t+1) = (P^{load}(t) + \hat{P}^{load}(t+1)) \cdot 0.5 + \hat{P}^{load}(t+1) \cdot 0.3 + \hat{P}^{load}(t+2) \cdot 0.2 \quad (8)$$

where, $P^{PV}(t)$, and $P^{load}(t)$ are the averaged measured values for actual production form the PV system (the last 10 values measured every minute in the 10 min interval before the next EMS call), and the actual aggregated load consumption of the MG, respectively.

IV. Experimental Setup & Results

The experimental setup used to validate the proposed three layers EMS system is presented in Figure 3. It consists of four three phase inverters (rated power 2.2 kW) connected to the same DC bus (these emulate (i) the PV system, (ii) the BESS, (iii) the aggregated load and (iv) one connection with the neighboring MGs) and one controllable source emulating the grid side converter. Due to hardware limitations all real power ratings (and measurements) were scaled within the hardware limits.

The studied test system is a UniRCon-microgrid with the characteristics described in the previous section. The system has been tested for the three clustering groups generated by the input layer (high PV power production, medium and low PV power production). The EMS layer provided the setpoints for the real-time application, where the actual PV power production and load demand were randomly selected from the historical data in the cluster group (uniform integer distribution). We carried out two sets of experiments in the physical layer, such that either the BESS or the grid was left to regulate the voltage of the DC bus.

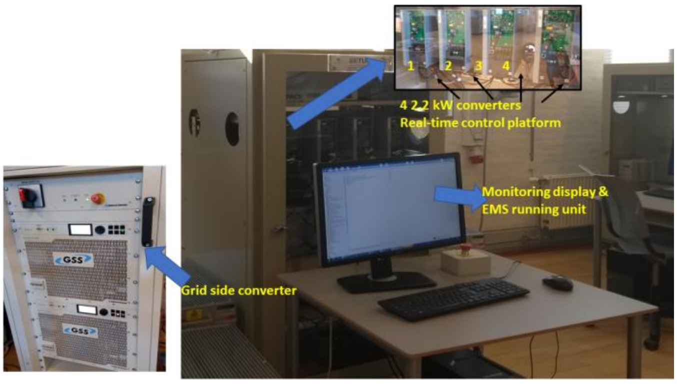

Figure 3: Experimental setup

The system has been tested for the three clustering groups generated by the input layer (high PV power production, medium and low PV power production). An off-line EMS provided the setpoints for the real-time application, where the actual PV power production and load demand were randomly generated from the historical data in the cluster group. We carried out two sets of experiments in the physical layer, such that either the BESS was left to regulate the voltage at the DC bus or the grid took this responsibility.

Figure 4 presets the initial EMS output as reference points to be sent to the physical layer in the first 15 minutes interval of the rolling planning horizon of 24 hours. In Figure 5 it is shown a comparison between the first estimates and the updated information (every 15 minutes using the real measurement data), and adaptive adjustments in the forecasts of PV and load time series is carried out within the real-time EMS call. Note that the measurements were transmitted from the physical layer to the EMS layer before the next decision making. Furthermore, for clarity and visual comparison, real power production form PV and the actual load demand is plotted on the same figure.

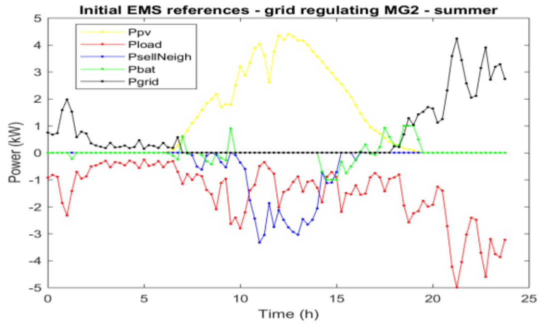

Figure 4: Off-line EMS references based on PV and load predictions

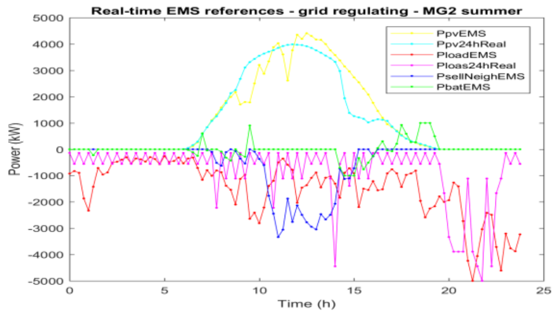

Figure 5: Adaptive Real-time EMS references

Figure 6 shows the actual real-time actions taking place at the physical layer, where the grid is regulating the DC bus voltage (thus, it does not follow the EMS references, but it adjusts its power output according to the real-time circumstances). It can be noted that in this case the grid accepts back-injection, which is the opportunistic case for the UniRCon architecture, like what we have today in most of the prosumer cases that benefit of NetMetering schemes. Note that in the EMS, for this implementation, a zero price was valued for the energy given back to the grid.

Figure 7 shows the real-time data for the case when the BESS plays the role of the voltage regulator for the DC bus. By comparing Figure 6 and Figure 7 it can be noted that, for this specific operation case, it is more advantageous to operate the BESS as bus regulator, because a larger self-produced energy from PV could be used in real time for satisfying the load demand.

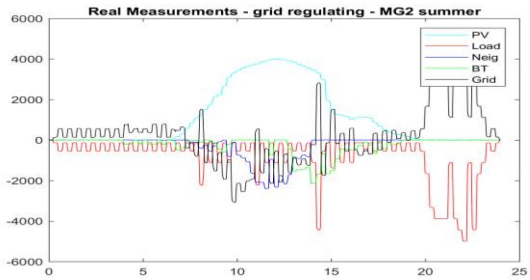

Figure 6: Physical layer real-time operation – grid regulating

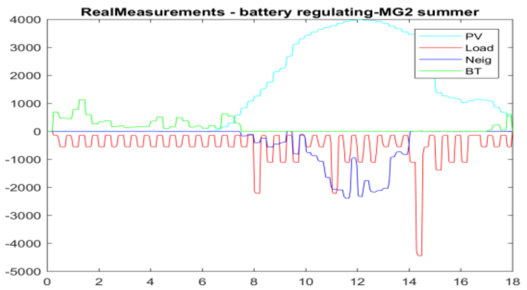

Figure 7:Physical layer real-time operation – BESS regulating

V. Conclusions

This work proposed and tested a methodology for achieving real-time three-layers EMS of a MG behaving as a UniRCon prosumer. The methodology used an adaptive-MILP approach, where interchange information from the lower layers was used for updating in real-time the rolling planning call of the EMS within the optimization time-horizon. Two use cases were evaluated: one when the legacy grid takes the role of voltage regulator and the other one when the BESS assumes this role. Compared with previous works, we have shown how the actual cost changes due to mismatches between forecasting data and the actual realizations, even in the case of adaptations to real time information coming from the field. Due to paper format limitation we only show the results for a summer day (high PV power production). In this work we have considered the case where the BESS can perform a single full cycle of charge/discharge per day. However, further investigations are needed though on how the utilization of the BESS as voltage regulator might influence its life-time expectancy. Another research direction would be a game theoretic approach for evaluating the benefits of a shared BESS at community level, instead of individual MG could give .

Acknowledgment

This work has received funding from the European Union's Horizon 2020 R&I Programme under the Marie Sklodowska-Curie grant agreement No 708844 and H2020 R&I Programme-Storage4Grid Project grant agreement No 731155.

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