Interfacing Power Electronics Systems for Smart Grids: Innovative Perspectives of Unified Systems and Operation Modes

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***Abstract*—The power distribution grid is centrally managed concerning the requirements of the end-users, however, with the appearance of smart grids, new technologies are arising. Therefore, distributed energy resources, mainly, renewables, energy storage systems, electric mobility, and power quality are viewed as encouraging contributions for improving power management. In these circumstances, this paper presents a power electronics perspective for the power distribution grid, considering innovative features, and including a power quality perception. Throughout the paper are presented relevant concepts for a concrete realization of a smart grid, supported by the integration of power electronics devices as the interface of the mentioned technologies. Aiming to support the innovative power electronics systems for interfacing the mentioned technologies in smart grids, a set of developed power electronics equipment was developed and, along with the paper, are shown and described, supporting the most important contributions of this paper.**

***Keywords*—Energy Storage, Power Quality, Renewables, Smart Grids, Power Electronics.**

I. INTRODUCTION

In many countries, the energy production is moving towards 100% renewable energy sources (RES) [1][2]. Aiming such objective, a special contribution is due to the recent technological advances and proliferation of small-scale RES, both at residential and industrial building levels [3]. This influence, directly, the spreading of smart grids and smart homes, which aims to properly integrate small-scale RES into the power system, ultimately, leading to the digitalization of energy [4]. Additionally, a special attention is also given to the potential synergies among small-scale RES, energy storage systems (ESS) and electric vehicles (EVs). In this context, e.g., a dynamic optimization approach for cost and emissions reduction, by maximizing the utilization of RES and EVs offering the vehicle-to-grid (V2G) capability is proposed in [5]; a schedule of energy resources to maximize the synergies among RES and EVs with V2G ability is proposed in [6]; an stochastic and robust energy scheduling considering RES and EVs uncertain behavior to minimize the expected cost and emissions is studied in [7] and [8], respectively; a detailed analysis of the synergies between RES, ESS and EVs is presented in [9]. At buildings level, a charging / discharging of EVs considering the RES and ESS systems in a parking lot is proposed in [10], aiming to maximize the use of RES and ESS to charge the EVs. The integration and coordination of EVs and RES at smart home is accessible in [11]. In such context, an EV smart charging methodology is proposed in [12] aiming to maximize the use of RES. In [13], a coordinated residential scheduling of RES and EVs is offered based on intelligent optimization algorithms. Similarly, a smart house management platform able to manage and control the load, RES, ESS and EVs is investigated in [14]. In addition, an EV smart charging strategy targeting the integration in smart home platforms is proposed in [15], while a control approach considering RES uncertainty and demand response strategies are proposed in [16] and [17], respectively. In this context, the massive integration of RES, ESS and EVs requires the improvement and scalable power electronics systems to make them comply with the system under high levels of operability, controllability, and interoperability.

Nevertheless, despite the relevance of the mentioned investigations, the fact is that existing practices rely on the development of individual interfaces for each type of resources considering their intrinsic characteristics (e.g., as presented in [18]). These individual interfaces with the power grid aim to optimize the operability and controllability of each resource, disregarding the interoperability and synergies among different interfaces. The proliferation of such individual interfaces will encompass difficulties in the communication and interaction between different interfaces in the distribution system. Moreover, the individual interfaces with the power grid involves the utilization of individual power electronics converters, including a particular emphasis on AC-DC. As the smart grid and smart home concepts grow, the common interface among various technologies for RES, ESS and EVs must be thought of. As key point, this challenge of integrating technologies through unified systems (i.e., with a common and single interface with the power grid), contribute to improve efficiency [19]. A common infrastructure supporting RES and EV charging, designed for parking lots, is proposed in [20]. Similarly, an EV

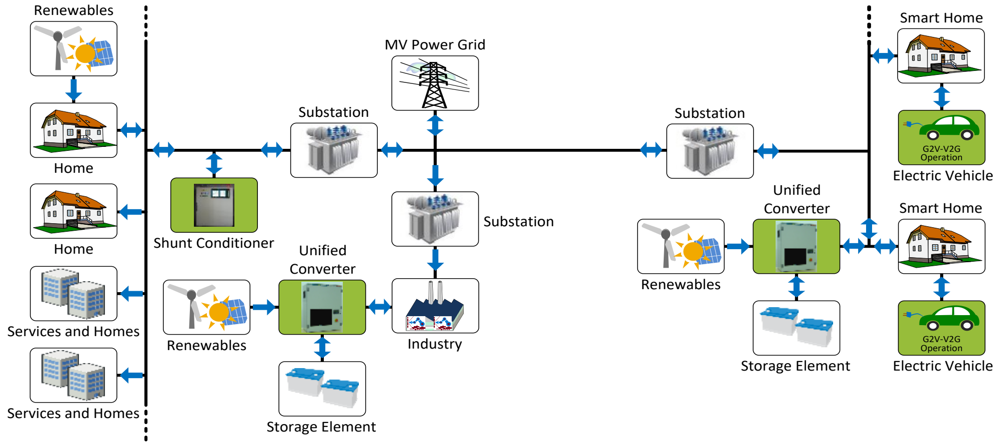

Fig. 1. Overview of a smart grid emcompassing the integration of single and unified interfaces of EVs, RES and ESS.

docking charging station supported by RES is proposed in [21]. The strategic operation and control of the docking station can be complex, depending on the uncertain RES production and the different EVs charging patterns [22]. In [23], a common interface supporting RES and EVs charging is proposed, sharing power electronics synergies using a single bidirectional DC-AC converter. At the residential level, a single interface supporting bidirectional converters for RES and EVs is considered in [24]. A combined system at residential and industrial levels, combining RES and EVs, is explored in [25]. The interface allows RES and EVs to share the same AC-DC converter connecting them to the main grid, while supporting EVs charging and discharging processes.

In these circumstances, this paper presents a power electronics perspective for the power distribution grid, considering innovative features, and including a power quality (PQ) perception. As main contributions, it can be highlighted: The power electronics presented along the paper were designed, developed, and tested aiming to develop innovative ways to improve the operation and control of the smart grid; Unified power electronics solutions for residential and industrial levels, considering an EV on-board charger (EV-OBC) operating under different operating modes, a unified shunt active power filter (USAPF) interfacing RES and ESS through a joint DC interface, and a unified shunt series active power filter (USSAPF) also interfacing RES and ESS also through a shared DC interface; The distinct operation modes are presented to prove the advantages of the innovative operation modes. After this introduction, the smart grid technologies in terms of power electronics, highlighting the modelling of single and common interfaces for RES, ESS and EVs, are presented in section II. The developed power electronics systems and the respective validation are presented in section III, and the most important conclusions are introduced in section IV.

II. Power Electronics Technologies in Smart Grid

Traditional power electronics systems are not prepared to fully integrate the operation of multiple systems, such as EV charging, RES and ESS, with a common interface with the power grid. Nowadays, most power electronics systems operate as a single interface that can be merged by a power management system, just in terms of controllability [14][18]. Within the smart home paradigm, this classical operation makes the system working with low levels of efficiency, as some power electronics devices (e.g., interfacing converters) can be reused by different resources. Therefore, the coupling of multiple interfaces can boost efficiency and reduce investment costs of the smart home system. This perspective of a common interface at the residential level (smart home) with the power grid considering multiple systems is also applied to the industry perspective, where operating power levels are higher (with a three-phase four-wire interface) and some additional requirements are critical in terms of PQ. It is important to note that, using a common interface on the grid-side, a bidirectional operation is established, where the ESS and EV are also interfaced in bidirectional mode, while the RES has a unidirectional interface. Therefore, the common interface with the power grid, or multiple interfaced systems cannot be defined as inputs or outputs of the whole system.

Fig. 1 depicts a global smart grid perspective in terms of power electronics, showing the interfaces divided in two main levels: residential (smart home) and industrial. Both comprise different power levels and operating modes, considering the interfaces of the RES, ESS and EV charging systems. At residential level, two main power electronics devices were developed, such as an EV-OBC, able to operate under different operating modes, and a USAPF interfacing RES and ESS. At the industry level, USSAPF interfacing RES and ESS were developed. Both USAPF and USSAPF take benefit of a common DC interface for RES and ESS.

A. EV Charging Technologies

One of the key elements to the success of the massive assimilation of EVs is the efficient and flexible EV charging technologies. EVs can be plugged-in, e.g., through on-board and off-board chargers, and wireless chargers (inductive wireless power chargers) [19]. Under the smart grid paradigm, EV chargers must be able to operate considering different operating modes, which can allow a controlled bidirectional flow of active and reactive power. More precisely, the EV can perform a pivotal position in the operation of the distribution grid by giving ancillary services to the distribution system operator (DSO). A closer look at key EV technologies, including operation and control algorithms for grid interoperability, can be found in [26]. To this end, the EV-OBC must operate under different modes, such as [19]: (i) Grid-to-vehicle (G2V) mode, which allows control active power from the grid to the EV batteries (with power management by the user or grid); (ii) Vehicle-to-grid (V2G) mode, in which is delivered active power to the grid (partially discharging the batteries), according to grid requirements and EV user interest; (iii) Home-to-vehicle (H2V) mode, which allows to control the EV current according to the total current at home, both during the charging and discharging processes; (iv) Vehicle-for-grid mode (V4G), which allows, in the perspective of the grid, to control the active / reactive power, and that can include also the operation as an active power filter, allowing the EV to compensate current harmonics of other electrical appliances; and (v) Vehicle-to-home (V2H) mode, where the EV operates as a voltage source, as an off-line UPS for smart homes. On-board and off-board EV chargers were developed, considering such characteristics. The detailed design and architecture of each developed power electronics system can be found in [19][25][27].

B. RES and ESS Interface

The increase integration of RES, mainly supported by solar PV panels, in the distribution system may imply the introduction of PQ problems, as well as brings uncertainty and variability to the system. The coupling between RES and ESS has been widely discussed in the literature, arguing that ESS systems can mitigate the uncertainty and variability of RES. As example, the main challenges of ESS prospecting the future of RES is discussed in [28]. In fact, ESS can be used to reduce the fluctuation of RES generation and, therefore, provide more power services to the grid. To accomplish with this strategy, a common interface can be of great interest to small energy systems at residential and industrial level. In addition of interfacing RES and ESS with a common power electronics device, through a dedicated control algorithm, the mitigation of PQ problems can also be addressed in the control. Therefore, besides transfer active power in bidirectional mode, the same power electronics device can operate as an active power filter. In this case, considering the residential level with a single-phase interface, problems of harmonics and low power factor are eliminated. On the other hand, considering the industry level, where the power electronics devices are linked to the grid using a three-phase four-wire interface, PQ problems of current unbalances can also be mitigated. Moreover, in some cases, as sensitive industries (or just some specific loads inside the industry with necessity of high-levels of PQ), power electronics devices with a shunt and series interfaces are required. In these circumstances, also PQ problems related to the voltages can be mitigated for the industry side (or only for some specific loads). Thus, besides interfacing RES and ESS, the same power electronics devices encompassing features of active power filters, as the USSAPF, can provide sinusoidal and balanced voltages and for the loads, as well as sinusoidal and balanced currents. Taking such abilities as the main basic characteristics for an improved power electronics device, two devices were designed and developed.

III. ASSESSMENT OF THE DEVELOPED POWER ELECTRONICS PROTOTYPES

Power electronics prototypes were developed at laboratory scale: (i) EV-OBC with innovative technology concerning the operation modes; (ii) USAPF for interfacing a RES and an ESS in the residential level; (iii) USSAPF for interfacing RES and ESS in the industrial level. Therefore, this section is divided into three main parts according to the development of each prototype, where for each case the main results are presented to illustrate the innovation and main features.

A. EV On-Board Charger

The developed EV-OBC allows operation in the different modes previously identified (cf. section II.A).

1) Control Methodology

The EV-OBC is composed by two parts: (i) an AC-DC converter linking the power grid; (ii) a DC-DC converter linking the batteries. Both converters are controlled in bidirectional mode and as a whole, where a single digital control platform is used, and the main control algorithm is responsible for controlling both converters. The workbench with the developed EV-OBC is presented in Fig. 2. Although it is a voltage-source converter, the AC-DC must be utilized with voltage or current feedback, varying according to the operation mode. The current feedback is used when power is exchanged with the grid in G2V, V2G, H2V, and V4G modes. On the other hand, the voltage feedback is used in V2H. Concerning the DC-DC, the control feedback is also adjusted according to the charging or discharging operation. The current feedback is used for charging the battery in the first stage of the charging process (constant-current) and for discharging the battery. On the other hand, the voltage feedback is used for charging the battery at the second stage of the charging process (constant-voltage).

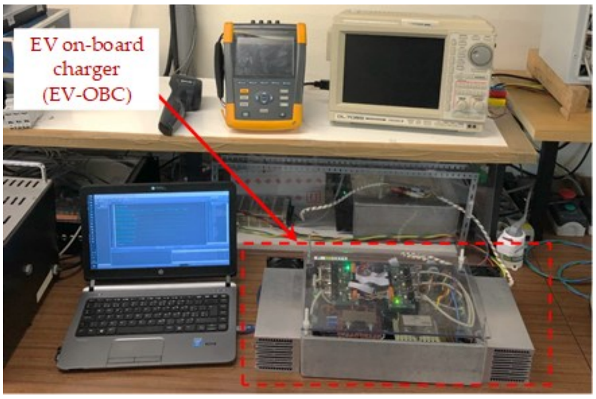

Fig. 2. Workbench showing the developed EV on-board charger (EV-OBC).

2) Prototype Assessment

Since the EV-OBC can operate in distinct modes, Fig. 3 presents the main results concerning its operation. Therefore, Fig. 3 is organized in the main cases. In case #1 the EV-OBC is in the operation that consists of simply charging the EV batteries, i.e., it is in the G2V mode. Additionally, in case #2, the EV-OBC changes the control to adjust its operating power, as it can be verified by the change that occurs in the consumed current. This case corresponds to the H2V mode combined with the G2V mode, where an abrupt change of the consumed current was considered to verify the controllability of the EV-OBC. Finally, in case #3, after the EV-OBC interrupts the previous mode (H2V), it starts to inject power with a constant value through the V2G mode.

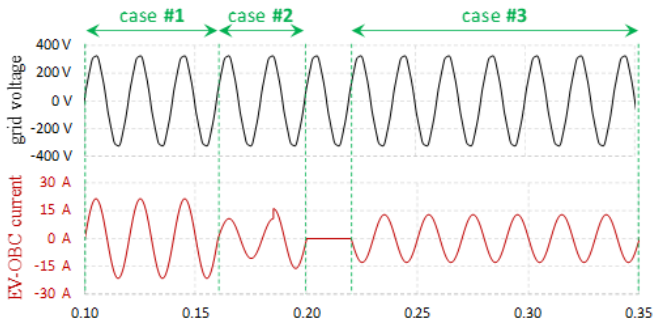

Fig. 3. Results of the EV on-board charger (EV-OBC).

B. Unified Shunt Active Power Filter for Interfacing a RES and an ESS at Residential Level

The developed USAPF allows the connection of a RES and an ESS. As RES, solar PV panels were used and as ESS, a set of batteries were used. Besides the interface of the RES and ESS on the grid-side, the system provides the operation as an active power filter.

1) Control Methodology

The USAPF is composed by three main parts: (i) Shunt AC-DC converter; (ii) DC-DC for interfacing the RES; and (iii) DC-DC for interfacing the ESS. The three power converters are linked by a common DC interface, where the digital control is implemented in a single platform based on a main control algorithm responsible for controlling the AC-DC and DC-DC. The workbench with the developed USAPF is presented in Fig. 4. The AC-DC is controlled with current feedback in two main operation cases: (i) As active rectifier to charge the ESS from the power grid; and (ii) As inverter when it is necessary to inject energy from the RES or ESS into the grid. Although this converter operates in these modes, where the controlled current is sinusoidal, simultaneously or not, it can also be manipulated as an active power filter, producing specific harmonic currents for compensating the distorted current of the installation. The DC-DC, also controlled with current feedback, employs a maximum power point tracking algorithm, optimizing the power extraction at each period defined by the main control system. This converter operates in unidirectional mode, which is only responsible for controlling the DC-side current of the RES. In counterpart, the DC-DC used to interface the ESS is operated in two distinct modes, which are defined according to the needs of the other two converters and the grid management in terms of consumed or injected power. These modes are distinguished as: (i) Charging the ESS with current feedback control, or with voltage feedback control, based on an algorithm of constant current-constant voltage, regardless of whether power comes from the power grid or RES; and (ii) Discharging the ESS with current feedback by imposing a constant or a variable value of current during the discharging process, i.e., according to grid management when part of the energy stored in the ESS is injected into the power grid through the AC-DC. Since it is a unified topology based on a common DC interface, the ESS can directly store the energy produced by the RES through the DC-DC of each system, without having to use the AC-DC, i.e., the power grid is not required in this process of exchanging power from the RES to the ESS. However, during this process, the AC-DC can also be controlled for the operation as shunt active power filter, but it is not required to exchange active power with the grid. This operation mode, which can be realized by the USAPF, represents an attractive functionality to improve overall efficiency compared to the classic approaches with separate converters. Moreover, the USAPF is particularly interesting for the residential level, since it encompasses the RES and ESS with a unique link with the grid.

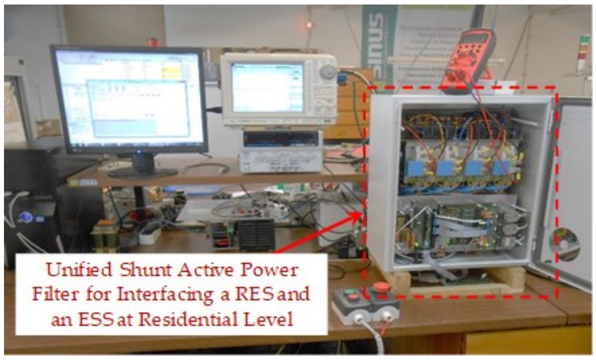

Fig. 4. Workbench showing the developed unified shunt active power filter for interfacing a RES and an ESS at residential level.

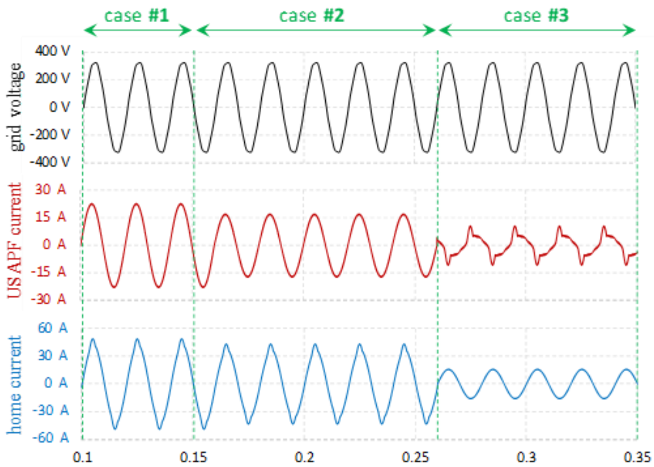

Fig. 5. Results of the unified shunt active power filter for interfacing a RES and an ESS at residential level.

2) Prototype Assessment

In Fig. 5 are illustrated the main results concerning the function of the proposed USAPF. Since the USAPF allows for various modes of operation, Fig. 5 is divided according to the most relevant cases. In case #1, it is verified that the current, i.e., the home current, is sinusoidal. This case represents a situation when the power from the grid is used to charge the ESS. In case #2, the RES starts the power production, being used to charge the ESS, and, proportionally, the required power is decreased, as can be observed in the home current. In case #3, the RES continues to produce power, but it is assumed that the ESS is already charged, forcing the power produced from RES to be fully injected into the grid. In addition, the system also compensates PQ problems of the current, as evidenced by the distorted waveform that is injected (USAPF current). The current on the grid-side (home current) becomes sinusoidal, while the current consumed by the loads does not change.

C. *Unified Shunt-Series Active Power Filter for Interfacing a RES and an ESS at Industry Level*

The USSAPF also allows the connection of a RES (solar PV panels) and an ESS (batteries) considering the DC link. However, since it is an USSAPF, beside the compensation of problems related with the current, also problems related with voltage can be accomplished.

1) Control Methodology

The proposed USSAPF is composed by four main parts: (i) Shunt AC-DC converter; (ii) Series AC-DC converter; (iii) DC-DC for interfacing the RES; and (iv) DC-DC for interfacing the ESS. The four power converters are linked by a common DC interface, but two digital control platforms were implemented. The current or voltage feedback control of the shunt AC-DC, and the control of both DC-DC converters, are very similar to the control of the unified equipment presented in the previous item. The differentiating factor is associated with the AC-DC series, accountable for regulating the voltages applied to the loads, regardless of the distortion presented in the grid-side voltages. Therefore, to operate according to the fluctuation of the grid-side voltages, the AC-DC series converter should be able to consume or inject power, e.g., to compensate voltage swells and voltage sags, respectively. The workbench with the developed equipment is presented in Fig. 6.

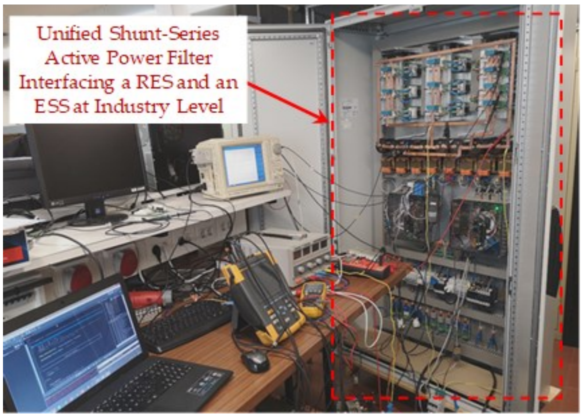

Fig. 6. Workbench showing the developed unified shunt-series active power filter for interfacing a RES and an ESS at industry level.

Comparing both AC-DC shunt and series converters, current and voltage feedback control are employed, respectively. In terms of USSAPF controllability, the series AC-DC converter is only accountable for regulating the voltage applied to the loads, ensuring that the voltages are sinusoidal, the voltage imbalances are eliminated, and the voltage RMS value corresponds to the nominal value of loads. To meet these requirements, the series AC-DC converter exchanges power with the common DC interface of the USSAPF, where the DC-DC converters (for interfacing RES and ESS) and the AC-DC are connected. Thus, the power exchanged by the AC-DC series converter, consumed or delivered to the grid, may originate from the power grid, via the AC-DC shunt converter, or from the RES or ESS.

The AC-DC shunt converter is responsible for compensating for current-related problems, ensuring that the currents on the grid-side are sinusoidal and that imbalances do not exist. In addition, this converter is also accountable for regulating the power required to charge the ESS or for the operation of the AC-DC series converter, and to inject power from RES, ESS, or from the AC-DC series converter.

The AC-DC shunt converter is controlled with current feedback in two main operating cases: (i) As an active rectifier, when it is necessary to charge the ESS from the grid; and (ii) As an inverter to inject power from the RES into the grid. Besides the operation in these two basic modes, where the controlled current is sinusoidal, simultaneously or not, it can also be controlled as an active power filter, producing distorted currents for counteracting the distorted currents of the loads. Although with a different topology, the DC-DC of the USSAPF is controlled based on the same principle of operation concerning the control feedback and the maximum power point tracking algorithm.

2) Prototype Assessment

Fig. 7 shows the main results during the USSAPF operation. As for the previously unified system, the USSAPF also allows several modes of operation.

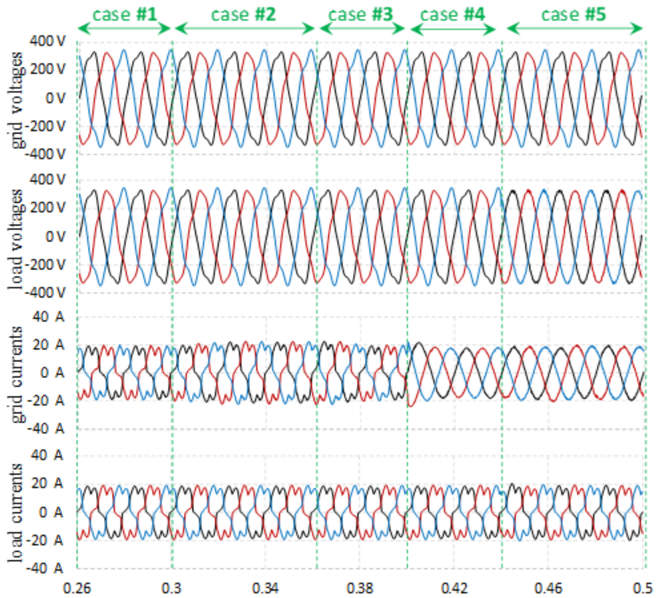

Fig. 7. Results of the unified shunt-series active power filter for interfacing RES and ESS at industry level.

For this reason, Fig. 7 is divided into five cases. Considering the similarity with the operating modes of the USAPF, the results obtained for the USSAPF focus more on the operation of the AC-DC series and shunt converters. In case #1, the USSAPF is not operating, where the grid currents are the same as the load currents and load voltages are the same as the grid voltages.

In case #2, the USSAPF starts the ESS charging operation, indicating that the currents are due to the loads and the USSAPF. In case #3, the USSAPF injects power from RES. As the power required for the ESS is superior to the obtained from the RES, therefore a portion of power is absorbed from the grid.

In case #4, besides the previous cases with RES and ESS, the USSAPF compensates PQ problems through the AC-DC shunt converter. The currents become sinusoidal and balanced, and the currents consumed by the load do not change. As the last case to be analyzed, in case #5, the system continues as it was in case #4, but additionally also compensates the PQ problems through the AC-DC series converter. In this case, the voltages applied to the load become sinusoidal and balanced, although the voltages on the grid-side exhibit significant distortion.

IV. CONCLUSIONS

This paper innovative perspectives of unified power electronics systems and respective sophisticated operation modes in smart grids perspective. The developed power electronics systems ensure the operation and control of electric mobility, renewable energy sources (RES), and energy storage systems (ESS), always with enhanced active power filter features. More specifically, three different power electronics prototypes are presented, namely an electric vehicle on-board charger (EV-OBC), a unified shunt active power filter (USAPF) contemplating the DC interface of a RES and an ESS, and a unified shunt-series active power filter (USSAPF) also contemplating the DC interface of a RES and an ESS. The paper shows the assessment of each developed prototype, highlighting its behavior under different scenarios. The results show the benefits of the proposed power electronics systems in terms of operation to preserve power quality, as well as the mitigation of power quality issues, which can be performed at the same time of the operation with bidirectional active power operation (e.g., injecting power from the renewable energy source or charging/discharging the energy storage system). The main distinct operation modes were validated, demonstrating the relevance of the proposed power electronics systems for smart grids, confirming the benefits in terms of innovative operations, as well as in the perspective unified systems, allowing to significantly diminish the quantity of power converters.

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