

Review

Ancillary Services in Hybrid AC/DC Low Voltage Distribution Networks

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Abstract: In the last decade, distribution systems are experiencing a drastic transformation with the advent of new technologies. In fact, distribution networks are no longer passive systems, considering the current integration rates of new agents such as distributed generation, electrical vehicles and energy storage, which are greatly influencing the way these systems are operated. In addition, the intrinsic DC nature of these components, interfaced to the AC system through power electronics converters, is unlocking the possibility for new distribution topologies based on AC/DC networks. This paper analyzes the evolution of AC distribution systems, the advantages of AC/DC hybrid arrangements and the active role that the new distributed agents may play in the upcoming decarbonized paradigm by providing different ancillary services.

Keywords: distribution networks; hybrid AC/DC networks; ancillary services

1. Introduction

Distribution systems have been traditionally designed, built and operated to fulfill the requirements of the large number of customers who are connected to them. Most of these traditional final users are characterized by absorbing power in an almost inelastic manner from the grid, i.e., irrespective of the energy price, to supply mainly electromechanical loads. The usual network design approach has considered these inherent characteristics of customers to achieve a reasonable quality of supply with the minimal investment cost and always considering the network expansion to face the gradual demand increase [1]. Nowadays, however, this traditional customer is steadily evolving to take advantage of the technological evolution which is paving the way to the smart grid paradigm. On the one hand, customers now may play an active role with the advent of the information and communication technologies (ICT), which offer the possibility of changing their consumption according to economic signals. On the other hand, the electronic-based loads are shifting the traditional electromechanical ones. This trend is unstoppable considering the expected massive deployment of electromobility [2–4] and distributed generation [5–7]. Without any doubt, this is a priority of our society which is focused on decarbonizing the transportation sector and increasing the participation of renewable energies in pursuit of the energy self-sufficiency. The most conservative forecast of the International Energy Agency (IEA) envisions an increase of the worldwide electric vehicle (EV) fleet from the current 2 millions up to 56 millions in 2030 [8]. Similarly, the International Renewable Energy Agency (IRENA) predicts a worldwide increase of the photovoltaic (PV) technology in the generation mix used to cover the demand from the current 233 TWh up to 1.104 TWh in 2030 [9]. In this new context, it will be of utmost importance to incorporate into the system new devices and procedures to

provide the required flexibility for a safe and secure network operation. Finally, a huge increase of battery energy storage systems [10–12] (BESSs) is expected at the distribution level from three major drivers: EV deployment, utility-scale applications to tackle the network congestions, and domestic storage units used to modulate the final user demand. It is important to note that IRENA predicts an increase of BESS installed power from the current 1 GW to 250 GW in 2030 [13].

As a result, the distribution business has to evolve to cope with the new constraints imposed by these new agents distributed throughout the network, with stringent regulatory issues, scarce investment capability and final users more and more concerned with the power quality of supply. However, it is possible to take advantage of the flexibility that these new agents may provide to the distribution system, turning the problem into a solution. In fact, PVs, EVs, BESSs (collectively referred to as “PEB” in the sequel) and other power electronic based devices may bring several benefits to the distribution system operation, if properly managed so that they provide a number of ancillary services to the distribution system in addition to their corresponding primary functionality.

Moreover, note that in this new context a huge number of electrical devices connected to the low voltage (LV) distribution networks (PEBs, variable-speed drives associated to different appliances such as air conditioning systems, etc.) could be connected to a DC supply. Therefore, it is arguable whether the current AC networks are still the most efficient way of distributing electricity, owing to the need to include AC/DC converters for these loads. These front-end components, based on power electronic elements, increase the cost of these loads, reduce their efficiency and pollute the distribution system with harmonic currents affecting the system power quality. The use of hybrid AC/DC networks can be considered a logical step forward from the current AC distribution system, allowing loads of DC nature to be directly connected to the DC side of the network.

This paper elaborates on the role that the new agents (PEBs) and other power-electronic devices (DFACTS) may play in the current AC and future hybrid AC/DC LV distribution systems to provide flexibility by means of ancillary services. The paper is organized as follows: First, the main characteristics of traditional AC LV distribution systems are analyzed, followed by an update of the challenges that they are facing with the incorporation of the new distributed devices. Second, a comprehensive review of the most promising hybrid AC/DC LV network topologies is included. Third, different ancillary services for both conventional AC and future hybrid AC/DC networks are detailed. Finally, the paper closes with the main conclusions and future research work on this topic.

2. AC LV Distribution Networks

The aim of the distribution system is to supply the loads of a large number of customers considering safety, service continuity, power quality, flexibility and expandability issues at the minimum cost [14]. The design of traditional distribution systems comprising MV and LV networks can be broadly grouped into the so-called American or European layouts. The American distribution scheme is characterized by an unbalanced MV network comprising three-phase main feeders with several single-phase or two-phase laterals which directly supply a group of LV loads through pole-mounted MV/LV transformers of reduced rated power. Therefore, the LV network of the American layout is not large, as the main network extension is done in MV in order to reduce the system power losses as much as possible. On the contrary, the European layout is based on a balanced three-phase distribution using three-wire and four-wire configurations for MV and LV networks, respectively. In this case, the MV/LV transformers are always three-phase units and the phase-to-neutral connection of single-phase LV customers is balanced as much as possible among the three phases. Therefore, the LV network extension for the European layout is typically much larger than in the American case. For this reason, the following subsections focus only on the European LV distribution systems.

2.1. One-Way LV Distribution Feeders

Figure 1a shows the one-line diagram of a typical European LV distribution system, which is fed from a secondary substation equipped with a MV/LV three-phase power transformer. Usually, the connection group of the transformer is Dyn or Yzn to distribute the neutral wire for connecting the single-phase LV customers. The transformer secondary winding is connected to a LV switchboard where the protection of the different radial feeders is embedded. This protection customarily consists of simple fuses, the most cost-effective solution considering the short-circuit power levels of LV distribution systems, the large number of existing LV feeders and their radial nature. The number of LV radial feeders mainly depends on the rated power of the MV/LV transformer, but it typically ranges 4–10. Unlike in the MV case, the LV feeders are structurally radial in most cases, i.e., there is no way to modify the normal topology by acting on normally open switches, which would be helpful for instance to reduce the restoration time after a fault [1]. It is common, however, to find specific locations where the end nodes of those radial feeders are really close to each other, especially in urban areas.

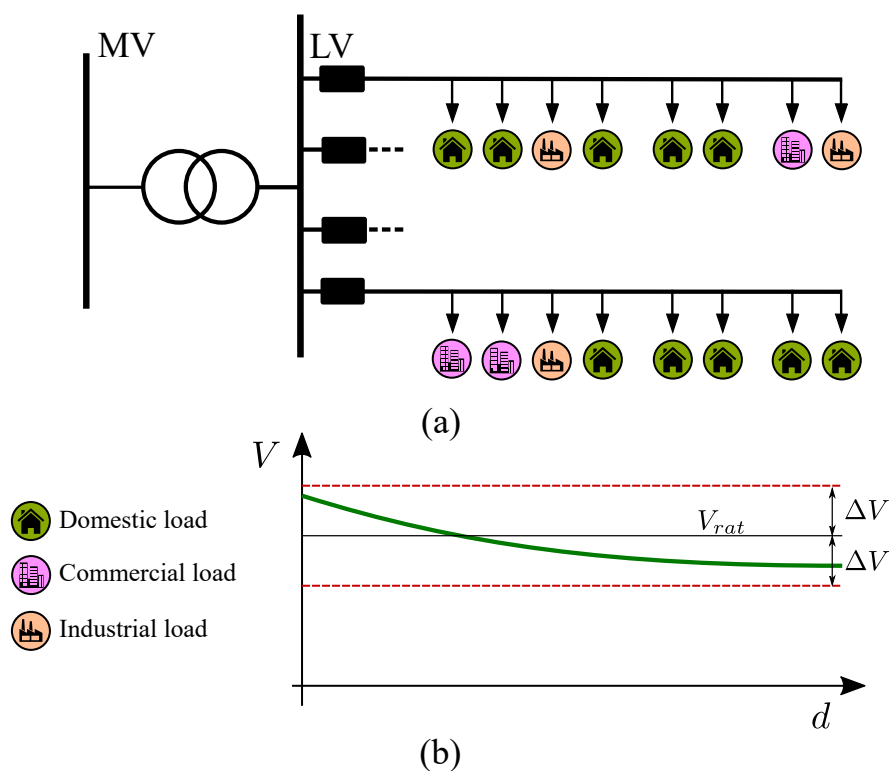


Figure 1. One-way LV distribution feeders: (a) one-line diagram; and (b) voltage profile along the feeder.

As a consequence of the radial design and the passive character of the final users, the power always flows in the same direction, from the secondary substation to the customers, and the voltage magnitude decreases monotonically, as shown in Figure 1b. In any case, the receiving voltage must be within the limits imposed by the standards [15]. For this purpose, the MV/LV transformers are equipped with off-load tap changers, allowing the utility to adjust the LV voltage at the head of the feeder to fulfill the voltage requirements. However, this device can be exclusively operated by disconnecting the transformer and interrupting the service to the final user. For this reason, the tap position is seldom readjusted once the transformer is commissioned. Those secondary substations close to the primary one feature higher MV voltages and, therefore, upper tap positions are usually selected to reduce the LV voltage. On the contrary, lower tap positions are used in those secondary substations far from the primary ones.

2.2. Two-Way Distribution Feeders

Figure 2 is the counterpart of Figure 1, updated in accordance with the smart grid paradigm arising by the incorporation of PEBs, which are transforming consumers into prosumers. These can play now a more active role by controlling their consumption/production profiles, considerably complicating the operation of the LV radial distribution system. First, the simultaneity coefficients of rooftop PV production and EV charging can be much higher than those of traditional commercial, residential or industrial loads. Second, the deployment of these new technologies within the distribution network is not homogeneous, being it possible to find different traditional customer versus prosumer ratios depending on several external factors. Third, the power flows are no longer one way, from the secondary substations to the final users. This completely modifies the voltage profiles along the feeders, as shown in Figure 2b, being it more difficult to guarantee that the final user voltage lies within the regulatory limits. Moreover, it is worth noting that this load/generation scenario is dramatically changing throughout the day, as the PV generation and the EV demand should be peaking during noon and midnight hours, respectively. Therefore, a massive penetration of PEBs may create distribution network congestions, i.e., currents above the ampacity ratings or voltages beyond regulatory limits, which cannot be alleviated by merely acting on the off-load tap changer of the MV/LV transformer.

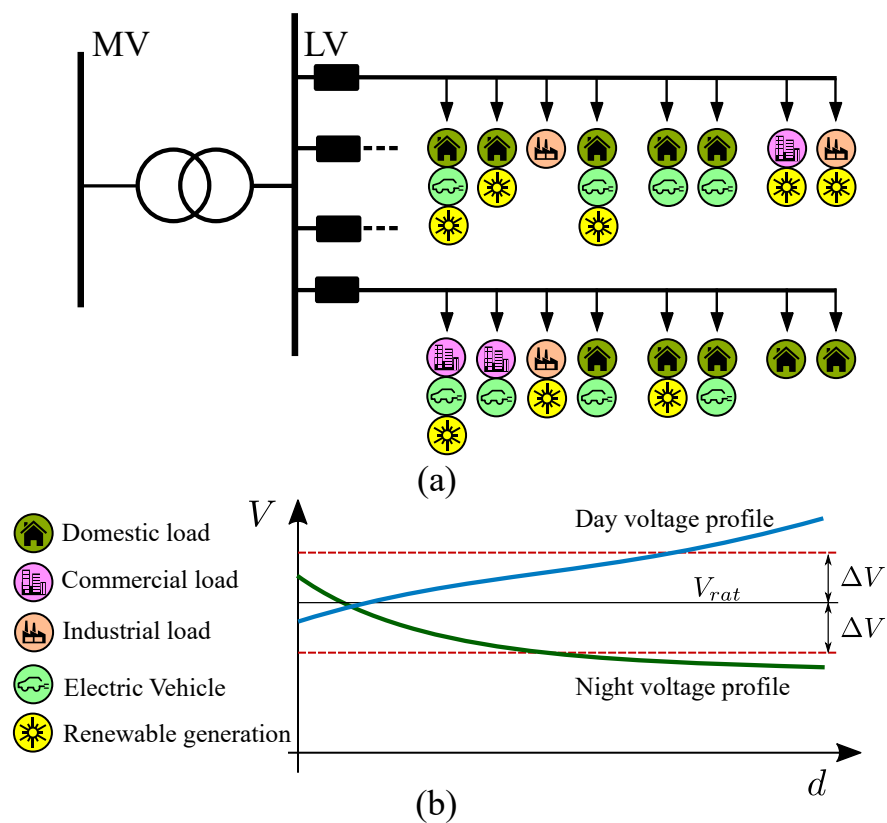


Figure 2. Two-way LV distribution feeders: (a) one-line diagram; and (b) voltage profile along the feeder.

Classical network reinforcement, i.e., increasing the cross-section area of cables or installing new LV feeders, may solve the voltage regulation problem. However, in cases where the feeder congestions arise a few days a year, it is questionable whether the investments in new assets are really justified. Moreover, those network reinforcements are not always straightforward from a practical point of view in densely populated urban areas where underground installations are used. The main issue, however, is that network reinforcement does not tackle the root of the problem, namely the radial topology of the LV distribution network, which constitutes the main technical barrier to the deployment of the new decarbonizing technologies.

A promising alternative solution to this problem comes from the application of new smart-grid technologies, particularly new power electronics-based devices and new control systems, as proposed in Figure 3 and discussed in the following subsections.

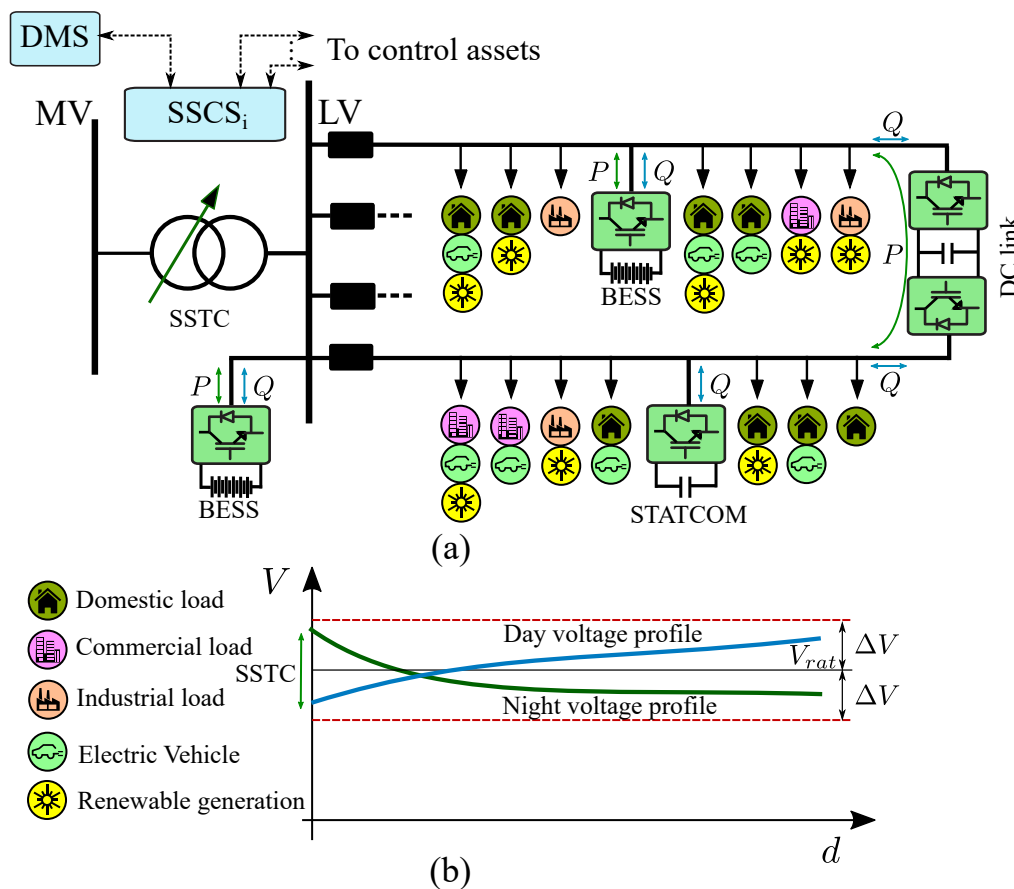


Figure 3. Advanced two-way LV distribution feeders: (a) one-line diagram; and (b) voltage profile along the feeder.

2.2.1. Utility-Scale Power Electronic Devices

Four different utility-scale devices are incorporated in Figure 3 to host as much PEBs as possible by providing additional flexibility:

- Solid-State Tap Changer (SSTC). The objective of this device is to regulate the voltage on the LV side by changing the turns ratio of the MV/LV transformer. This device uses a set of static switches, usually made up of two antiparallel thyristors instead of the traditional mechanical switches. These switches, installed in the MV transformer regulation winding, are always operated in on/off mode, therefore preventing the risk of introducing harmonic distortion in the system, at the cost of regulating the voltage in a stepwise manner, as shown in Figure 4a [16]. Other SSTC topologies based on IGBT technology have been proposed in the specialized literature, which are able to regulate the LV voltage in a continuous manner, at the cost of higher power losses and harmonic distortion [17]. In any case, these devices are serious competitors of the traditional on-load tap changer (OLTC) based on mechanical switches, owing to the absence of movable parts, unlimited number of maneuvers, fast voltage regulation and almost null maintenance cost.
- STATCOM. This device is based on a Voltage Source Converter (VSC) equipped with IGBTs and an isolated DC bus, as shown in Figure 4b. The aim of this device is to inject reactive power to the system to control the voltage of its point of connection [16,18,19]. In addition, it is possible to operate this device to mitigate the inherent imbalance of the LV system [20]. For this purpose, four-wire topologies are preferred so that zero-sequence components can be compensated [21–24].

- BESS. This asset is composed of a VSC with a battery for energy storage connected to the DC bus, as shown in Figure 4c [25]. The main goal of this device is to inject or absorb active power to the system to provide different ancillary services, ranging from frequency regulation [26], peak shaving [27] and energy shifting [28]. In addition, it is possible to contribute to the voltage regulation by means of active and/or reactive power injections.
- DC link. The aim of this device, also known as flexible link, is to create a controllable loop between the radial feeders to which it is connected. It is composed of two VSCs connected in back-to-back configuration sharing a common DC bus, as shown in Figure 4d [29]. This device may control the active power flow between the interconnected feeders and two independent reactive power injections. This provides an extraordinary flexibility to the distribution system operation [30,31]. In fact, this device can fully overcome the barrier related to the radial nature of the LV distribution system, because network congestions in one feeder can be alleviated using the neighbor feeder as a back-up supply point. The use of this DC link is advantageous when compared to a conventional meshed operation, where the active and reactive loop flows cannot be controlled. In addition, the meshed operation requires an expensive protection system to cope with short-circuit faults [32]. On the one hand, the short-circuit current increases as both interconnected feeders contribute to the fault current. On the other hand, note that the protections of both interconnected feeders should trip in the case of a short-circuit fault and, therefore, disconnecting a larger number of customers in comparison to the radial operation case. The use of DC links, based on back-to-back VSCs, prevents this undesired effect, as the healthy feeder can be quickly isolated from the faulted one by just inhibiting the gating signals to the IGBTs. This way, it is possible to maintain the conventional, simple and reliable protection system used in LV radial distribution networks. It is worth noting that it is possible to interconnect N feeders by means of multi-terminal arrangements. This multi-terminal device, composed of N converters, has $2N - 1$ degrees of freedom, $N - 1$ of them corresponding to active power flows (as one of the VSCs must control the DC bus voltage) and N to reactive power flows [33]. Finally, it is interesting to highlight that the DC bus of this device may incorporate a PV generator, a battery or even an EV fast charger station, providing even more flexibility of operation [31]. Alternative topologies have also been proposed to reduce as much as possible the rating of the power electronic components, aimed at reducing its cost [34].

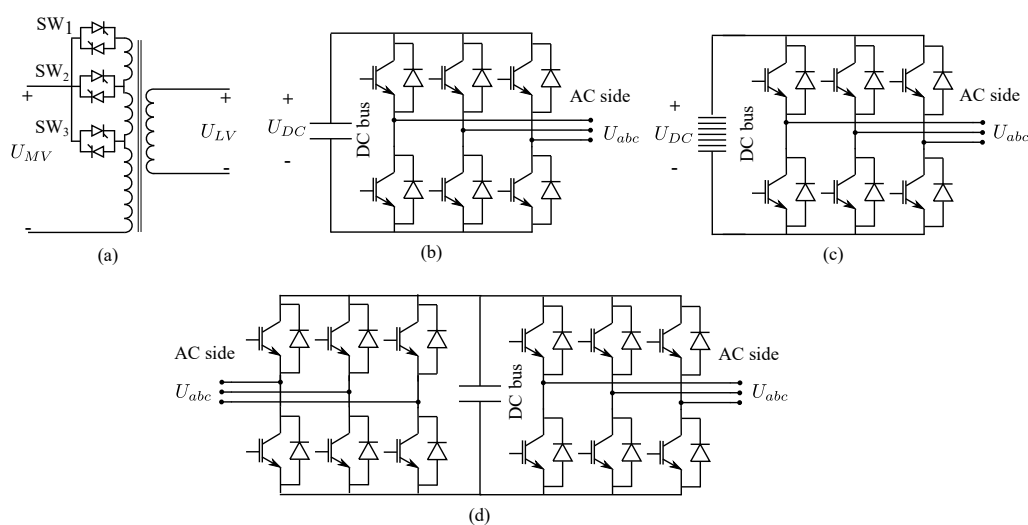


Figure 4. Power electronic devices incorporated in the smart grid distribution system: (a) solid state tap changer (SSTC); (b) three-phase, three-wire STATCOM; (c) three-phase, three-wire BESS; and (d) DC link composed of two back-to-back VSCs.

2.2.2. Control Systems

The new paradigm arising around the active distribution systems discussed above and depicted in Figure 3, involves the development of a Secondary Substation Control System (SSCS) [35]. After decades of incremental technological advances, this constitutes a leapfrog with respect to the current status of LV AC distribution networks. Nowadays, those networks are unobservable in real-time, being equipped in the best cases with just a data concentrator to gather the data from the smart meters downstream [36]. This Advanced Metering Infrastructure (AMI), however, is thus far exclusively used for billing purposes, its extension for improving the network operation still being on the blackboard. The aim of the control system included in Figure 3 is twofold:

- Determine, in a coordinated fashion, the control actions of the different assets spread along the distribution system to improve its operation. In this sense, the control assets may belong either to the utility or third-parties, such as PV generator or EV charger, which may provide different ancillary services. These control actions can be obtained by means of algorithms specially tailored to each specific application. Mimicking the customary structure of AC transmission control systems, those algorithms can be hierarchically organized in three control layers with different time scales. The primary control level provides fast reactions aimed at rejecting any system perturbation and maintaining the controlled variables close to their reference values. This is usually implemented locally, following a linear droop, which calls for a slower secondary control intended to eliminate the steady-state error associated to the primary control. Finally, the third and slower control layer is devoted to computing the optimal reference values for the controlled variables by introducing some optimization criteria [37].
- Interact with the Distribution Management System (DMS) of the utility: (i) to provide aggregated data of the downstream system state; and (ii) to receive control requirements to provide ancillary services to the MV network.

The adoption of this hierarchical control scheme, as shown in Figure 5, is advisable in case of distribution systems where the number of power assets and prosumers is huge [38,39]. The traditional centralized approach, where a unique control center is in charge of receiving and processing all the raw field measurements, as well as computing the required control actions for the set of control assets [40], is not scalable if the whole LV network is incorporated, as this may entail thousands of components for a single primary substation. Undoubtedly, ICTs will play a crucial role in this new context, as they are required for exchanging the information between the different agents [14]. The ICT requirements are quite demanding if real-time network operation is envisaged, in addition to back-office functionalities such as billing of customers. Therefore, special attention must be paid to ICT resiliency, time latencies and cybersecurity issues.

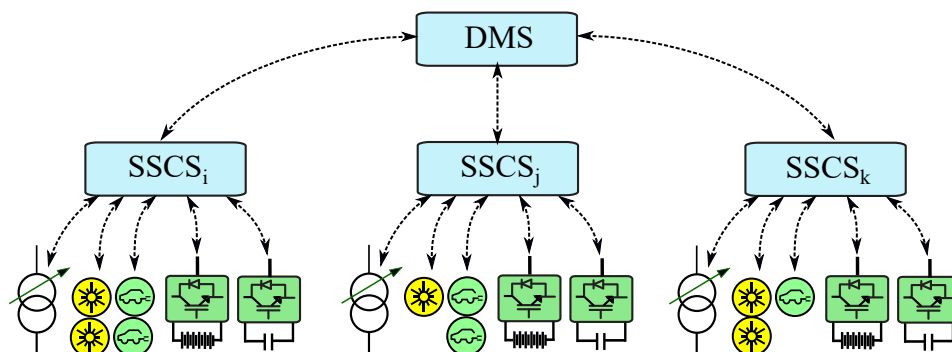


Figure 5. Hierarchical control of active distribution systems.

3. Hybrid AC/DC Networks

Hybrid networks, composed of AC and DC parts, are not new in power systems. Their existence dates back to the fifties of the last century in transmission applications when the first HVDC was

built to supply the Götland Island [41]. The use of HVDC has been mostly restricted to applications characterized by the need of transmitting large power through large distances, where AC lines are constrained by stability issues [42]. The technological evolution in terms of rated power and DC voltage has since been impressive. Some installations of modern HVDC based on VSC technology reach 1.8 GW with a rated voltage of ± 500 kV [43,44] while some traditional HVDC units based on thyristors go up to 8 GW and ± 800 kV [45,46]. HVDC has also been used to evacuate the active power of large off-shore wind power plants to the transmission system due to the reduced capability of long AC submarine cables [47,48].

In the opposite extreme of the grid spectrum, hybrid AC/DC networks have also been explored in microgrids. The microgrid concept [49], originally proposed in 2002 as a building block of the future distribution system, has been of interest for the scientific community due to the new advances in power electronics and digital processors with extended computation capability [50,51]. During the last years, different microgrid proposals based on either DC or AC technologies have emerged without a clear consensus on the best topology aiming at optimizing DC [52] and AC [53] resources simultaneously. Hybrid AC/DC networks represent a natural evolution of microgrids, merging their advantages. Wang et al. [54] proposed these hybrid networks as an efficient solution for supplying DC loads. This achieves a reduction of intermediate conversion stages with the subsequent cost reduction of electronic devices. In addition, the power quality of the AC network, mainly imbalances and harmonic distortion, can improve, because of the use of advance control algorithms in the centralized power converters used for connecting both networks. Multiple configurations of hybrid AC/DC networks can be found in the specialized literature, which can be classified according to different criteria: network topologies, involved power electronics converters and applied control algorithms. The following subsections are devoted to analyzing each of these topics.

3.1. Network Topologies

The simplest hybrid AC/DC network is based on the use of the back-to-back VSCs for supplying the DC loads from the DC bus [55,56]. However, it is also possible to find more futuristic approaches where a hierarchically organized power system composed of several hybrid AC/DC subnetworks connect each other by a number of power electronic converters, somehow mimicking the architecture and behavior of the Internet [57,58]. Due to this diversity of solutions, [59] raised an interesting taxonomy of the different existing topologies including a comparison with regard to different technical criteria.

In any case, to assure an adequate deployment of hybrid AC/DC networks, it is required to rely on two basic design principles: (1) to leverage as much as possible the already existing infrastructure of the existing AC network in line with [60]; and (2) to minimize the number and complexity of power devices used for the active management of the network. Considering these underlying ideas, Figure 6 shows a straightforward derivation of a LV hybrid AC/DC distribution network by adding just the DC conductors to the already existing four-wire AC branches. The existing reserve conduits of underground installations can be sometimes used for placing the new conductors. In this topology, the DC network is supplied from a central VSC within the secondary substation but also from other AC/DC links which can be distributed along the network. AC loads are supplied as usual while DC ones are directly plugged into the DC network, eventually using DC/DC converters. It is important to point out that the bridges between the AC and DC networks allow a bidirectional flow of active power. This opens the possibility of optimizing the power flows between the AC and DC sides to obtain the best operation in terms of power losses while maintaining the power quality to the final user.

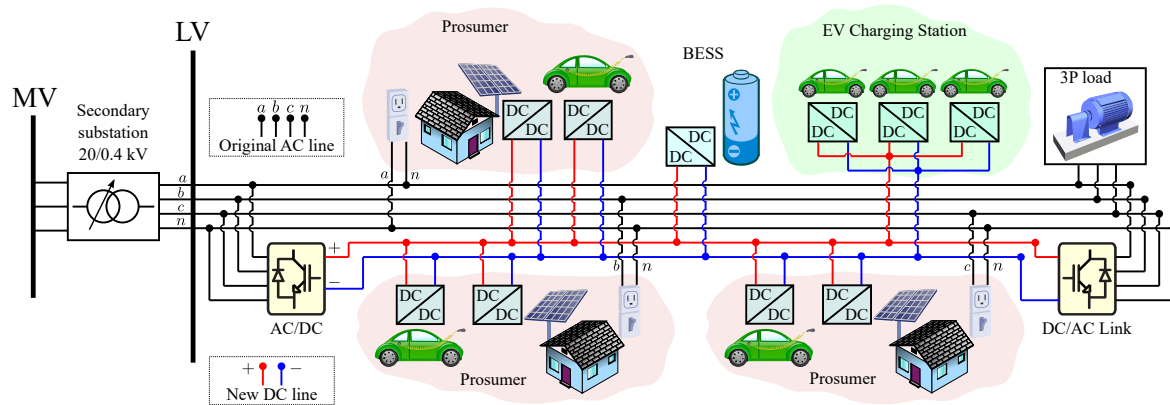


Figure 6. Hybrid AC/DC LV distribution network by adding new DC conductors.

It is worth noting that the hybrid AC/DC grid proposed in Figure 6, which is derived from an original AC grid, increases the network loadability because of the new DC lines. However, this loadability increase is limited by the rated power of the MV/LV transformer within the secondary substation. A possible alternative, which maintains the existing LV line infrastructure, is shown in Figure 7. In this case, two AC phases are transformed into DC lines. The single-phase AC and DC loads are directly fed from the AC and DC networks, respectively, while the three-phase ones require the use of three-phase VSCs supplied from the DC bus (in general, however, three-phase loads are a minority in LV systems). The DC network is supplied from the secondary substation with a three-phase and four-wire central VSC but additional single-phase VSCs can be connected to create bridges between the AC and DC sides.

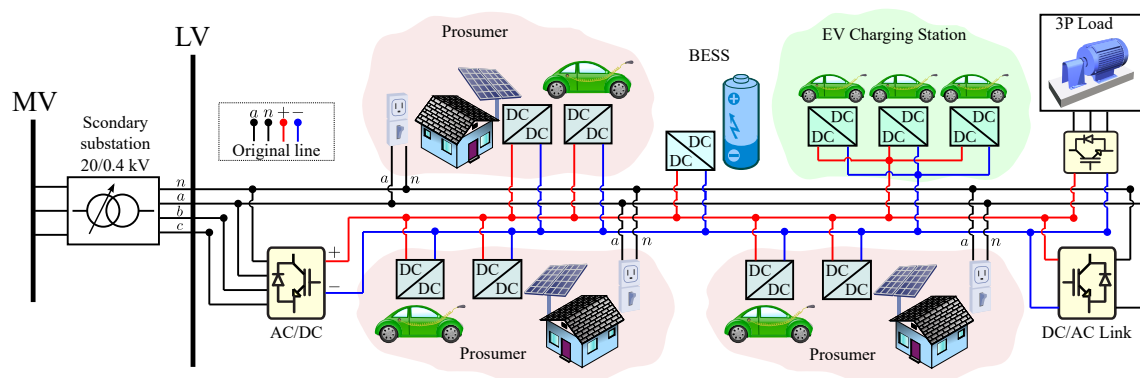


Figure 7. Hybrid AC/DC LV distribution network by replacing two AC conductors by DC ones.

Finally, it is worth noting that those two network topologies are not mutually exclusive, depending on the characteristics of the customers. This way, LV networks with a predominant presence of domestic users, which are characterized by DC and single-phase AC loads, should be adapted to the topology proposed in Figure 7. On the contrary, Figure 6 is preferred for those networks with commercial and industrial users with DC and three-phase AC loads.

3.2. Power Electronic Converters

Undoubtedly, AC/DC and DC/DC power electronic converters are the cornerstone of the AC/DC hybrid networks. In the case of three-phase AC systems, traditional three-phase converters are usually applied [54,55]. However, for single-phase AC systems, it is possible to find different alternative solutions to the conventional single-phase VSC [61]. For example, the authors of [62,63] presented a single-phase high-power density converter with two stages composed of a DC/DC regulator and a classical AC/DC bridge.

On the other hand, DC/DC converters have been widely used for adapting the voltage levels of renewable power sources and energy storage systems, both in isolated [64,65] and non-isolated arrangements [66].

3.3. Control Algorithms

Hybrid AC/DC networks are inherently flexible distribution systems, as they are composed of several AC/DC converters bridging AC and DC sides at different nodes. As a result, it is possible to apply different real-time control strategies aimed at maximizing the network performance. For instance, [67] controlled the EV charges in an effective way so that technical constraints violations are eliminated. In [68], the distributed generation is scheduled to satisfy the demand at minimum supply cost. [69] solved a centralized dispatch of generation and storage units in a hybrid AC/DC network considering the variability of the renewable energy sources. [70] analyzed the application of hybrid AC/DC networks within buildings equipped with renewable energy sources, energy storage and controllable loads. As can be noticed, a wide range of control algorithms can be found in the specialized literature. The interested reader is referred to the hierarchical classification and technical characterization proposed in [71].

It is important to highlight that the control architecture usually poses a hierarchical layout, similar to the one shown in Figure 3 and discussed in Section 2.2.2, where the centralized controller acts as a tertiary control level in charge of computing the optimal set-points for the AC/DC and DC/DC converters. In turn, those devices are equipped with primary controllers which are in charge of tracking the references sent by the central secondary controller [72]. In this sense, it is worth stressing that the centralized controller solves an optimization problem to minimize a given objective function, including a set of inequality and equality constraints, of the form:

$$\begin{aligned} \min \quad & f(\mathbf{x}, \mathbf{u}) \\ \text{s.t.} \quad & \mathbf{g}(\mathbf{x}, \mathbf{u}) = \mathbf{0} \\ & \mathbf{h}(\mathbf{x}, \mathbf{u}) \leq \mathbf{0} \end{aligned} \quad (1)$$

where vector \mathbf{x} comprises the dependent or state variables and vector \mathbf{u} the control variables. The inequality constraints take into account the technical limits of the network (ampacity limits of lines and maximum nodal voltage variations) and the AC/DC and DC/DC converters (maximum converter current and DC voltage range). The equality constraints stand for the network equations comprising both AC and DC parts. This requires specific formulations, such as the one proposed in [73–75] for solving the load flow problem in the presence of VSC-based HVDC networks and/or microgrid systems. Finally, note that these optimization problems should be fed with real-time measurements from the field, if they are to be used for control purposes. For this reason, it is essential to rely on state estimators for computing the maximum likelihood state of the network from the raw field measurements [76]. However, suitable models for the specific case of HVDC systems have recently been developed [77–79].

4. Ancillary Services in AC and Hybrid AC/DC LV Distribution Systems

The advanced AC and hybrid AC/DC LV distribution grids presented in the previous sections, comprising several power electronics based components with accurate and fast control capabilities, allow an unprecedented and sophisticated active network management. In this upcoming paradigm, the new controllable assets may improve the distribution grid operation by providing different ancillary services, mimicking to a large extent the well-known operation of transmission systems.

The definition of ancillary service is somewhat fuzzy, as it encompasses any service required by the transmission or distribution system operator to maintain the integrity, stability and power quality of the system [80]. In fact, there is no unique or harmonized definition even for countries within the European Union, where different provision schemes are articulated [81]. In this work,

the following ancillary services for AC and hybrid AC/DC LV distribution grids can be defined: voltage control, congestion release, imbalance reduction, harmonic distortion mitigation, power smoothing, inertial response and power frequency response. A classification of these ancillary services and the side of the network where they can be applied is detailed in Table 1. The following subsections outline each of these ancillary services, some of them related to the frequency and voltage control, others dealing with power quality issues.

Table 1. Classification of ancillary services for AC and hybrid AC/DC distribution networks.

Ancillary Service	Nature	Dynamic Charac.	AC Side	DC Side
Voltage control	Voltage control	Dynamic	✓	✓
Congestion release	Congestion release	Quasi steady-state	✓	✓
Unbalance reduction	Power quality issue	Quasi steady-state	✓	
Harmonic distortion mitigation	Power quality issue	Quasi steady-state	✓	✓
Power smoothing	Power quality issue	Dynamic	✓	✓
Inertial response	Frequency control	Dynamic	✓	
Power frequency response	Frequency control	Dynamic	✓	

4.1. Voltage Control

The objective of this ancillary service is to maintain the voltage levels at the different nodes of the distribution system within the technical limits [15]. The presence of distributed generation within the AC distribution system may create voltage rises due to inverse power flows that were not common in distribution systems [82]. On the contrary, the massive EV integration may create deep undervoltages. Active power curtailment has been proposed to mitigate this problem [83,84]. However, the practical difficulties of its implementation, related to a fair curtailed power allocation between the involved generators, and the high cost of the curtailed power, prevent its use. As an alternative, reactive power injections by distributed generators [85–87] or EV charging stations [88] can be used for controlling the voltage. The reactive power injections can be done depending on local voltage measurements [89] or according to control signals computed by a centralized algorithm [90]. The utility-scale power electronic devices previously outlined (BESSs, STATCOMs and DC links) can also be used for providing this ancillary service. Note that BESSs [91] and DC links [30] may also contribute with adequate active power management. In addition, SSTCs play an important role in the voltage control of LV distribution systems [92]. This is even more relevant in those cases where the high R/X ratio leads to a low sensitivity of voltage with respect to the reactive power injections [93]. In those situations, controlling the voltage by means of reactive power injection is not a cost-effective solution, which prevents the use of large utility-scale devices or oversized distributed generators. Undoubtedly, a coordinated control of all these resources is the best option to provide the voltage regulation within the AC distribution system [94].

Regarding the voltage control on the DC side of the hybrid AC/DC distribution systems, it is important to highlight the lack of standards on DC networks, beyond those related to data centers and ICT infrastructures [95,96]. In any case, this ancillary service has to be done by adequate active power management of the DC generators, BESSs and AC/DC converters supplying the DC network from the AC side [97–99]. In this sense, the use of AC/DC bidirectional converters spread along the network is of special interest to regulate the active power flow on the DC and/or AC sides, depending on the network loading.

4.2. Congestion Release

This ancillary service aims to maintain the power flows through the different branches of the distribution system below the ampacity limits. In traditional passive systems, this problem can

only be solved by network reinforcement. However, this is not the best solution considering the cost, connection time and the spare capacity of the new assets over a large number of hours per year [100,101]. The active management of the future LV distribution systems offers multiple solutions for maximizing the loadability of the existing assets below their ratings. Considering the utility-scale devices, in addition to BESS [102], the DC link is probably the most promising solution for congestions release in radial distribution systems [30,31,34]. Moreover, PV generation or EV charging can be connected to its DC bus, facilitating the integration of these new components [33]. As far as distributed generation is concerned, it is possible to resort to generation curtailment [103], but also to the exchange of reactive power aimed at maintaining the voltages within acceptable bounds [104,105]. Similarly, the EV charging can be done in a controlled fashion to minimize its impact on the distribution system [106,107]. However, the most interesting results are obtained by exploiting the synergies between the distributed generation and EV charging [108,109]. In fact, the use of hybrid AC/DC networks maximizes this synergy, as the active power flow through the AC/DC bridges corresponds to the net active power of EV and distributed generation, minimizing their impact on the AC side.

4.3. Unbalance Reduction

Load unbalance, mainly due to the presence of unevenly distributed single-phase customers but also to domestic single-phase PV installations, is one of the main power quality problems of LV distribution networks [20,110]. The phase unbalances lead to several problems such as neutral and ground currents, neutral point-shifting and higher losses than in balanced operation [111]. For this reason, the voltage unbalance is usually limited in the current standards [15,112]. In this situation, those technologies based on VSCs (STATCOMs, BESSs, PV generation and DC links) may provide the unbalance reduction as ancillary service to the distribution grid. Some of these devices may have the unbalance reduction as their main target (e.g., STATCOM) but it is also possible to rely on alternative devices equipped with advanced control algorithms with other primary functionalities (e.g., BESSs, PV generation or DC links). For this purpose, those devices have to inject different current in each phase trying to balance the current upstream of their point of connection [113–115]. This implies injecting not only positive sequence current but also negative and zero sequence components. Particularly, the VSC plays an import role in this regard [21]. As three-phase, three-wire VSCs may only inject positive and negative sequence components, four-wire topologies are needed capable of injecting zero sequence currents. Different topologies have been proposed for the three-phase, four-wire VSC [22,23], which can be also composed of a set of three single-phase units [24]. Finally, it is also worth noting that the use of SSTCs with individual phase operation capability may also contribute to reduce the system voltage unbalance [116,117].

4.4. Harmonic Mitigation

Harmonic distortion is a relevant power quality issue in AC distribution systems because of the proliferation of non-linear loads. The use of power electronic devices, thyristors and/or diodes, for rectification purposes creates $m \cdot k \pm 1$ low order harmonics where m represents the number of pulses of the device. The problems created by these harmonics are well documented, including increase of power losses, overload of capacitor banks, electromagnetic interferences, overvoltages, malfunction of protection devices, and overload of neutral conduct and resonances among others [118]. Harmonic distortion is limited by several standards [15,112,119] and traditionally have been reduced by applying passive filtering techniques [120]. However, the development of power electronics, particularly the self-commutated technology [121], has enabled the application of active filtering [122]. Despite the shunt active filter being probably the most common topology, series and shunt-series active filters have also been proposed for reducing the rating of the power electronic components and increasing the filtering performance [123]. However, any device based on VSCs (STATCOMs, BESSs, PV generation and DC links) may incorporate this advanced functionality and provide this ancillary service to the distribution system [124]. Basically, the operation principle is

similar to the one used for the unbalance mitigation: injection of harmonic currents to achieve an almost sinusoidal current upstream of the point of connection. However, note that the local compensation of harmonic currents usually does not lead to a global reduction of the harmonic distortion [125]. For this reason, coordinated control strategies have to be applied for achieving this global goal [126–128]. Regarding the harmonic reduction on the DC side of hybrid AC/DC networks, the harmonics caused by the previously mentioned line commutated converters are of orders $m \cdot k$. Despite methods for computing the harmonics of DC networks being available for special applications, such as HVDC installations [129], there is not a clear standard limiting them. However, the harmonic reduction on the DC side of the hybrid AC/DC systems can be provided either by the DC/DC or AC/DC converters connected to them.

4.5. Power Smoothing

The introduction of renewable generation relying on uncontrollable primary energy sources may produce large variations of the active power injections, which may lead to several problems in the power system. These variations are perceived by the conventional power plants based on synchronous generators as power ramps, which have to be compensated to maintain the power balance in the system [130]. These power ramps are especially problematic in weak AC networks where system operators try to limit their magnitude to assure the system stability [131–133]. Conversely, the power variations also have to be limited on the DC side of hybrid AC/DC networks to control as much as possible the DC voltage fluctuations [99]. This ancillary service can be provided by distributed generators, BESSs and other energy storage systems [134] depending on the rate of power change. Fast power variations, with time scales lower than 60 s, can be compensated by distributed generation equipped with advanced controllers, such as the rotor inertia control [135] and pitch angle control [136] in wind energy systems, without even involving complementary energy storage device. In addition, it is possible to use fast energy storage systems, such as supercapacitors [137], which are able to manage large amounts of active power in short-time periods without any risk of accelerated aging. Conversely, BESSs are most suitable for slow power variations [138] with different control strategies based on moving average [139] or ramp-rate control [140] algorithms.

4.6. Inertial Response

The introduction of renewable generation is displacing the conventional units based on synchronous machines, which are the main source of inertia of the power system. The inertia of a synchronous generator counteracts the frequency changes by injecting or absorbing an additional active power, instantly taken from the kinetic energy of the rotor [37]. Thus, as the penetration level of renewable generation increases, the system inertia decreases and its dynamic control becomes challenging [141]. A possible solution to overcome this shortcoming is to incorporate BESSs, either in standalone installations or combined with generation assets, to emulate the behavior of the synchronous generators, namely to provide virtual inertia. This ancillary service can be provided following different strategies [142]:

- Exact synchronous generators model-based methods, where the objective is to mimic the exact dynamic behavior of the electrical machine by means of a detailed mathematical model in the control algorithm of the converter interfacing the storage system. The following methods can be framed within this category: synchronverters [143,144], virtual synchronous machine [145] and KHI topology [146].
- Swing equation-based control schemes. These control schemes simplify the exact equations of the synchronous generators, retaining only those terms related to the swing equation. ISE topology [147] and Synchronous Power Controller [148] can be cited within this group.
- Frequency-based response techniques. In this case, the control algorithm reacts on any frequency disturbance and, therefore, provides an inertial response on an indirect way. Virtual synchronous generators [149] have been proposed within this category.

4.7. Power Frequency Response

The objective of this ancillary service is to contribute to the frequency regulation of the power system when a frequency disturbance, due to an imbalance between generation and load or any frequency stability issue, appears in the power system. Primary frequency response is implemented in the governor control of the synchronous generators by defining a given power versus frequency droop curve. This local implementation allows an immediate reaction against frequency variations without the intervention of any higher supervisory control [141]. This primary frequency response is slower than the inertial one outlined in the previous subsection, with an actuation time scale from a few milliseconds up to 30–40 s. The progressive integration of renewable energy sources replacing traditional generation requires the provision of this ancillary services by BESSs. On the one hand, it has to be considered that BESS, as a power electronics based device, has a faster response in comparison to traditional synchronous generators. On the other hand, it has to be considered the limitations of this technology. First, BESSs are constrained in energy which prevents its use as conventional generation units. Second, BESSs are constrained in power with limited ramping rates. Third, the number of frequency events and their duration are related to the number of cycles and the depth of discharge of the battery which are strongly related to its aging [150,151]. A straightforward way of providing this ancillary service is by implementing a power versus frequency droop curve in the BESS controller in such a way that active power is injected or absorbed when the frequency decreases or increases, respectively [152,153]. To reduce the cycling of the battery, it is usual to incorporate a dead band around the fundamental frequency [154]. In addition, this ancillary service can be at least partly provided by renewable generation units, which usually operate maximizing the power conversion from the primary energy source [155]. As an alternative, the plant can be operated below the maximum power point, allowing reactions to frequency excursions of both signs [156,157]. Otherwise, the non-dispatchable generation units may act exclusively on over frequency events.

5. Conclusions

This paper analyzes the evolution of LV distribution systems from the traditional AC passive networks to future hybrid AC/DC systems, and the role that the new power electronics based technologies may play in this new distribution paradigm by providing ancillary services. This change is being driven by the technological substitution of the traditional electromechanical devices by the new power electronics ones and the development of control systems based on advanced communication infrastructure. The new distributed agents, including PV generation, EV chargers and other utility-scaled devices such as SSTCs, STATCOMs, BESS and DC links, allow an active management of the distribution system to be implemented. The paper outlines the basic operational principles of each of those technologies and their use for an improved operation of the distribution grid. Actively operating the LV distribution grid requires the intervention of a control system in charge of supervising and determining the adequate set-points for each control asset. For this purpose, a hierarchical scheme is described where each LV distribution network departing from a secondary MV/LV substation is locally controlled. Once the LV AC distribution system has been transformed from a passive to an active network, by incorporating the power and control elements previously mentioned, it is questionable if the AC topology is the most adequate one, considering the DC nature of many of those power devices. The authors' opinion is that hybrid AC/DC LV networks constitute the logical way of incorporating new DC components to the existing AC LV systems. This is envisioned as a smooth transition, trading off the need to maximize the use of the AC legacy assets while allowing a massive roll-out of the DC technology. In any case, irrespective of whether the LV network is purely AC or hybrid AC/DC, it is of utmost importance to duly consider the contribution that the new controllable assets may bring to the whole system, by the provision of ancillary service. The paper has ended by outlining different ancillary services related to frequency regulation, voltage control and power quality issues, which will be required in the near future at the distribution level. The evolution of the power systems throughout the 20th century declared Tesla as the undisputed winner of the war of the

currents after Edison's fleeting initial success. The expected evolution over the 21st century, however, will very likely reveal that the last battle has not yet finished. The DC system revival for integrating the new technologies described in this paper is technically and economically feasible nowadays for the last mile distribution systems. In the authors' opinion, however, the harmonized coexistence of both systems through the deployment of hybrid AC/DC networks is the most cost-effective solution for integrating the new technologies into the current AC networks. Undoubtedly, hybrid AC/DC grids will provide extended flexibility allowing the new technologies to provide the required ancillary services for an optimal, secure and sustainable network operation.

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Abbreviations

AC	Alternating Current
AMI	Advanced Metering Infrastructure
BESS	Battery Energy Storage System
DC	Direct Current
DFACTS	Distribution Flexible AC Transmission System
EV	Electric Vehicle
HVDC	High voltage DC
ICT	Information and Communication Infrastructure
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LV	Low voltage
MV	Medium Voltage
PEB	Power Electronic Block
PV	Photovoltaic

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