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Adaptive distributed EMS for small clusters of resilient LVDC microgrids

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***Abstract*—Microgrids, storage technologies and renewables are cited as viable options to address resilience challenges faced by the power grids due to natural or man-made disasters. They are also cited as enablers for the recent research interest in low voltage DC microgrids. In this work, an architecture of a resilient small community of microgrids is presented. Furthermore, a distributed and adaptive energy management system is proposed for the tertiary power flow control of a small cluster of DC microgrids, that operate in a cooperative manner to achieve a high level of independence and resilience. To do this, each microgrid accepts to share its storage and generation resources either for economic reasons or for security in case of emergency situations. The proposed EMS replaces the conventional tertiary control that adjusts the power set points of the microgrids' cluster with a cooperative-based power exchange regulator. The model is based on a general-consensus problem and by making use of modern stochastic optimization techniques, such as stochastic-adaptive mixed integer programming. On the physical layer, where the actual commands are sent from the EMS layer to each power flow converter, an exchange of data occurs only with its neighboring converters (adjacent nodes). This is modeled as a sparse communication graph spanned across the microgrids' cluster.**

Keywords— DC microgrids; energy management system; general consensus problem; mixed integer linear programming; stochastic and adaptive programming;

I. INTRODUCTION

The need for resilient power grid architectures is becoming more stringent in recent years when natural or provoked disasters echoes larger economic and social impact than ever before [1], [2]. Microgrids, storage technologies, power electronics and renewables are cited as viable options to address resilience challenges faced by the power grids due to natural or man-made disasters [3]. This combination of technologies also forms the main components of major proposed architectures for low voltage (LV) direct current (DC) microgrids (MGs) [4]–[6].

Despite convergent opinions on the benefits of renewables (especially wind power and solar photovoltaics installed in low voltage distribution systems) to combat climate change, to enhance power systems availability or power loss reduction in distribution power networks there still are several economic, technical and regulatory barriers that hinder their further expansion. Moreover, for renewables and storage to play an important role in improving resilience of power grids (e.g. extreme events such as natural disasters), connections based only on grid-tied inverters that comply with IEEE Standard 1547 (that requires this type of PV inverter to get turned off during power outages) or with newly issued grid codes in Europe shall be replaced with more flexible and independent options [1]. To overcome some of the above mentioned barriers we have recently proposed a UniRCon architecture as a viable economic and technical alternative to the classical PV-grid connected prosumers [7], [8]. The behavior of UniRCon is similar in some sense with concepts like "no-back generation" or "consumer only behavior" from the distribution system operator (DSO) point of view.

Resilience of power systems, including microgrids is a relatively recent research concept, that still lacks a general agreement on definition, characteristics and main features as well as a general framework to quantify it [1], [12]. Other authors treat resilience in the context of cyber-physical system concept [9]–[11], where a large portion of the analysis is related to communication layer and interdependencies between the physical layer (where the control of the electrical network takes place) and the information or cyber layer (where the Denial of Service attacks might take place).

A key element in the development of microgrids and subsequently the DCMGs is the development and widespread adoption of power electronic converters (PEC) for the interconnection of distributed energy resources (DER) - most often renewables (e.g. photovoltaics - PV), energy storage systems and loads, or with the main grid [12]. Besides technology enablers, a well-known approach for operating DCMGs is based on hierarchical control architectures that consists of three levels: the primary control which ensures the stability of the MG and is directly provided by PECs, the secondary control which requires coordination between multiple PECs in order to maintain the voltage levels within the operation limits, and the tertiary control which is in charge with the power flow optimization or the energy management within the MG [13].

Tertiary control methods were studied recently for DCMGs in the context of optimal management of the power flow, economic dispatch or power loss reduction [14]–[17]. This

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tertiary control could be characterized as centralized (like what is implemented in large power systems at transmission level), distributed or decentralized. The first two need communication at a larger or lower extent, while the latest was shown to be suboptimal [14], [15]. For the energy management system as a distributed tertiary control model the approaches were limited to a quadratic cost function based either on a classical fuel cost function for thermal distributed energy resources [14] or to approximations for power flow losses in the DC distribution system [15], [16], [18]. To be noted that all the above methods could not be directly applied to the proposed architecture for UniRCon compatible DCMGs cluster.

The rest of the paper is organized as follows. Section II introduces an extension model for the resilient UniRCon architecture with emphasis on possible business use-cases and technical/functional features to sustain the resilience property. Section III presents the distributed energy management system for the proposed architecture as general consensus problem (GCP). Section IV describes the test system and discusses the viability of the framework through a simulation implemented in Simulink. Section V concludes the paper.

II. Description of DC UniRCon – Resilient by Design Microgrid

The first proposed UniRCon architecture for connecting any prosumer to the main grid was based on a classical AC connection with the main feature to be able to disconnect and continue to function independently when there is a disturbance in the grid [8]. The main technical, economic advantages of the UniRCon architecture compared to similar approaches are summarized below:

(a) a risk-free return of investment (RoI) over the lifetime of the system;

(b) increased self-consumption of the locally produced energy (RES-based), close to unity factor;

(c) increased resilience of the microgrid (MG) which is the network owned by the prosumer: in case of grid outages it ensures a smooth transition to islanding mode of operation; the islanding operation is sustained by the local generation and storage unit.

(d) the design is based on a "plug-and-play" expansion plan at community or even distribution grid level.

In this work we expand the UniRCon concept to a cluster of direct current low voltage microgrids (DC LVMGs), connected in such a way to preserve a well-established and cited definition for MGs (system operating as a single entity from the grid point of view and having a single point of connection (PCC) with the external environment) [19], [20] which was recently proposed as a standard [21]. We resume our interest to a direct current (DC) architecture for this type of MGs due to several technical and economic reasons, such as: easy decoupling and no need for synchronization, energy sources and storage in the proposed architecture are DC in nature, while most of the critical loads to be served are also native or DC-compatible. The proposed extended UniRCon architecture makes use of an energy router (ER) that forms the "single connection point" of each individual MG with the external environment, as it can be seen in Fig. 1. The structure of the newly formed system includes local electrical battery energy storage system (BESS) in conjunction with PV-local generation, that is recognized as a viable buffer to smooth out the propagation of disruptions from the main grid or neighboring microgrids into the microgrid of interest. The ER also insures that any internal disturbance within the microgrid of interest does not propagate to the external environment (the grid or neighboring MGs). Furthermore, the BESS helps in reducing or even eliminating dependencies on external infrastructures (e.g. a MG with a diesel generator instead of BESS has a diesel fuel tank as storage; this type of storage creates a dependency on transportation infrastructure for example).

Note that when we analyze the properties of resilience for the proposed architecture, we follow the definition and features described in [1]. These features are: (1) to withstand in unpredictable events (i.e., to sustain operation even during hazards like natural disasters when the connection with the main grid is totally lost); (2) speed of recovery (how long it takes to recover with respect to a given level of disruption); (3) preparation/planning capacity (the ability to implement measures that reduce future effects on power grids' performance in similar or unpredicted hazards, i.e. "lessons learnt"); (4) adaptation capability (the ability to react to hazardous conditions through business management decisions). The last feature emphasizes the role of the energy management system in such circumstances. Thus, a decentralized, coordinated decision would be needed to sustain this last feature.

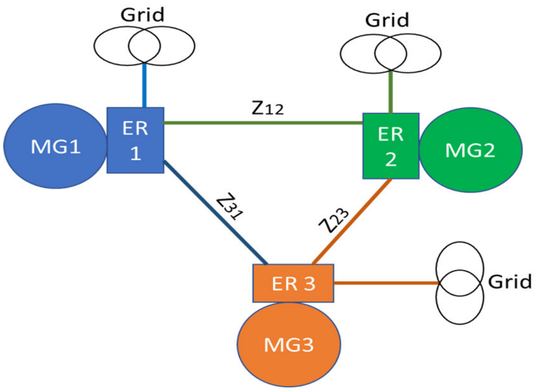


Figure 1:LVDC-MGs' cluster - UniRCon compatible. ER is acronym for energy router, MG is acronym for microgrid. Grid denotes here the legacy (DSO operated) electricity network

Furthermore, the proposed architecture benefits of several other advantages in terms of controllability and resilience, such as: decoupling the need for synchronization (grace to the DC nature), smooth connection to the main grid with no need for planning or changes in the current state of the art architectures of the power distribution grid and its operation procedures. Besides ensuring continuation of own-load serving in islanding mode of operation, the interplay between BESS, PV/wind distributed generation and neighboring interconnections form the core of the proposed architecture as a viable option for increasing self-consumption of the locally produced energy in the normal mode of operation (interconnected). Thus, formation of resilient communities arranged as a cluster within a defined (usually, small) territory is also appealing due to the potential of buying and selling locally produced renewable energy (local energy market), while also reducing the risk of RES curtailment in weak distribution networks. This fact is favored by: (a) the smoothing effect of load aggregation; (b) reduced power losses in the local distribution grid to which prosumers are connected; and (c) potential of sharing energy locally.

Besides the features provided by the technical design and operation, a number of business use cases were also identified and studied recently by the authors [22] in order to sustain long term economic and sustainable benefits. Subsection II.A below summarizes their major characteristics.

A. Business use cases for the DC UniRCon Architecture

1) Storage as a service where one could further identify three sub-cases such as: (a) prosumer to prosumer contracts, (b) prosumer to grid and grid to prosumer contracts (e.g. energy trading contracts) and (c) prosumer to grid ancillary service (black-start grid capability).

In sub-case (a) it is assumed that at least one of the two contractual prosumers have a BESS, and it will allocate a share of it to absorb the surplus electricity from the other contractual party (neighboring prosumer), which otherwise would be curtailed by the DSO due to, for example, grid constraints reasons.

In sub-case (b) it is assumed that in the case of a consumption reduction request from the grid operator (e.g. due to network constraints) the prosumers connected to the legacy low-voltage network can use the local BESS in order to inject the locally generated electricity into its own LV network, thus being able to reduce the power requested from the upstream MV/LV transformer. This is a service for enhancing network capacity without investment on DSO side. In fact, it can be a stacked business case, combining peer-to-peer energy transaction and network capacity enhancement.

In sub-case (c) it is assumed that the prosumer, capable to deliver such black-start and grid-former service, is expected to be financially remunerated. Such a case could be a section of the grid with load matching the available electricity to be supplied from microgrid installations only.

2) Resilience by design service where the prosumers have a hybrid solution, i.e. including a DC bus to which all sensitive loads are directly connected. The business scenario is that the prosumer invests in own storage and in an energy router, and it is based on appropriate selection of the DC-loads and the overall loads' priority, while the prosumer is expected to be incentivized by the contract with the DSO in the connection agreement (based on maximum load).

3) Advanced cooperative resilience by design service for communities formed by clusters of prosumers, each deploying a hybrid solution (internal DC bus for all sensitive loads) and, in addition, a DC link for electricity exchange with the neighborhood.

B. Simplified Simulink test system and resilience use-cases

Besides the business use cases that could extend the economic benefits of each individual microgrid, the following use cases are defined to test the resilience features described in Section II. A major assumption for the resilient UniRCon architecture for communities of LV DCMGs is that the power coming from the grid is seen as a constant, known a-priori scheduled value for the evaluation time interval (steady state approach). This assumption is based on the DSO desire to reduce at minimum the costs associated with bi-directional power flow due to distributed renewable energy sources. In other words, a "load-only" behavior of each interconnected MG would satisfy this operation constraint. This translates for the local/community operation that ensures the balancing mechanism through the EMS like the case of a disconnected MG.

In order to test the resilience features described in Section II as they were proposed in [1], we propose the following use-cases to test these features:

1) *Use case 1*: a disturbance on the local power production from PVs or on the loads side allows the microgrid(s) to still work based on the grid former and grid balancer reactions (ER role), and meanwhile the power set points for the DSO remain unchanged ("non-undisturbed" DSO).

2) *Use case 2*: whenever a disturbance occurs on the DSO side, which may change the scheduled power to be provided by the DSO to the MG, the internal balancing mechanism of the MG is able to compensate by using the same mechanisms (battery/storage plus distributed low-level control). For this specific use case, we assume that there is a sudden decrease in the power provided by the grid (DSO) e.g. decrease of 25% from the requested/scheduled amount.

3) *Use case 3*: an extension of the use case 2 where there is a total loss of the scheduled power to be provided by the grid (DSO).

The proposed resilience use-case will be tested using the following simplified MG configuration (UniRCon compatible) which was implemented in Matlab/Simulink (Fig. 2). The characteristics of the Simulink model are summarized in Table 1. Note that they are identical with one of the three MGs to be interconnected within a small territorial cluster, as they will be defined in the following section, dedicated to the general consensus distributed EMS.

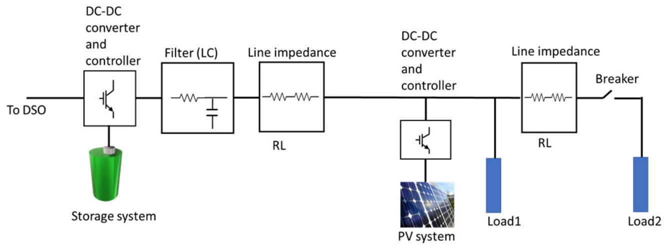


Figure 2: Simplified Simulink model for a UniRCon compatible MG

In Table I, *Cap* denotes the capacity of the BESS; *Pch* and *Pdch* are abbreviations for the charging and discharging power of the BESS respectively; while R, L and C are the conventional abbreviations for resistance, impedance and capacitance, respectively.

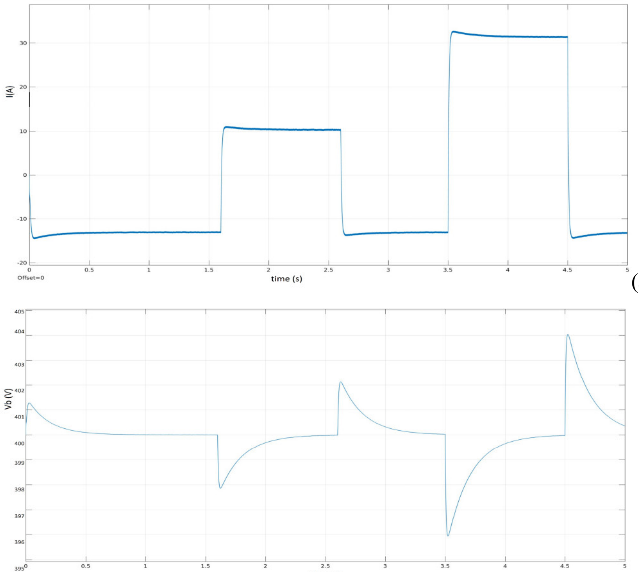
TABLE I. CHARACTERISTICS OF THE MICROGRID TEST SYSTEM IN SIMULINK

Storage	**Filter**	**Line impedance**	**PV system**	**Load1+Load2**
Cap=7.5 kWh *Pch/Pdch*=3 kW	L=0.5 mH C=10 µF	R=0.1 Ω L=50 µH	5 kW (peak)	5 kW (aggregated peak)

The connection of the simplified microgrid model with the external environment (e.g. the grid/DSO) is simulated using a combination of solid state transformer and DC/DC converter that plays the role of the energy router (e.g. SST/DC-DC converter).

C. *Resilience tests and evaluation*

The resilience tests consider a sequence of use-case 1 and use-case 3. Note that use-case 2 is less severe that use-case 3, therefore it is not shown here. Thus, the simulation scenario is: at the beginning (t=0) we have the normal, scheduled operation to supply only Load1; at time t=1.6 s, we connect Load2; then, at time t=2.6 s Load2 is disconnected (note that Load2 is 25% from the sum of Load1 and Load2); then, at time t=3.5 the scheduled power intake from the grid is disconnected; while at time t=4.5 s, the power infeed (from the grid) is restored to the scheduled value. The results of this simulated scenario are presented in Fig. 3. The battery current is shown at the output of the battery and input of the power converter that controls its operation modes.



(a)

(b)

Figure 3: BESS current (a) and voltage (b) waveforms

The following convention is used for the signs of the current signal: when the current is negative the battery is in charge mode, while when it is positive the battery is in discharge mode. The results show that the battery changes from the charge mode to discharge mode to maintain the required power balance within the microgrid. When the second perturbation takes place (i.e. the power to be provided by the grid is completely lost, due to an unscheduled event on the grid side) the battery ensures all the needed energy (and power) required by the microgrid, with minimum or no intervention on load reduction. The time of the transition of the current from one reference value to the other is practically limited by the inductance of the power converter. During that transition the capacitor is the component that must support the voltage. However, since the energy that is stored in the capacitor of the storage unit is smaller than the one required to keep constant the voltage on the DC bus, the latter will decrease.

III. EMS AS A GENERAL CONSENSUS FORMULATION

The problem is formulated using the framework of general-consensus problems, a concept that is imported from the fields of distributed computing and multi-agent systems. For a system to achieve reliability at the whole-system level in the presence of several faulty processes it requires the processes to agree on some data value that is needed during computation. This translates for our coordinated control and energy management at the MGs' cluster level to "agree" on a global variable (e.g. energy flow exchange in each node). To do so, a state observer (where the state of the system we are looking for is the power/energy flow in each point of common coupling with the neighboring MGs) is constructed using the distributed consensus algorithm that gives as output a global average value. Thus, the observer at MG *i* receives its neighbors' estimates (only from the adjacent MGs *j-s*). Then, the observer calculates its own estimate by averaging the neighbors' estimates and the local state measurement.

A. *General Consensus Problem*

In the setup of the problem, we consider a system managed by *N* distributed energy routers (ER) that play the role of independent *agents* from other similar approaches. It is assumed that each ER is able to perform computations and a data-exchange protocol in order to communicate with its neighbors. Thus, each ER measures/calculates its local variables x_i (e.g. the power of each internal node) and has a certain objective function $f_i(x_i)$ (e.g. to minimize the operation cost of the respective MG). In the general form consensus problem, the objective is to globally minimize the sum of all the local objective functions f_i.

$$minimize\ \Sigma_{i=1}^{N} f_i(x_i) \tag{1}$$

Subject to: $x_i - \widehat{z_\iota} = 0$

and other system specific constraints

For the rest of the implementation we follow closely the approach in [15], where an alternating direction of multipliers method (ADMM) is defined. However, note that we apply it to an economic dispatch type of formulation for the EMS instead of optimal power flow (OPF). Thus, we first form the augmented Lagrangian (L_p) of the problem as shown in (2) and then we apply the three-step iterative algorithm, as shown in Table II.

$$L_p(x,\mu,\rho) = \Sigma_{i=1}^{N} f_i(x_i) + \mu_i^T(x_i - \widehat{z_\iota}) + \frac{\rho}{2}\left\|x_i - \widehat{z_\iota}\right\|_2^2 \tag{2}$$

$$x_i^{k+1} = argmin_z(f_i(x_i) + \mu_i^{kT}(x_i - \widehat{z_\iota}) + \frac{\rho}{2}\left\|x_i - \widehat{z_\iota}^k\right\|_2^2)$$

$$z^{k+1} = argmin_{x_i}(\Sigma_{i=1}^{m}(-\mu_i^{kT}(\widehat{z_\iota}) + \frac{\rho}{2}\left\|x_i^{k+1} - \widehat{z_\iota}\right\|_2^2)$$

$$\mu_i^{k+1} = \mu_i^k + \rho(x_i^{k+1} - z^{k+1})$$

Where, x_i is the local decision variable for each ER, $\widehat{z_\iota}$ is the mapping of the global variable for consensus at each ER, μ is the Lagrange multiplier, ρ is the step size of the ADMM and k denotes the iteration process. We use the same value of the step size as it was proposed in [15].

TABLE II. ITERATIVE 3-STEP LAGRANGE AND ADMM

Step1: each ER minimizes its own objective function and obtains a new set of local variables x_i^{k+1} (completely decentralized step). **Step2:** the components of the global variable z^{k+1} are updated. For this step we need the communication between adjacent ER to be recalled. This step implies averaging all entries of $x_i^{k+1} + \frac{1}{\rho} * \mu_i^k$ that map to the same global index (adjacency nodes).

Step 3: the Lagrange multipliers μ_i are updated according to the difference between the local and global variables (completely decentralized step).

B. *Three-layers EMS for local variable calculations*

Fig. 4 presents the concept of a three-layer energy management system (EMS) that is performed by each individual MG (agent-based approach). The physical model assumes a small distance between neighboring microgrids, thus the proposed EMS ignores the transmission/distribution line impedances. The detail implementation and associated algorithms could be consulted in [23].

Note that within the second layer, we exploit the three-step general consensus algorithm presented in Table II. The ER is the power regulator that uses an observer that processes neighbors' data to estimate the average power exchange needed in each connection point of the LVDC microgrids' cluster.

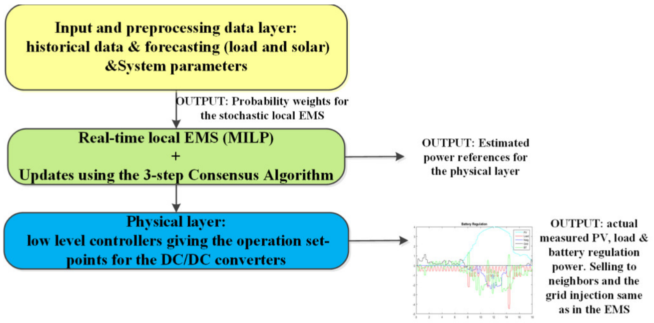


Figure 4: Three layers - individual EMS system

IV. CASE STUDY

The test system for applying the proposed decentralized general consensus EMS is the ring configuration of a small cluster of three MGs presented in Fig. 1. The characteristics of the test system are summarized in Table III.

We consider characteristic summer profiles of 24h, which are a-priori known for both the aggregated load and the aggregated local distributed generation (e.g. PV) power production. These profiles are the output of the first layer of the EMS, pre-processing of data, and they were described in detail in [23]. Note that these profiles were obtained using real measured data for one year with a 10 minutes resolution, from a residential location in Cyprus. The data was scaled out to fit the three MGs general characteristics and they were dissociated for three different days to avoid unrealistic overlaps (e.g. same temporal shape for all MGs, which is not desired).

TABLE III. CHARACTERISTICS OF THE CLUSTER MGS TEST SYSTEM

	MG1	**MG2**	**MG3**
Load	5 kW	3.5 kW	7 kW
PV	5 kW	2 kW	5 kW
Cap_{BESS}	7.5 kWh	2 kWh	10 kWh
$Pch/Pdch_{BESS}$	3 kW	1 kW	5 kW

Each individual MG first runs its local EMS, a scheduling based on mixed integer linear programming optimization as it was described and analyzed in detail in [23]. The output of this local EMS are the local variables of the associated ER (step 1 from the algorithm presented in Table II) of the MG. The vector of this local variable contains the local scheduling (initial intention) for the power references for each individual power electronic controlled sources, loads and BESS of the corresponding MG. An example of the output of this local EMS applied to MG1 is given in Fig. 5. Same for MG2 is presented in Fig 6. Note that the convention of signs is positive for the energy supplied and negative for the energy consumed. The following abbreviations are used in the legends of the results figures: *Ppv* represents the aggregated local power production form photovoltaics; *Pload* is the aggregated load demand, *PsellNeigh* is the available power/energy to be traded with the neighboring MGs; *PbuyNeigh* is the power accepted to be bought from neighboring MGs; *Pbat* is the charging/discharging power of the local BESS; and *Pgrid* is the power scheduled to be bought from the grid (DSO).

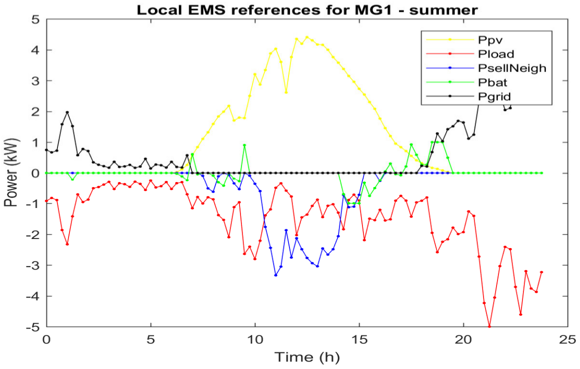


Figure 5: Local EMS references for a single MG (step 1)

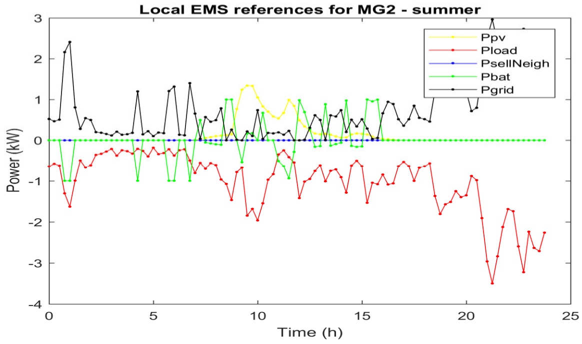


Figure 6: Local EMS references for MG2 (step 1)

We may see that MG1 has available power to sell to its neighbors in the time interval where there is a surplus from its

PV power production that could be otherwise stored. This reference will be communicated to the neighbors in Step2 (information sent to the ERs of MG2 and MG3, respectively).

From Fig. 6 we may see that in the case of MG2 there is a scheduled energy from the grid almost in all time intervals within the 24 hours operation, energy that could be easily supplied from the surplus available from MG1.

When applying steps 2 and 3 of the consensus algorithm the local scheduling changes to other values according to the global, sum of all local objectives optimization. The results of the new scheduling for the MG1 remain unchanged, in the sense that all the surplus energy was traded for selling to neighbors, while for MG2 changed to what is shown in Fig 7.

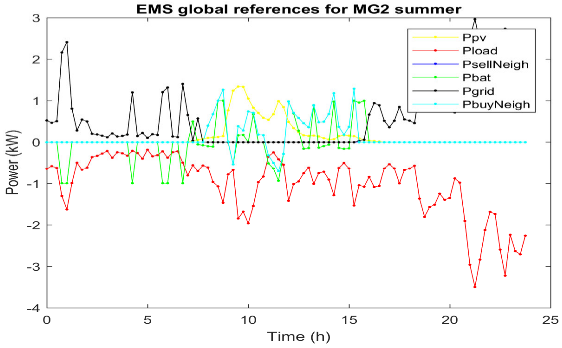


Figure 7: Results of rescheduling from global EMS - MG2

It can be noticed that at rescheduling MG2 buys energy from its neighbors instead of buying from the grid because this is a cheaper option. Also, MG2 prefers to charge its battery with energy coming from neighbors, energy that otherwise would be lost, not being allowed to be injected into the grid.

V. CONCLUSIONS

The paper proposes a resilient architecture for a small cluster of LVDC MGs. To prove the concept several resilience features previously proposed in the literature were tested. Furthermore, a distributed EMS is analyzed based on the well-known general consensus problem framework, an approach imported from applications in computer networking. The major contributions of this work are in providing insight into a set of business and resilience use-cases for the proposed architecture and the means for daily operation of such a system using an easily expandable and adaptive approach, such as a distributed EMS. This work intends to open the path for further investigations for long term resilience and sustainability in aggregating such clusters to form the back-bone of the distribution system on larger areas, as well as their application at the smart grid level.

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