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RESEARCH ARTICLE

Dispatchable Microgrids: An Extended Provision of Systemic Ancillary Services to Low-Voltage Distribution Grids

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ABSTRACT Grid-connected advanced microgrids are controllable entities that can actively interact with low-voltage distribution systems, becoming demand response providers and dispatchers of ancillary services. However, in general, microgrids' management strategies only exploit a limited portion of their potential for ancillary services provision, being usually designed case-by-case to target one particular application. This paper presents an extended outlook on systemic ancillary services that can be provided by an advanced microgrid comprising bidirectional power controllability at its point-of-common-coupling. It is demonstrated that the microgrid operation can be shaped according to several electrical principles (e.g., resistive, capacitive, inductive, voltage-controlled behaviors, etc.), allowing the upstream low-voltage distribution grid to benefit from these particular functionalities. In addition, this paper discusses several fundamental aspects required to fully exploit the capability to provide such an extended range of ancillary services by microgrids. It also discusses the needed control and physical infrastructures, as well as their expected market-related interactivity. Experimental results carried out on two different low-voltage microgrid prototypes are presented to demonstrate that the offering of such multiple ancillary services can be implemented in real-life applications.

INDEX TERMS Ancillary services, demand response, energy management, low-voltage distribution systems, microgrids.

I. INTRODUCTION

The microgrid (MG) concept has been extensively explored in the past decades, particularly because it is one of the most promising solutions to ease the management of low-voltage (LV) distribution power grids with a high penetration of distributed energy resources (DERs) [1], [2], [3]. In general, DERs are systems based on either small-scale renewable energy sources (RESs) or energy storage systems (ESSs), which are interfaced by power electronics converters and operate under grid-tied mode [4]. With regards to MGs, they partition the power system by aggregating DERs within well-established boundaries [5], [6], consequently facilitating the management of their operational needs and providing improved controllability of power flows. In addition, a MG can traditionally operate as a single-controllable entity that responds to the current status of the [7] distribution grid, interactively changing its behavior to offer energy services

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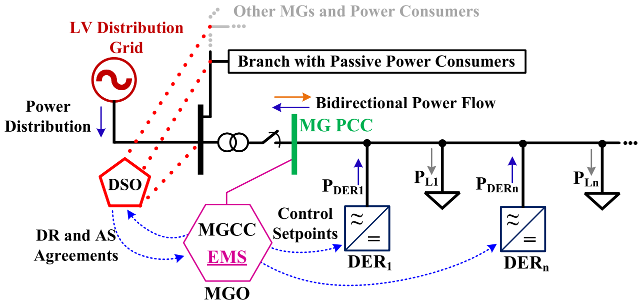

FIGURE 1. Layout of the dispatchable MG supporting the distribution grid on its operation through interactions between the DSO and MGCC.

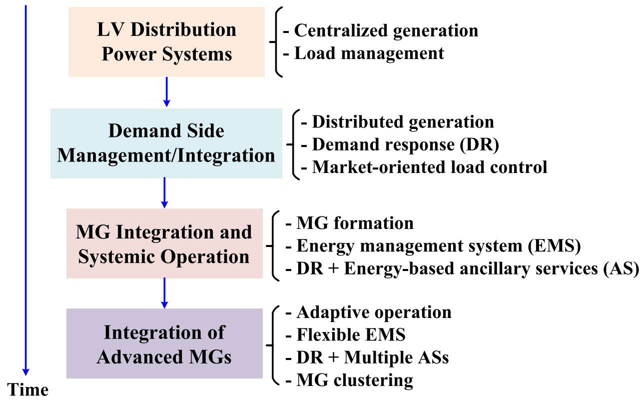

FIGURE 2. Foundations of the systemic and flexible implementation of grid-supporting services provided by advanced MGs.

resulting from a controllable exchange of power terms. Hence, energy management systems (EMSs) [8] are typically implemented by MG operators (MGOs), providing means for coordinating the operation of loads and DERs, to obtain a technically harmonized and cost-effective use of the MG assets [9], [10]. Note that, within this paper, MGO indicates the entity responsible for physically implementing and managing the MG central controller (MGCC) [7], [11], which monitors and coordinates the operation of all MG assets. Hence, the MGO is the entity responsible for choosing the MG's EMS features and for establishing market agreements considering the MG power flow exchange with the upstream grid.

The possibility of steering LV MGs to act as independent entities allows the distribution system operator (DSO) to take advantage of their power dispatchability [12] to: reshape power flows either offline or online, meet energy supply and demand expectations (i.e. by the so-called "energy services"), provide energy re-routing capabilities [13] to facilitate power system maintenance [14], and multiple other functions [15]. As noted from Fig. 1, if proper management of DERs and loads is achievable, an interconnected MG can be interpreted as a dispatchable entity (i.e., seen from upstream its point-of-common-coupling (PCC) with the distribution grid). Consequently, if full controllability is implemented, such a dispatchable MG can regulate the power flow downstream the PCC to meet its internal demands, as well as provide services to the upstream distribution grid. Thus, MGs can play a role in energy markets by offering demand response (DR) functionalities and ancillary services (ASs) [16], [17], which commonly take into consideration classic short-, medium-, or long-term energy provisions (e.g., load-shifting, spinning power reserves, load-leveling, etc.) [7].

DR and ASs have been important research topics since the 1970s [18], being studied for several perspectives of power systems, including LV distribution grids [19]. As shown in Fig. 2, and as thoroughly discussed in the literature [18], [20], [21], and [22], the evolution of energy services provision has grounds on the decentralization of energy generation sources, as well as the implementation of demand side management and integration, which allowed the deployment of market-oriented load control [18]. More recently, the possibility to form MGs and include their integrated operation within the power management of distribution grids, by means of an EMS and a supervised control by MGOs, allowed a systemic offering of DR and energy-based ASs. Hence, several management approaches have been proposed in the literature, presenting efficient methods to regulate how such MGs offer DR and ASs [12], [23], [24]. In addition, nowadays, the evolution to the so-called advanced MGs [25], which are dispatchable systems capable of accurately controlling power flows and presenting improved power quality management, expanded the frontiers of how DR and AS functionalities can be exploited and/or sold in energy markets.

The deployment of advanced MGs has been extensively explored for what concerns their networked and autonomous operation without the presence of the distribution power system [26]. Hence, most of the related research works propose EMSs that do not take into consideration the DSO's demands nor their impact on the real energy market [3], [11], [27], [28], [29]. On the other hand, when the distribution grid is present and the MG operates under grid-connected mode, additional challenges appear, since the MG dispatchability must be controlled in order to not deregulate the DSO's overall management of the power grid. In addition, market considerations (e.g., price signaling, balance of supply and demand, etc.) must be taken into account to meet economic expectations [10]. In [7], a wide range of DR and AS functionalities provided by a LV MG is implemented based on a hierarchical EMS, and market prices are also an important input handled by the MGO.

Discussions related to the improvement of LV power systems resilience are found in [3], based on the exploitation of grid-connected MGs. In [3], the aggregation of MGs targeted the formation of clusters, focusing on the implementation of control loops and setting pre-planned DR actions predicting the occurrence of extreme grid events. For instance, EMS functionalities (e.g., situational awareness, formation of energy hubs, self-adaptive communication) are proposed in [3] to devise ride-through capabilities to MGs considering contingencies in the overall power system. Provision of services based on the implementation of EMSs for MGs are also proposed in [13] and [30]: control architectures, communication infrastructures and energy scheduling are discussed, endowing MGs with adaptive capabilities for exchanging power with the grid. However, none of the above-mentioned proposals provides an overview of how to achieve management flexibility for the concurrent offering of multiple DR and ASs functionalities.

A few other studies in the literature, such as [9], [28], [31], and [32], present EMSs that focus on the market interactivity of MGs and on the implementation of energy services for power flow control (i.e., actions based only on the dispatchability of active power through the MG's PCC). Although DR actions are considered in such approaches, neither the offering of power-quality-related ASs nor the electrical features (i.e., power capabilities) of DERs are taken into account. At last, the work in [33] proposes a single EMS to handle the complex control of the low-, medium- and high-voltage levels simultaneously. DR and ASs are considered in [33] to support the grid on classic energy services, as well as on a few power quality interventions, such as reactive power compensation and power factor correction. Nevertheless, capacitive/inductive reactive control, per-phase controllability of the MG PCC, and multiple other ASs discussed in this paper are neither theoretically explored, nor experimentally validated. It is also worth noting that none of the previous works discusses the fundamental features required to implement a flexible management framework for MGs offering grid-supporting services. Hence, such gaps in the literature motivate the discussions within this paper.

A. PAPER CONTRIBUTIONS

This paper focuses on the scenario of advanced MGs, which operate under grid-connected mode and provide controllable power dispatchability at their PCC. It will discuss MG provision of DR and ASs to support operational improvements for the upstream distribution grid. Herein, it is considered that the MG is managed by a MGO, which deploys an EMS to control DERs to achieve the intended operational goals. Hence, the contribution of this paper is three-fold:

- An extended outlook on systemic services provided by a dispatchable MG is presented, and classic energy services provided by MGs are discussed. Other novel behaviors to be emulated by MGs are proposed, striving to achieve operational improvements for the upstream LV grid. For instance, this paper proposes ASs related to grid-support and power quality improvement such as: *i*) the reactive shaping, the resistive shaping, and the per-phase shaping of the MG PCC; *ii*) the voltage/frequency controlled dispatchability behavior; and *iii*) other novel perspectives. This paper also demonstrates that the proposed ASs can be flexibly offered by the MG to adapt to different conditions of the upstream LV grid. Moreover, it is discussed how such systemic services have the potential of being seen as innovative ASs to be traded on energy markets;
- A critical discussion is proposed in this paper with regards to the practical implementation of ASs by means of advanced MGs. Hence, the fundamental principles needed to implement the proposed operational flexibility of a dispatchable MG are discussed: the MG physical and control infrastructures are detailed, its required market interactivity is highlighted, and an operational planning for exploiting the MG DERs' power capabilities is proposed, providing a generalized perspective for deploying grid-interactive MGs in the LV scenario.
- To fill and additional gap of the existing literature, experimental tests are presented to demonstrate that LV MGs can operate with flexible power dispatchability at their PCC, proving that the proposed provision of ASs can be implemented in real-life scenarios.

B. PAPER ORGANIZATION

This paper is structured as follows. In Section II, the extended provision of ASs by a grid-connected MG is presented. Section III discusses the features of the MG management framework required to fully exploit the proposed flexible service provision. Section IV presents experimental results considering multiple DERs, and demonstrates that the proposed functionalities expected for the MG can be achieved in real scenarios. Conclusions are presented in Section V.

II. EXTENDED OUTLOOK ON MG-BASED SYSTEMIC ANCILLARY SERVICE PROVISION

The main motivation behind the offer of DR and systemic ASs is the improvement of operational conditions of the power system, regardless of if it occurs based on actions having short- or long-term impact. Traditionally, such services are simply energy-based interventions provided by active entities [16], [17] (e.g., standalone power generators, active distribution networks, and energy consumers willing to adapt their power demand profile). Hence, the changes in energy demand or supply from such entities have supported the power grid in reducing losses and balancing the energy flow [7], [11], mostly through supervised adjustments on their power processing [34].

Recently, grid-connected MGs have also emerged as active providers of services, mainly due to their bidirectional power flow controllability at the PCC [7], [35]. In particular, under an adequate coordination of the EMS, MGs can precisely respond to changes in energy demand in a controlled way: in fact, they can, either quickly or slowly, absorb or dispatch more/less active power, as long as their DERs have the capability to do so [14], [36]. In addition, since MGs are usually DER-based power systems, their power electronics interfaces even allow multifunctionalities to be offered when active power processing is not possible (e.g., PV-based DERs operating during night, battery-based ESSs having low state of charge, etc.) [37], [38]. For instance, it is well-known that DERs can process reactive power, without requiring an ESS

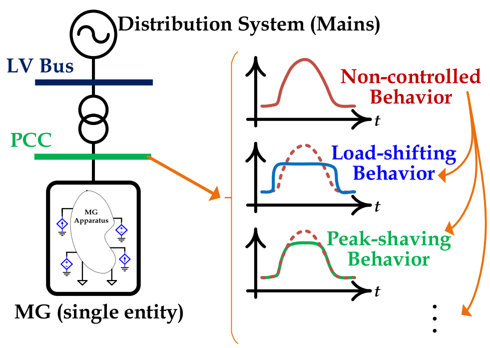

FIGURE 3. Example of classic DR functionalities provided by MGs based on the exchange of active power through the PCC.

or a distributed generation source, devising complementary alternatives for routing energy in MGs [13], [39].

Energy-based DR and AS functionalities provided by MGs have been discussed in the literature, with no practical differences from what is already performed in classic applications [40]. For example, the deployment of MG actions devising load-shifting, spinning and non-spinning reserve behaviors, as well as actions based on load shedding and capacity firming and many others are well established [7]. Fig. 3 shows a representation of the MG providing classic services through the adjustment of its active power exchange with the upstream grid. Most of these services re-model the MG energy consumption based on commands from the DSO, allowing shifting the active power exchange through the PCC according to different principles and throughout different periods of a day. Nonetheless, such classic DR functionalities do not fully exploit the MG's capability to contribute to a more efficient operation of the upstream grid (i.e., the MG usually only supports balancing energy supply and demand). On the other hand, in Fig. 4 some extended functionalities are presented, indicating additional behaviors that can be emulated at the MG's PCC. Each of these possible actions, which allow to re-model the MG's electric interactions with the main grid, could be used by the DSO to improve the grid's overall operation conditions, being also potentially valuated to be sold in energy markets by MGOs.

To further clarify such actions, let us take the general case of a grid-supporting MG operating interconnected to a branch (B_{mains}) from the upstream LV distribution grid, as seen in Fig. 4. In Fig. 4(a), the so called *self-consumption* operational mode is demonstrated, representing the condition in which the MGO receives a signal for the MG EMS to force the power flow to zero at the PCC. Under such a condition, the MG is not able to import/export active/reactive power, causing an insignificant impact on the distribution grid. Since the MG will operate as a self-sufficient entity with regards to energy generation and consumption, this behavior could, for instance, alleviate the distribution grid's burden of dispatching large amounts of power during peak hours. It is important to highlight that such an operational mode does not correspond to the islanded MG mode [29], [41]. Hence, the impact of such behavior would be even more attractive upon the coordination of multiple networked MGs. To achieve such a behavior, the management framework must be capable of supporting the planning of the MG energy balance, as well as steering dispatchable DERs to quickly absorb or inject power (i.e., depending on the conditions of the non-dispatchable DERs).

In Fig. 4(b), the *reactive shaping* the MG PCC is demonstrated, which could be performed aiming at different purposes. Such a functionality consists of changing the reactive power dispatch at the MG PCC to emulate a single-controllable entity acting according to a capacitive or inductive behavior. By doing so, the DSO could reduce or even mitigate the steady-state reactive power circulation at specific circuit branches, allowing the reduction of energy losses and the deployment of bulky and costly passive filters [42]. For instance, knowing that power consumption at LV grids usually presents an inductive behavior, the MGO could receive operation setpoints from the DSO, aiming at steering the MG DERs to use their remaining power capabilities to process capacitive reactive power, counterbalancing the amount of inductive reactive power at B_{mains}. Note that such a behavior could also be applied to scenarios in which the reactance of cables is relevant (i.e., acting with an inductive behavior) or when shunt reactors are present (i.e., acting with a capacitive behavior), allowing the MG to compensate for their interactions with the grid through its reactive power flow circulation at the PCC.

Other two novel ASs that could be offered for grid-connected MGs aim to support *voltage or frequency regulation* in LV grids. As shown in Fig. 4(c), the active and reactive power flow at the MG PCC can be regulated not only to meet DR goals, but also to respond to undesired voltage or frequency deviations by simply adjusting the EMS operation goals. Both Volt-Watt and Volt-VAR controls could be implemented at the power system level (i.e., different from device level approaches commonly found in the literature [43], [44]): if the voltage amplitude or frequency exceeds (above or below) their nominal limits at B_{mains}, mitigation actions are taken by regulating the active or reactive power dispatch/absorption at the MG PCC. Thus, the DSO could use grid-connected MGs as active voltage regulators, without the need of signaling actions, and eliminating the necessity of (or minimizing the need for) capacitor banks or tap-changing transformers. Although, it is important to highlight that the exploitation of the MG capabilities should be carefully planned in order to implement such ASs, since the DERs present limited power ratings and the allowed MG internal voltage ranges should be respected. Consequently, a proper coordination should be implemented for the DERs, coping with the MG's internal and external operational constraints.

Figs. 4(d) to 4(f) present other novel ASs that can be implemented upon power quality or energy efficiency motivations, all of them taking advantage of the flexible control over power terms circulating at the MG PCC. First, in Fig. 4(d), it is noted that if the non-active currents drawn

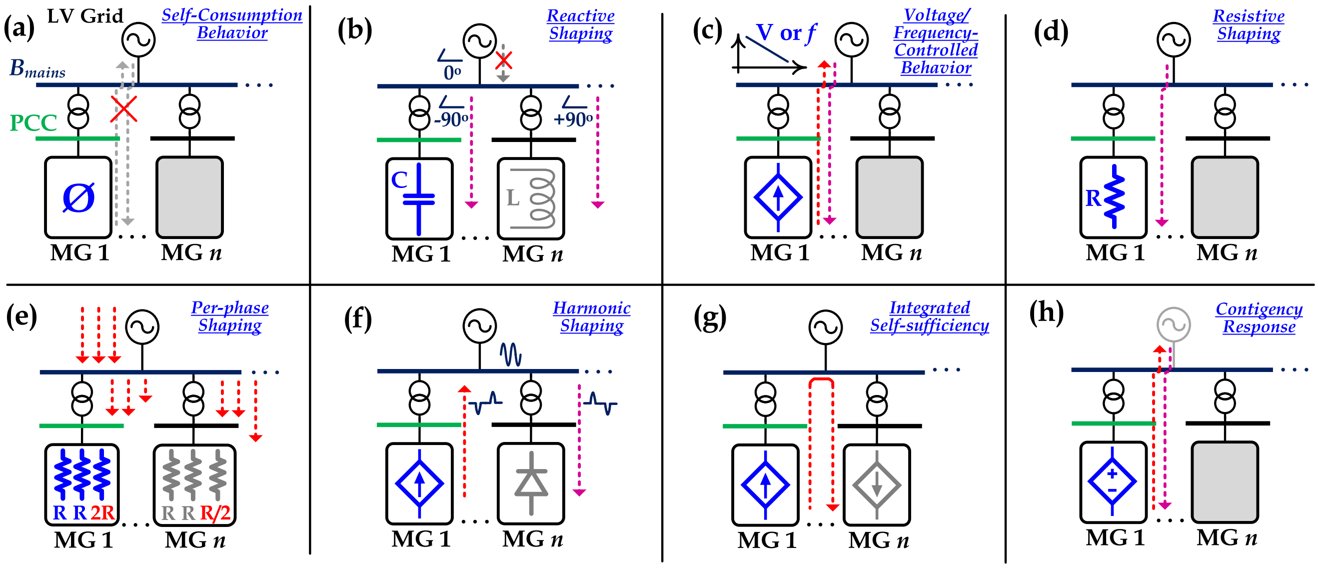

FIGURE 4. DR functionalities and extended ASs offered by a dispatchable MG interconnected to an LV distribution power grid.

by the MG internal loads are provided by the DERs placed closed to them (i.e., internally to the MG), mostly active power circulates at the PCC, allowing the upstream grid to interpret the MG operation as a pure resistor, achieving a *resistive shaping* behavior [45]. Thus, neither reactive nor harmonic power are demanded from the main grid since they are compensated, reducing the incidence of power quality issues (e.g., resonances [45]) and increasing energy efficiency by lowering non-active current circulation upstream the PCC. Note that, such a behavior could also be set by the MGO as a response to requests from the DSO for increasing the power factor at the MG PCC, reaching levels close to unity [46].

Alternatively, for the second approach shown in Fig. 4(e), the advantage of the MG *per-phase shaping* is highlighted. Through the flexibility of regulating the active and reactive power absorption independently for each phase, the MG can support the upstream grid by mitigating unbalanced power dispatch. For instance, if MG_1 in Fig. 4(e) is capable of individually adjusting its power absorption/dispatch at a certain phase (i.e., supporting per-phase control, as discussed in Section II), the DSO can use that functionality to counterbalance an exceeding power demand caused by others MGs or passive branches (see Fig. 1). The third approach shown in Fig. 4(f) follows the power quality principle of mitigating harmonics and avoiding their wide circulation in the main grid. By knowing that B_{mains} is suffering from high demand of harmonic currents drawn by loads, the MG placed on an adjacent node can perform *harmonic shaping*, exporting controlled distortion power to minimize the effects resulting from harmonic interactions [47]. It is important to point out that a harmonic sensitive analysis of the grid should be considered before deploying such a service, to avoid triggering resonances internally to the MG and stressing existing distribution transformers [48]. In fact, the prior realization of sensitive analysis studies are advised to all AS scenarios, since each MG presents its own particularities (e.g., grid topology, line impedance parameters, DERs features, etc.).

Finally, the last two services demonstrated in Figs. 4(g) to 4(h) relate to the autonomy of MGs, upon signaling from the DSO, helping them to achieving self sufficiency or a minimum dependence on the distribution grid's services. Fig. 4(g) shows a scenario in which the DSO commands a MG (or a cluster of MGs) to provide controlled amounts of active and reactive power to meet the demand of other adjacent MGs that are either not dispatchable or operate with limited power capabilities. By doing so, the power flow at B_{mains} can be regulated in such a way that power is practically not drawn from the upstream grid, but mostly circulates internally to the adjacent MGs. Such a functionality copes with operational goals such as the one of diverting power flow for the DSO to perform line maintenance and other services [14], avoiding overloading of lines and providing more precise control of consumer-level energy supply/demand. On the other hand, a contingency-driven behavior can also be provided by isolated clusters of MGs if they present DERs with sufficient dispatchable power capabilities, as shown in Fig. 4(h). The PCC dispatchability can be controlled aiming at steering the internal DERs of a MG to form the grid (i.e., impose voltage and frequency), while also exporting power through B_{mains} to feed adjacent passive branches for short periods of time upon the fault clearing and during the restoration process of the grid after extreme weather events [49].

Note that all the before-mentioned DR actions and ASs could have their impact enhanced. For that, their usage could be extended to the context of networked MGs [26], in which multiple MGs offer the same service, striving for increasing the impact of their individual actions on the distribution grid operation. Moreover, more than one AS presented in Fig. 4 could be offered concomitantly, or even adapted, to further customize supporting conditions for the upstream LV grid. It is important to highlight that this paper does not intend to develop power flow models nor formulate optimization problems to regulate the MG dispatchability. The main goal is to present novel behaviors to be emulated by MGs, opening new perspectives for the integration of ASs into power flow studies and LV grids modeling.

III. FUNDAMENTAL CONCEPTS FOR IMPLEMENTING A FLEXIBLE MG OPERATION

In order to fully exploit the extended AS provision discussed in Section II, some fundamental concepts need to be taken into consideration for the MG physical implementation, management and monitoring. Such concepts are integrated into a generalized management framework presented in Fig. 5, which indicates the key factors that a MG should present to achieve a flexible operation and easily shape its behavior to meet multiple operational expectations from the DSO. Such a framework relies on six major aspects that are split into three main groups (i.e., Groups 1 to 3). Note that, if all these aspects are incorporated into the EMS ruled by the MGO, market and technical features can be merged forming a MG-interactive system [50].

The first group within such a framework comprises two fundamental technical features that allow a MG to operate as an interactive system (e.g., a transactive energy system [50], [51]). To trade energy with external agents, the MG needs to steer DERs to support a dispatchable PCC (or multiple interconnection terminals, if that is the case [52]). This means that, with respect to the distribution grid, the MG should adjust the coordination of DERs to bidirectionally control the power flow being imported or exported through its PCC [34]. Such a feature is necessary because energy transactions are mainly formulated on the basis of power dispatch and consumption, as well as of economic aspects. In addition, if power dispatchability is sufficiently flexible to incorporate several purposes into a single action, the MG possibility of offering ancillary services is broadened to a systemic (i.e., power system level) perspective [7], [34]. Inside Group 1, the second feature to support the access to energy transactions is the capability to physically interact with external agents, which is usually determined by ICT infrastructures: the MGO must be able to exchange information with the DSO to set service agreements. Thus, communication is indispensable for integrated systems, even when the MG EMS is devised by fully decentralized management perspectives [30].

The second group supporting flexible MG transactive control comprises market-oriented features, which bring economic motivations to light. Fundamentally, a grid-connected MG needs to comply with interconnection agreements that establish limits for power dispatchability, and ensure grid code compliance [53]. Such contracts are obtained from market interactions between the MG and its upstream grid, and they constrain the flexibility to offer whichever

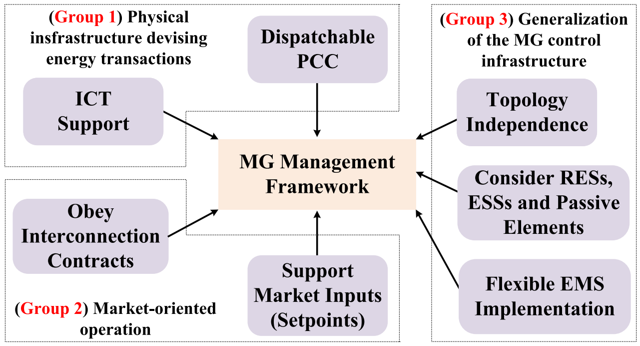

FIGURE 5. Generalized management framework for implementing flexible dispatchable MGs supporting multiple ASs.

energy services are desired by the MGO. Nonetheless, if interconnection requirements are met, the MG can respond to any operation inputs established from overlaying market interactions. For instance, a MG may sell a certain amount of active power export to the DSO at a given time period. Hence, putting such an operational functionality into action can be flexibly implemented if control setpoints for the PCC power dispatchability are simply implemented [33], [54]. Of course, energy planning and forecasting are matters that need to be considered, and, referring to Fig. 5, this is not achievable without implementing Group 1 (i.e., dispatchable PCC and ICT support). Providing an answer to market inputs is also crucial to the provision of energy services, as the active and reactive power dispatch of the MG can be devised to support, for example, voltage control, as well as to emulate classic energy services such as spinning reserves and others [55].

The third group highlighted in Fig. 5 refers to the generalization of the control framework, extending its applicability to generic MGs (i.e., this group supports the implementation of interoperable MGs). Since transactive systems may incorporate MGs of different natures, such as those designed as single-phase, poly-phase [56], or hybrid infrastructures [57], achieving a framework which is independent of topologies brings appealing market accessibility. For example, different MGs operating according to similar transactive control frameworks can be grouped as networked market players [28], [58], in providing integration of energy capacities, thus becoming more important agents in energy planning. The concept of model-free control [54] is also incorporated within such a topology independent principle, supporting a simplified coordination of DERs. Hierarchical control topologies [59] could also be an option to facilitate the implementation of a generic control framework. In addition, if a strategy supports independent control over each phase of the MG, a higher degree of freedom is obtained for the provision of energy services [38]. It is worth mentioning that accounting for different DER topologies in MG management frameworks is an emerging research topic in the literature, which has been only marginally explored so far [38], [41]. However, note that the implementation of a generalized control framework can only be achieved if the deployed

EMS is flexible enough to consider multiple operational goals simultaneously, and promptly adapt the MG behavior upon new control considerations.

It is also important for energy management frameworks to accommodate DERs operating according to different natures [37], allowing more functionalities to be offered, and increasing the flexibility of operation of the MG. Coordinated operation of dispatchable DERs, such as the ones based on ESSs or non-renewable energy sources, is capable of supporting precise controllability over the power flow at the MG PCC [7], while also being a key element of the economic profitability of MGs [1]. Note that non-supervised dispatchable DERs may also exist in the MG [6], as long as coordinated DERs are present and have sufficient power processing capabilities to still regulate the power flow controllability at the PCC. Additionally, without non-dispatchable energy generation (e.g., PV- or wind-based DERs), it is not trivial for MGs to reach a desired level of operational independence from the upstream grid and other market players, since more power would need to be imported. An exception to that is, for instance, a particular scenario in which diesel generators exist and take the role of being the main suppliers of energy to meet the MG's internal demand [60]. Consequently, the existence of non-dispatchable DERs should be incorporated into any generalized management framework targeting transactive control over MGs.

It is worth highlighting that, although this paper discusses a management framework for LV MGs, the approach could also be extended to medium and high voltage levels [61]. At last, a flexible MG framework should be capable of managing power dispatchability through the PCC while considering different loads consuming energy. Besides typical resistive, inductive and capacitive loads, a MG must endure the existence of non-linear loads [62], which are more and more common in LV grids and known for imposing challenging operational scenarios, due to the circulation of active, reactive and harmonic powers.

A. MANAGEMENT OF MG SERVICES ACCOUNTING FOR DERs' STATUS

Although multiple AS functionalities are enabled by the implementation of the framework discussed in Section III, an adequate implementation of the MG actions must be planned and processed by the EMS, since internal and external requirements are enforced in daily operational conditions. For instance, each individual MG presents internal operational constraints related to the management of its DERs and loads. In addition, its market interactivity and operational shaping to devise the provision of ASs and DR functionalities should respect nominal power ratings, and both energy storage and generation capabilities.

Thus, Fig. 6 presents a simplified operational planning to be implemented within the MG's EMS, considering priorities related to internal MG assets and the external expectations of the main LV grid. Above all, the MG must respect its definition of being an autonomous energy system by first meeting its internal needs: providing energy for the operation of its assets (e.g., loads); planing the usage of the locally generated energy; balancing the charge/discharge of ESSs; striving for advantageous economic operation; etc., [15]. Upon having extra availability of energy stored at its ESSs or being capable of generating surplus energy through its DERs, the offering of DR and energy-related ASs can be planned by the MG. For instance, the MG can sell its power production in energy markets, acting as a DR provider that exports energy to the distribution grid. Moreover, the MG could for example dispatch active power through its PCC to support voltage or frequency regulation.

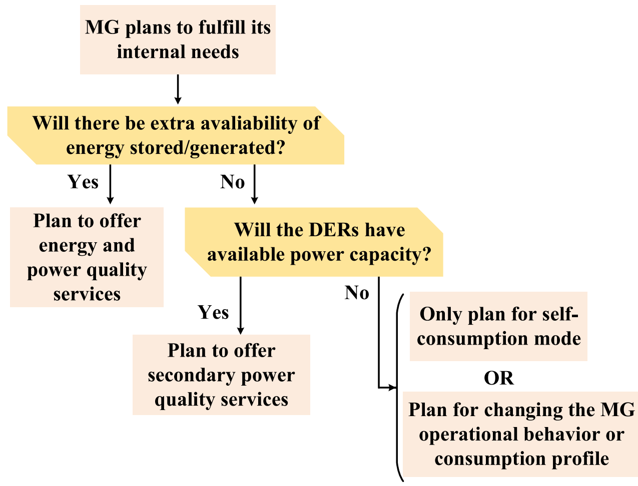

FIGURE 6. Generic operational planning for the MG operation while integrated to the LV grid and accounting for DERs' status.

On the other hand, if the MG is not capable of storing significant amount of energy, it can offer secondary power quality services. By coordinating the exploitation of the remaining power capabilities of DERs, the MG can shape its behavior to process reactive power (e.g., according to the behaviors shown in Figs. 4(b) to 4(e)), allowing it to support the grid on controlling the circulation of reactive currents, providing voltage-controlled behaviors (e.g., Volt-VAR/Watt), mitigating unbalanced currents, etc. However, if the DERs do not present available power capacities, the MG can still be a supporting entity by engaging on the self-consumption mode, causing minimum electrical impact on the main grid. As another possibility, the MG can plan changing internal load profiles (e.g., by imposing load shedding), which would allow it to still provide DR functionalities.

IV. EXPERIMENTAL RESULTS

Herein experiments are discussed to show that the ASs presented in Section II can be implemented in real-life scenarios. Particularly, two MG prototypes are used to demonstrate different functionalities and highlight the generalization principles of the MG management framework discussed in

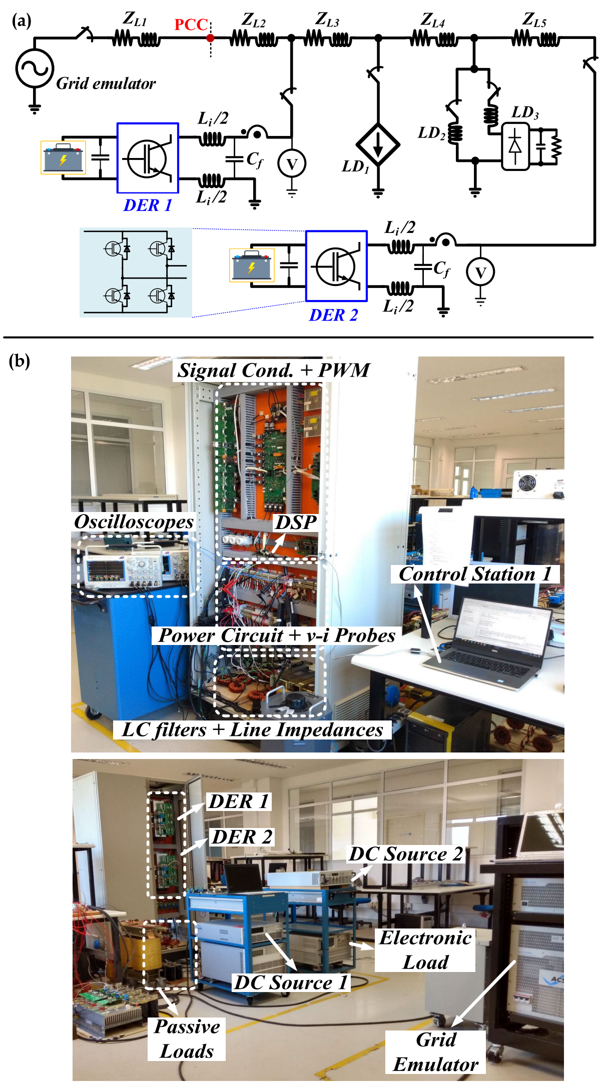

FIGURE 7. Single-phase MG prototype and circuit implemented for the experimental results from Figs. 9 and 10.

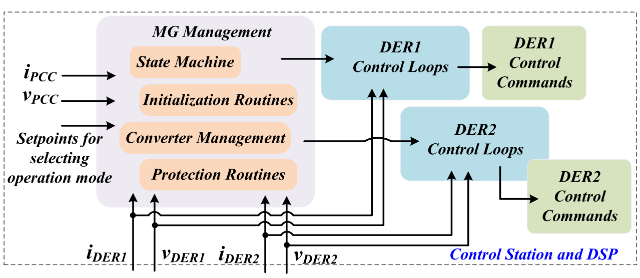

FIGURE 8. Single-phase MG prototype control layout implemented.

Section III. Both MG prototypes have been assembled at the Sorocaba Institute of Science and Technology (ICTS), at São Paulo State University (UNESP), and compose the laboratory infrastructure of the *Group of Automation and Integrated Systems (GASI)*.

TABLE 1. DERs and MG parameters in the single-phase prototype.

Parameter	Value
DERs	
DER_1 nominal power	1.85 kVA
DER_2 nominal power	2.5 kVA
LC filter: L_i and C_f	3.0 mH and 2.2 μF
Switching frequency	12 kHz
Sampling frequency	12 kHz
DC link voltage (V_{DC})	270 V_{DC}
PR current controllers: KP_i and KI_h gains	0.20 p.u. and 358 p.u.
MG and Loads Parameters	
Grid nominal voltage (phase-neutral)	127 V_{rms}
Grid nominal frequency	60 Hz
Line impedances: Z_{L1} to Z_{L4}	$(0.02 + j0.188)\ \Omega$
Line impedance: Z_{L5}	$(0.01 + j0.094)\ \Omega$
Load LD_1	16 Ω
Load LD_2	40 mH
Load LD_3 Inductor	5 mH
Load LD_3 Capacitor	2.35 mF
Load LD_3 Resistor bank	41.8 Ω

First, a single-phase dispatchable MG prototype comprising two DERs and different loads was assembled as shown in Fig. 7, and used for the experimental results shown in Figs. 9 and 10. It is worth mentioning that DER_1 and DER_2 were configured to process active and reactive currents, as well as harmonic currents of the 3rd and 5th orders. Hence, proportional resonant (PR) current controllers were implemented for the DERs, comprising proportional (KP_i) and resonant (KI_h) gains being designed according to [63]. A TMS320F28355 digital signal processor (DSP) was used for the single-phase MG prototype, being programmed and managed by a control station. A summary of the DERs and MG parameters is presented in Table 1. The DERs coordination strategy integrated into the EMS was the one found in [62], in which the peak currents circulating at the PCC and at DERs are processed by a centralized control algorithm, presenting periodic interruptions of 16.67 milliseconds (i.e., once in a cycle of the fundamental voltage). Moreover, the considered loads were: a resistive load (LD_1), which was emulated by an electronic device, an inductive load (LD_2), and a non-linear load (LD_3). All the loads operating together produced a power consumption of approximately 1.5 kVA. The LV main grid was set by a 30kVA 4-quadrant grid emulator. A simplified control layout of the single-phase MG prototype is presented in Fig. 8, demonstrating how the MG management algorithms were implemented. The reader can refer to [45] for a more detailed description of such a prototype.

A. THE MG SELF-CONSUMPTION FUNCTIONALITY

The experimental results in Fig. 9 consider different operational goals set by the EMS of the MG. The first experimental scenario was the demonstration of the MG self-consumption mode, in which its impact on the grid was meant to be minimum. In Fig. 9(a) such a condition is seen, presenting two intervals. Initially, it can be noted from the waveforms (i.e., at the top plot) that the grid emulator imposed the

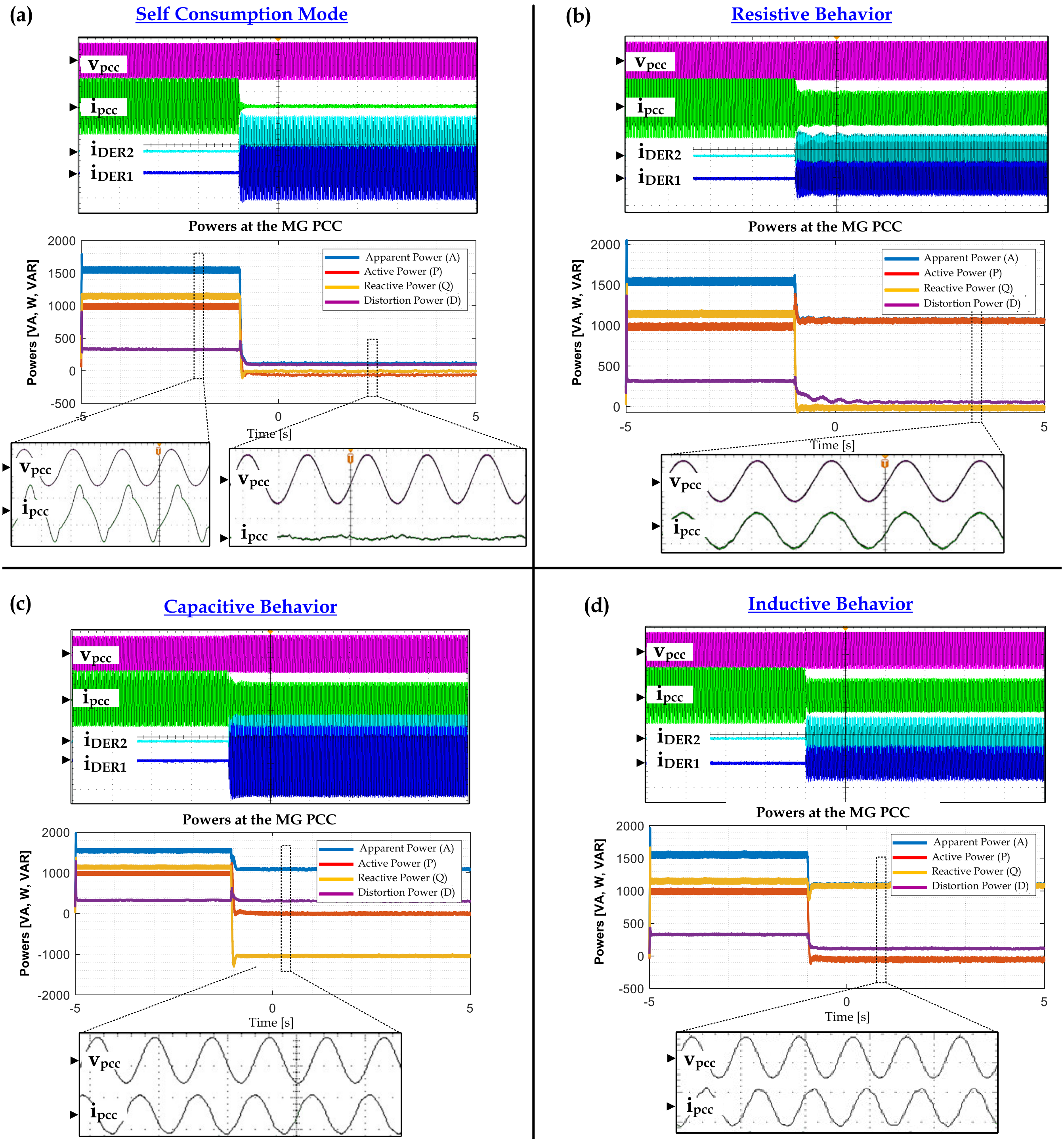

FIGURE 9. Experimental results for the MG operation considering the provision of several ancillary services: (a) self-consumption mode; (b) resistive behavior; (c) capacitive behavior; (d) inductive behavior. PCC voltage and currents, and DERs' currents [top]; PCC powers [bottom].

voltage at the PCC, and the DERs were not processing any currents. Hence, only the loads were drawing power, which is also shown in the plots of the apparent, active, reactive and distortion powers [64] measured at the PCC. Note that the loads drawed 1.58 kVA of apparent power (blue line), which can be split into approximately 1.0 kW of active power (red line), 1.14 kVAR of reactive power (orange line) and 327 VA of distortion power (purple line). It is worth mentioning that the distortion power used in paper is defined according to [64].

Thus, in the second interval in this experimental case, the DERs were controlled by the MG EMS to set the self-consumption mode. Note that, by the time the DERs started processing currents, the amount of power measured at the MG PCC was significantly reduced (i.e., being practically negligible from the upstream grid perspective). For instance, the active, reactive and distortion powers at the PCC were −75 W, −9 VAR and 94 VA respectively. Such a result demonstrates that the MG practically operated being self-sufficient, using the power processing of the DERs to feed internal loads, as expected for the AS from Fig. 4(a).

From a power dispatch perspective, one can observe that: *i*) even though the MG operates under grid-connected mode, its impact on the power flow of the distribution grid is practically negligible; and *ii*) due to the very low active, reactive and distortion power consumption at the PCC, minimum impact in power quality occurs at the distribution grid (e.g. the minimized circulation of reactive and distortion currents result in more steady voltage profiles, higher energy efficiency and lower probability to trigger harmonic resonances).

B. THE MG RESISTIVE SHAPING FUNCTIONALITY

The second operational perspective is presented in Fig. 9(b), demonstrating the resistive behavior that can be emulated at the MG's PCC. For this experiment, the MG considered the same initial conditions as in Fig. 9(a), then having the EMS configured to compensate the reactive and harmonic currents, aiming at achieving only active power circulation at the PCC. It can be noted from Fig. 9(b) that, upon the initialization of the DERs, the reactive and distortion powers at the PCC were 7 VAR and 93 VA, respectively, which indicated that they were significantly compensated (compared to the initial values of 1.14 kVAR and 327 VA, respectively).

Hence, since an amount of 1.06 kW of power was measured at the PCC, mostly active power was drawn from the upstream grid, indicating that the MG operated similarly to a pure resistor, which could be beneficial to reduce losses and avoid power quality issues through the distribution grid, as discussed by Fig 4(d). Note that, in practice, such a proposed functionality provides high power factor operation at the MG PCC, and could be seen as a service available for DSOs to buy in energy markets, having as primary goal the reduction of the MG's reactive power consumption at specific time periods, facilitating the regulation of power flows and allowing to tackle issues such as power system congestion [65], [66].

C. THE MG REACTIVE SHAPING FUNCTIONALITY

A third service provision is presented in Figs. 9(c) and 9(d), focusing on the reactive shaping of the MG (i.e., Fig. 9(c) shows the capacitive shaping, and Fig. 9(d) the inductive shaping). Both of these experimental results presented two intervals of operation: the first one demonstrates the MG operating with only the loads drawing currents (i.e., note, on the top plots that the DERs' current waveforms were initially null); while in the second interval, the EMS was configured to steer the DERs to feed the loads with active, reactive and harmonic currents, besides providing additional processing of reactive power to achieve either capacitive or inductive shaping at the MG PCC. For instance, note in Fig. 9(c) that, when a setpoint of −1 kVAR was set for the reactive power circulation at the PCC, the DERs started processing currents. Consequently, the active and reactive powers at the PCC were 15 W and −1.06 kVA, respectively, which indicates a predominance of capacitive behavior, since mostly negative reactive power was drawn from the upstream grid (also note the leading PCC current waveform in the zoom-in-view).

The dual perspective of the capacitive shaping of the MG is seen in Fig. 9(d), in which an inductive behavior was targeted by setting a reactive power circulation of +1 kVA at the PCC. The results shows that, after the DERs started processing currents, the active and reactive powers measured at the PCC were −100 W and +1.07 kVA, indicating a predominance of inductive behavior, which is confirmed by the lagging PCC current seen in the zoom-in-view figure. The experimental results for the reactive shaping functionality demonstrate that, since such an AS can be adaptively exploited (i.e., capacitive and inductive behaviors are set as desired, upon respecting the MG power capabilities), the DSO can implement it to: *i*) alleviate system overloading [67]; *ii*) improve voltage stability margins [68]; *iii)* and mitigate congestion [65].

D. THE MG VOLTAGE-CONTROLLED BEHAVIOR FUNCTIONALITY

A last experimental result using the single-phase MG is shown in Fig. 10, in which the voltage regulation capability is considered by shaping the MG PCC behavior. Although the experimental results always considered a nominal voltage of 127 V_{rms} at 60 Hz, in Fig. 10 the grid emulator was set to impose 122 V_{rms}. Hence, the MG EMS was configured to dispatch active power aiming at regulating the PCC voltage to its nominal value, operating as a voltage-controlled energy source. Regarding the two time intervals seen in Fig. 10: *i)* the experiment started with the DERs disabled and the loads operating; and later, *ii)* the EMS was initialized in the second interval, steering the DERs to provide the power drawn from the load, in addition to dispatching active power through the PCC to perform Volt-Watt control.

Note, in the middle plot of Fig. 10, that the reactive power was practically null and the distortion power was also significantly low during the second interval. For instance, the reactive and distortion powers were 9.91 VAR and 177 VA, respectively, resulting that the MG's voltage-controlled behavior was mainly regulated by the active power dispatch. Most importantly, the active power measured at the PCC during this experiment was approximately −1.25 kW, which indicates power dispatched by the MG to the upstream grid. Moreover, the voltage plot at the bottom of Fig. 10 clearly shows that, due to the Volt-Watt control provided by the MG management, the nominal voltage magnitude at the PCC was

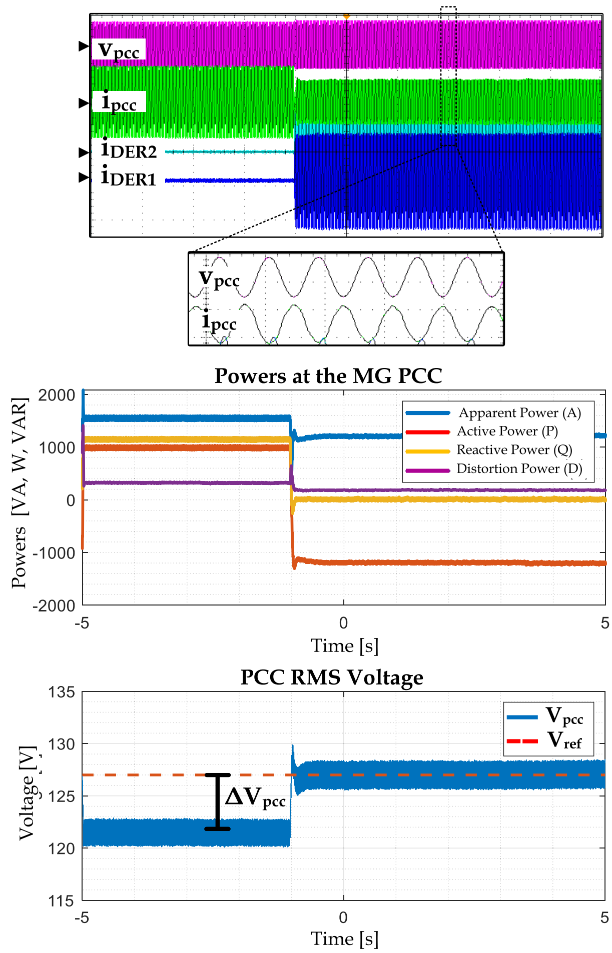

FIGURE 10. Experimental result for the MG operation considering the voltage regulation functionality: PCC voltage and currents, and DERs' currents [top]; PCC powers [middle]; PCC RMS voltage [bottom].

re-established to its expected nominal value (i.e., 127 V_{rms}). Hence, such a systemic Volt-Watt functionality resulted in a magnitude displacement (ΔV_{pcc}) of approximately 5 V_{rms}, allowing the MG to operate as a single-controllable entity that responded to the voltage conditions at the PCC. Such a result validates the grid-supporting AS proposed in Fig. 4(c).

E. THE MG PER-PHASE SHAPING FUNCTIONALITY

Complementary experimental results are finally presented in Fig. 11, demonstrating the implementation of the *per-phase shaping* of the MG. For that scenario, a three-phase four-wire MG was implemented considering two DERs and loads according to the circuit depicted Fig. 11(a). A picture of such a laboratory MG prototype is shown in Fig. 11(b). The DERs were three-phase inverters operating as controlled current sources, presenting L output filters and PR controllers implemented in a TMS320F28379D DSP, also considering a MG management scheme similar to the one presented in Fig. 8. Moreover, the DERs were coordinated by the strategy found in [69], which takes advantage of [64] to

TABLE 2. DERs and MG parameters in the three-phase MG prototype.

Parameter	Value
DERs	
DER_1 nominal power	5 kVA
DER_2 nominal power	3.3 kVA
L filters: L_i	3.0 mH
Switching frequency	18 kHz
Sampling frequency	18 kHz
DC link voltage (V_{DC})	500 V_{DC}
PR current controllers: KP_i and KI_h gains	0.14 p.u. and 583 p.u.
MG and Loads Parameters	
Grid nominal voltage (phase-phase)	220 V_{rms}
Grid nominal frequency	60 Hz
Line impedance: Z_L	$(0.11 + j.10^{-3})\ \Omega$
Three-phase balanced resistive load	142 Ω
Unbalance resistor (between phases a and b)	16 Ω

provide decoupled control of active, reactive and unbalanced currents in a LV MG. With regards to the loads, they were composed of a balanced three-phase resistor and another resistor connected between phases a and b, which created an unbalanced load. The grid emulator was again used, to form a three-phase balanced grid. The MG parameters are summarized in Table 2, and a complete description of such a prototype can be found in [70].

The PCC phase a voltage and three-phase currents are shown in Fig. 11(c), demonstrating that the MG operated with a significant condition of unbalanced currents, which resulted in an asymmetrical power flow among phases a, b and c. Such a scenario was similar to the one discussed in Fig. 4(e). Thus, if a flexible EMS is implemented, allowing the MG to re-model the power dispatchability at the PCC for each of the three phases, unbalanced power flows can be mitigated. Note that two perspectives are possible: *i*) the first one relates to the MG correcting its own unbalanced currents at its PCC; and *ii*) the second one relates to one MG (or multiple MGs) dispatching different amounts of power terms at each phase to correct an unbalanced power flow caused by other MGs or passive branches of the LV distribution system. The former perspective was experimentally tested here.

Figs. 11(d) shows the MG operation when the EMS was enabled and Fig. 11(e) demonstrates the steady state condition. The MG operational goal was to primarily achieve *per-phase shaping* control by adjusting the power flow at PCC to be the same at the three phases. In addition to balance the power dispatchability of the MG, another AS was simultaneously implemented: the *resistive shaping* behavior was selected, imposing only active power to flow through the PCC. Hence, note in Fig. 11(e) that the three-phase currents did not present an unbalanced behavior at the PCC, being also in-phase with the PCC voltages. As a result, such an operation made the MG present a systemic behavior similar to a balanced three-phase resistor. It is also worth noting that the MG was able to smoothly transition to the steady state condition when the EMS was enabled, as seen in Fig. 11(d). Since the per-phase controllability was flexibly

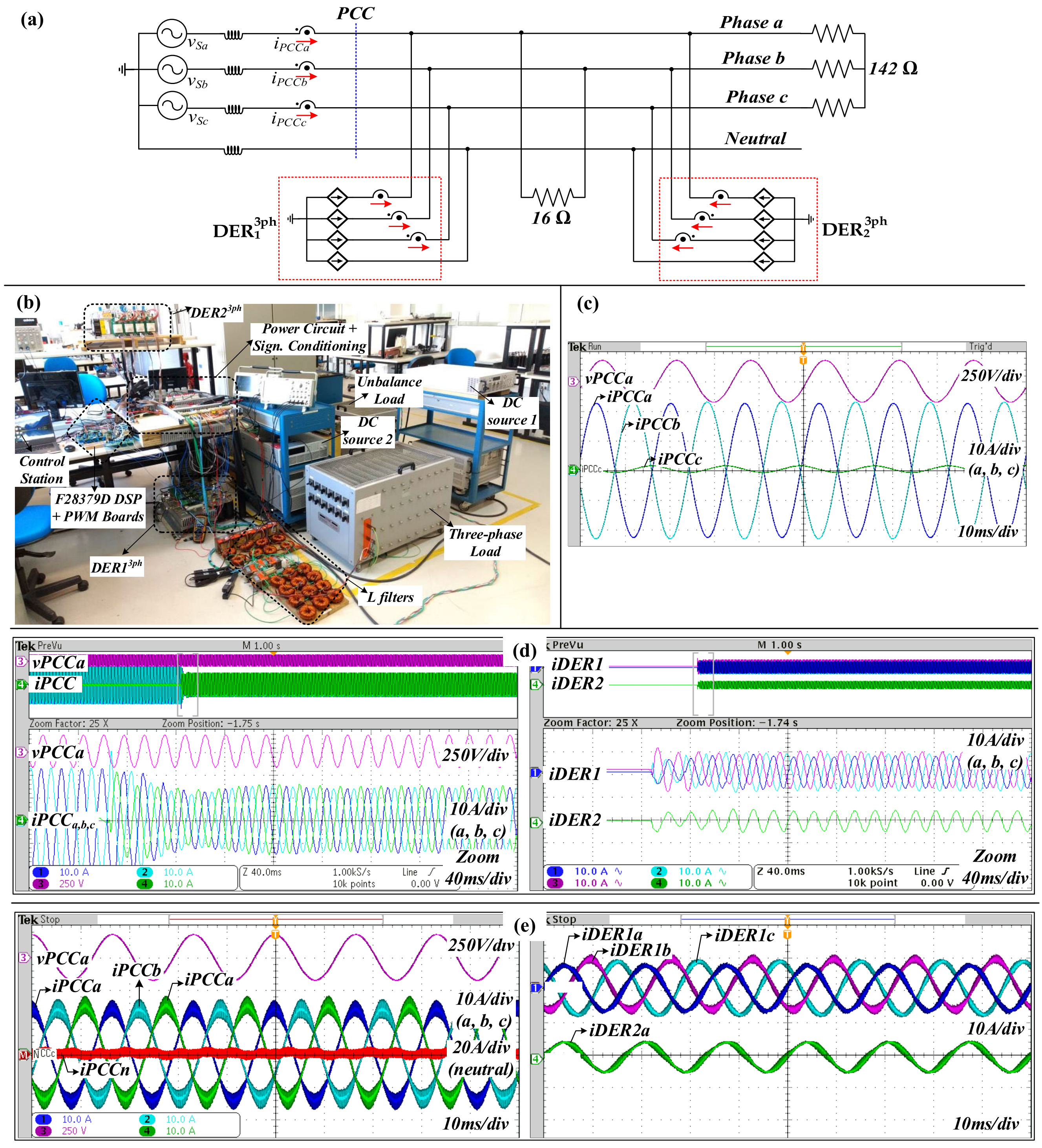

FIGURE 11. Experimental results for the three-phase MG considering the *per-phase shaping* AS, targeting a condition of unbalanced power flow: (a) the implemented MG circuit with unbalanced loads; (b) a picture of the MG prototype; (c) PCC phase *a* voltage [top] and phase currents [bottom]; (d) PCC voltage and currents [left] and DERs currents [right] upon initialization of the EMS; (e) PCC voltage and currents [left] and DERs currents [right] upon reaching steady state condition.

managed by the MGO, it would also be possible to increase the power dispatchability at any specific phase to provide an intentional asymmetrical power flow, if desired by the DSO and supported by the DERs nominal capabilities.

This last experimental result further proves that the multiple ASs proposed in this paper can also be provided by three-phase dispatchable MGs, allowing them to interactively contribute to better performances for distribution grids.

V. CONCLUSION

This paper presents structured discussions about the usage of advanced MGs to provide systemic services to support the operation of LV distribution grids. The provision of novel ASs incorporated into EMS functionalities is discussed, demonstrating that a grid-connected MG can exploit its capability to dispatch power to increase the energy efficiency of the upstream grid, as well as contribute to power quality improvement and add flexibility to energy management. For instance, resistive, reactive and per-phase shaping services can be used to adapt how the MG behaves at its PCC, enabling different electric interactions with the upstream grid. The main advantage of implementing a flexible EMS capable of exploiting multiple ASs relates to the fact that an adaptive behavior is attained for MGs, allowing them to quickly and smoothly adjust their behavior to better meet the distributions grid goals. Nonetheless, the disadvantage of implementing such an adaptive perspective of operation lies on the complexity behind designing an EMS capable of handling more and more input parameters (i.e., operational conditions), since the decision making algorithm need to take into account the requirements and statuses of the MG internal components and the upstream grid.

It is demonstrated in this paper that, upon receiving control commands from the DSO, the self-consumption functionality can be deployed to allow the MG to provide minimum impact on the operation of the upstream grid, resulting in active, reactive and distortion power consumption being fully supplied by the internal DERs. Thus, the MG is capable of alleviating the power dispatch burden of the distribution grid in specific intervals. On the other hand, this paper also discusses the offering of the reactive shaping service, which can be implemented to support the regulation of power flows in the distribution grid, making the MG act according to either capacitive or inductive behaviors, allowing the DSO to tackle issues such as congestion conditions, as well as strive for loss minimization. Upon the existence of unbalanced power flows, the MG can also exploit its per-phase control capability to export/absorb different amounts of active and/or reactive powers through the PCC, contributing to attain a balanced energy demand at the distribution system. Another AS proposed in this paper has the potential to provide support to voltage or frequency regulation, by means of a controllable active and/or reactive power dispatchability at the MG PCC. In addition, other complementary control functionalities proposed in this paper target an integrated self-sufficient operation of multiples MGs and the offering of contingency response actions, both serving as means to increase the reliability of LV distribution grids.

Discussions related to the fundamental concepts required to implement the proposed provision of ASs by MGs have also been presented in this paper. Hence, the physical and control infrastructures, as well as the market interactivity of the MG, partake in a generalized framework that provides flexible management of the MG assets and functionalities. At last, experimental results based on two different MG prototypes (i.e., one single-phase and one three-phase system) prove that the proposed ASs can be implemented in real-life applications, resulting in performance improvements for LV grids. For instance, its has been practically proved that: *i*) a power factor close to unit can be obtained with the resistive shaping functionality; *ii*) a practically null power flow through the MG PCC is obtained with the self-consumption mode; and *iii*) the voltage regulation at the PCC can be precisely regulated.

With regard to future work, the authors intend to study the clustering of MGs operating under non-ideal voltage conditions, assessing how their operation can be coordinated to achieve higher energy efficiency and improve power quality. Moreover, an optimal management of such MGs is also planned to be investigated, striving to develop a mathematical modeling capable of exploiting the resources and the power dispatchability of the MG to increase the hosting capacity of the upstream grid. At last, the heavy integration of electric vehicles in MGs and their impact on high frequency harmonic distortions shall also be taken into account in future works.

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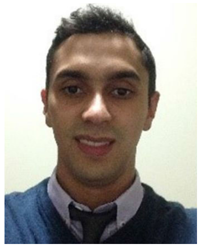

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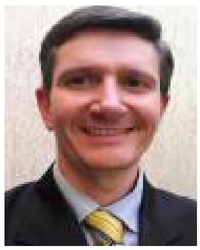

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