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Review

Review of a Disruptive Vision of Future Power Grids: A New Path Based on Hybrid AC/DC Grids and Solid-State Transformers

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Abstract: Power grids are evolving with the aim to guarantee sustainability and higher levels of power quality for universal access to electricity. More specifically, over the last two decades, power grids have been targeted for significant changes, including migration from centralized to decentralized paradigms as a corollary of intensive integration of novel electrical technologies and the availability of derived equipment. This paper addresses a review of a disruptive vision of future power grids, mainly focusing on the use of hybrid AC/DC grids and solid-state transformers technologies. Regarding hybrid AC/DC grids in particular, they are analyzed in detail in the context of unipolar and bipolar DC grids (i.e., two-wire or three-wire DC grids), as well as the different structures concerning coupled and decoupled AC configurations with low-frequency or high-frequency isolation. The contextualization of the possible configurations of solid-state transformers and the different configurations of hybrid transformers (in the perspective of offering benefits for increasing power quality in terms of currents or voltages) is also analyzed within the perspective of the smart transformers. Additionally, the paper also presents unified multi-port systems used to interface various technologies with hybrid AC/DC grids, which are also foreseen to play an important role in future power grids (e.g., the unified interface of renewable energy sources and energy storage systems), including an analysis concerning unified multi-port systems for AC or DC grids. Throughout the paper, these topics are presented and discussed in the context of future power grids. An exhaustive description of these technologies is made, covering the most relevant and recent structures and features that can be developed, as well as the challenges for the future power grids. Several scenarios are presented, encompassing the mentioned technologies, and unveiling a progressive evolution that culminates in the cooperative scope of such technologies for a disruptive vision of future power grids.

Keywords: future power grids; smart grids; hybrid AC/DC grids; solid-state transformers; unified multi-port converters; power electronics; power quality

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1. Introduction

Over several decades power grids have progressed, aiming to ensure universal access to electricity, up to the point of considering a global power grid connecting continents [1]. Despite initial recurring attempts at distributed generation, centralized power grids covering entire countries promptly gained preponderance [1]. Throughout the evolution process of the power grids, it was essential to guarantee their operation, as much as possible, in a stable and predictable manner. Step-by-step efforts were directed towards ensuring controllability, with the goal of improving availability, reliability, efficiency, and energy costs. Additionally, the perspectives of real-time grid monitoring and the analysis of cascade faults have assumed a significant preponderance for power grids, as considered in [2], where challenges regarding modeling and failure analysis are highlighted, as well as new research perspectives within these topics. Specifically regarding resources of power management, a review of multilevel power management systems for future power grids has been presented in [3], aimed to maximize the stability and power quality, discussing advantages and disadvantages, as well as challenges and limitations in hierarchical management.

In line with the above-mentioned aspects regarding monitoring and management systems, several technologies are emerging and assuming predominance for the future power grids, promoting synergies between different areas. In this sense, [4] presents a future vision of power grids based on their autonomy and on controlling the integration of a large amount of distributed energy resources, both for consumption and production. In a review of the blockchain paradigm for future power grids, [5] demonstrates the importance of this technology and presents the security challenges, ongoing projects, and related products. In [6], a blockchain-based data-driven approach is proposed for future power grids, ensuring an intelligent and secure solution that allows cost minimization. In [7], a careful and extensive review of cyber-physical attacks and security issues in future power grids is presented, categorizing existing cyber-physical attacks and defense approaches, as well as future challenges and opportunities. In [8], the contribution of machine learning technologies to future power grids is presented, aiming at their stability and management, and considering the profile of residential consumers and the dynamic behavior of the power grid. In [9], an exhaustive review on the application of blockchain to ensure cybersecurity in power grids is presented, introducing the latest insights, as well as implementation architectures and techniques. In [10], a review is presented that aims to highlight the participation and importance of deep learning technologies in power grids, highlighting recent advances and future perspectives for dealing with big data and decision-making strategies. These issues, which are interlinked with aspects of power grid management, have proved to be, to a certain extent, a priority, because over the last two decades power grids have been the target of radical changes as a corollary of the intensive integration of new technologies (e.g., renewables, controllable electronic loads, electric mobility, energy storage systems, electrical railway systems, and new lighting systems) and the consequent need for power management resources covering the needs of all technologies [11–13].

In this context, the change in power grids remains very active and, today more than ever, with greater investment predictability due to the growing penetration of modern and new technologies, as well as from the perspective of a fundamental contribution to mitigating climate changes and advanced distribution management strategies [14]. In fact, the reality is that one of the main and radical changes in power grids is already underway and is related to the migration from a paradigm of centralized power production to a paradigm of decentralized power production [15–18]. Alongside this revolution is the change from a unidirectional power flow to a bidirectional power flow, which forces the adoption and development of new solutions, both in terms of power management and in terms of power electronics equipment with new features, as analyzed in the review presented in [19]. The fundamental importance of these themes is widely investigated and disseminated for the next decades regarding issues related to sustainable energy, as investigated in [20,21], with simulations also playing a relevant role in the development of future power grids [22], as well as innovative test platforms for the penetration of new technologies [23]. In [24], the foreseen challenges for future power grids are addressed, where the most effective approaches to deal with the development of technologies are identified.

As a result of the development and presence of increasingly intelligent power grids, these are widely disseminated as smart grids, and the term “future smart grids” is beginning to take on special prominence. In this context of smart grids, residential users are also actively participating, leaving from a passive and simplistic approach of individual control and power consumption to an active approach of collective and participatory control and, above all, offering a perspective based on three power pillars: consumption, storage, and supply. This new perspective for residential users is commonly identified as “prosumers”. In [25], a generic demand model is proposed that considers the impact of prosumers on the future scenario of power grids and takes into account the optimization of self-consumption, as well as the participation in peer-to-peer power management schemes. In [26], a systematic review is presented on the coordination of intelligent power management systems at the residential level, aiming at the fulfillment of objectives related to the load profile and consumption/generation patterns, cost reduction, and managing the power resources. In this alignment, microgrids are also gaining enormous preponderance, allowing for the integration of distribution systems with loads, production, and storage systems, which can operate in a controlled and coordinated manner, connected to the main power grid or in islanded mode with autonomous operation. The influence of converter-based resources on the safety of microgrids considering radial distribution is presented in [27] and considering protection systems is presented in [28]. Strategies for detection and protection of faults in microgrids are presented in [29] with a view to reliable and precise protection as an important challenge in the proliferation of microgrids. In [30], a real-time digital system for estimating the harmonic content of converters is proposed in a future context of controllability, trust, and resilience in microgrids, either in grid-connected or island modes, demonstrating the importance and the negative effects that can emerge from poor power quality. In [31], a review of interconnected microgrids is presented from a perspective of resilience, robustness, and efficiency, where methodologies for the operation and control of microgrids are highlighted, as well as opportunities, challenges, and possible innovative solutions for microgrids. In [32], a comprehensive review of control algorithms for power electronics converters is presented, as well as control strategies for AC/DC microgrids. In this context, dedicated control strategies and synchronization mechanisms also assume a relevant preponderance for different scenarios of application, e.g., a remote microgrid synchronization avoiding the necessity of measurements at the point of common coupling is proposed in [33], adaptive synchronization mechanisms for power converters are proposed in [34], and advanced synchronization control of power converters in microgrids is proposed in [35].

In line with new technologies for future power grids and with the developments in power electronics, traditional substations are also changing, mainly in line with future DC grids. In [36], a review of multilevel converters with thyristors for HVDC applications is presented, and in [37], future electrical substations are presented considering the integration of HVDC grids, operating as a transmission layer of future hybrid AC/DC grids, showing the decisive role of the various technologies and topologies of power electronics converters. On the other hand, [38] presents the various possible configurations and a comparative evaluation for DC substations, while hierarchical control strategies are presented in [39]. In this context, it is easily recognized that power electronics is of vital importance for the evolution and modernization of power grids, as well as from the perspective of contributing to the development of more efficient solutions with greater control flexibility, as investigated in [40]. In [41], the role that power electronics can play in future power grids is analyzed, taking into account that it is introduced in a distributed manner, which allows for an economic approach to controlling the grid, with the aim of contributing to achieving global operating objectives with high penetration of various technologies. In [42], new and futuristic perspectives on the use of power electronics solutions are presented.

In Figure 1 the technologies that will be present in future power grids are identified, where the interfaces of such technologies will be supported by hybrid AC/DC grids and solid-state transformers (SST), as well as by unified multi-port solutions, all of them based on power electronics. The highlighted technologies are divided into various categories, including renewables such as solar PV panels (in offshore conditions, at home level, at and power plants), wind turbine (WT) technologies (in offshore conditions, power plants, and micro WT at the home level), energy storage systems (at a large scale in the power grid and at the home level), electric mobility (both bidirectional on-board and unidirectional off-board chargers), hydroelectric systems (power plants and micro-hydroelectric), factories (traditional and smart factories, e.g., with microgeneration and bidirectional power operation), and home (including traditional and smart homes with bidirectional power operation).

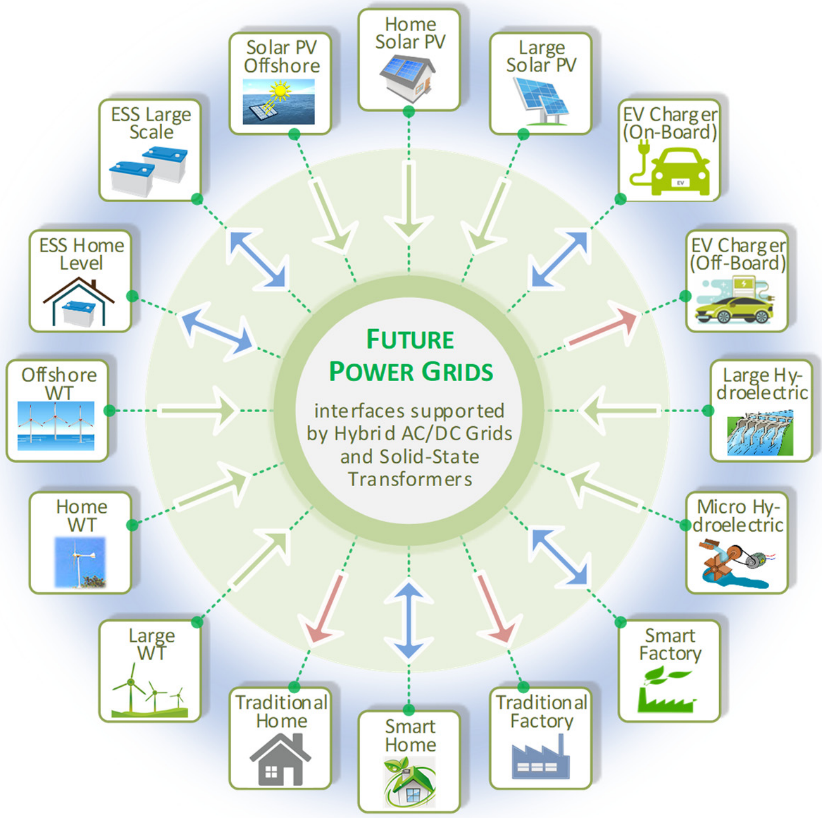

Figure 1. Technologies that will be present in future power grids, where the interfaces will be supported by hybrid AC/DC grids and solid-state transformers.

Several papers addressing hybrid AC/DC grids and SST can be found in the literature, however, in an exclusive way, and there is no global paper focusing on these aspects, on their direct relationship, and on the decisive role for future power grids. The papers that independently address hybrid AC/DC grids and SST are used as support of this paper and are properly presented and referenced. Encompassing the mentioned strands, this paper presents as its main contribution, when compared to the existing literature, the grouping together of a disruptive vision of future power grids in a single paper, essentially focusing on a path based on hybrid AC/DC grids and SST, as well as the decisive contribution of unified multi-port systems. Throughout the paper, these technologies are discussed individually from the perspective of future power grids, but also regarding the possible interconnections between them, as well as the interconnection with unified multi-port systems and with other important technologies such as those listed in this introduction. An exhaustive review of these technologies and the contribution of each one is carried out, covering the most relevant, recent, and diverse characteristics, structures, and models aiming at future power grids. Following this introduction, Section 2 presents the context of hybrid AC/DC grids in future power grids, the structures that can be created, and the addressed challenges. Section 3 presents the context of SST, its absolute importance for future power grids, as well as its challenges and opportunities. Section 4 presents unified systems and their importance to optimize the power transfer between systems and to reduce the number of power converters, both in AC and DC grids. Section 5 presents a discussion on these themes and associated technologies that play a preponderant role in future power grids. Finally, Section 6 presents the main conclusions.

2. Hybrid AC/DC Grids

New architectures of power grids are emerging as alternatives to the century-old AC grids, offering a set of significant challenges and opportunities in several areas. Particularly, approaches based on DC grids are emerging, which is not a new idea, as it goes back to the beginning of the implementation of power grids, with special emphasis on the technological dispute waged by Edison and Tesla/Westinghouse, as reported in [43]. AC grids prevailed, mainly due to the ease of use of transformers in facilitating the change of voltage levels, which allows for the transmission and distribution of power in a simple and efficient way. This advantage prevailed and continues to prevail as very important, as electrical equipment has always been designed to be connected to the AC mains. Despite this, due to technological advances in the field of power electronics and the fact that many technologies operate natively in DC, it will be more efficient to create a DC grid for directly coupling these technologies. In terms of technologies, at the top of the list and with special emphasis, are renewables (mainly solar PV), energy storage systems (mainly batteries and ultra-capacitors), and all aspects of electric mobility that require the power grid for charging purposes. Specifically, contemplating these technologies in future power grids, it is important to establish advanced metering infrastructure and demand-side management strategies (e.g., to deal with the uncertainties of power production from renewables, the consumption profiles of loads in different sectors, and cooperation of variable production of renewables with energy storage [44]), including the participation of buildings, the residential sector, and even data centers, as well as the impact of prediction errors in scenarios of demand-side management [45–50]. Specifically, the contextualization of a High Variable Renewable Energy Penetration in hybrid AC/DC grids is presented in [51].

In this context, it is evident that power grids are facing demanding challenges and the revolution in this regard has already begun, with DC grids gaining a natural preponderance due to several factors, namely the emerging and available technologies, which are the influence of modern solid-state power electronics devices. The main factors that have contributed to the development of DC grids are related to: (i) the installation of solar PV in houses and power plants is increasingly common; (ii) for the residential sector, batteries are mostly used as energy storage systems, and systems based on ultra-capacitors are also gaining popularity; (iii) lighting systems are increasingly based on LED technologies, so it makes perfect sense to establish low voltage DC grids only for the lighting systems; (iv) the integration of electric mobility into the power grids, through the residential sector and charging stations, assumes more and more prominence as functionalities available for the user increase, and therefore, as the storage systems are mostly based on batteries, the integration with DC grids in the bidirectional mode is logical; (v) in a DC grid, the voltage drop in the inductive reactance of the line impedance is eliminated, as well as many power quality problems (e.g., harmonics, power factor, and negative and zero sequence currents due to unbalanced loads) are mitigated; (vi) as the number of conversion stages using power electronics are drastically reduced, the elimination of multiple stages of conversion is possible, which translates into increased efficiency; (vii) elimination of built-in passive AC-DC rectifiers simplifies the design and cost reduction of electrical equipment developments; (viii) control systems for power electronics are simpler in DC grids; and (ix) DC grids can be operated independently (with controlled production/consumption) of the main AC grid.

However, this is a change that is not feasible to be carried out in a radical way in a short period of time, therefore, the cooperative conjugation of AC with DC grids is more than likely. In fact, it is possible for AC and DC grids to cohabit and cooperate in terms of power management. This possibility is well identified and is starting to become well-rooted for different contexts, being identified as "hybrid AC/DC grids". In [52], a comparative vision for the planning of microgrids based on hybrid AC/DC grids is presented, and in [53], a study demonstrates the feasibility, as well as the challenges, for the harmonization of hybrid AC/DC grids. It is revealed, on the one hand, that an AC grid allows for inertia and well-understood responses to disturbances that may occur. On the other hand, a DC grid generally has a lower fault tolerance and allows for faster responses. Thus, in an interconnected solution of hybrid AC/DC grids, it is possible that very complex dynamic and transient interactions occur.

Figure 2 shows the structure of a hybrid AC/DC grid, where technologies connected to both AC and DC grids are presented; power sharing between both grids can also be identified using power electronics. In this context, in [54], the decisive importance of power electronics systems from the perspective of DC distribution grids is highlighted. In [55], a DC grid with a multiterminal structure is proposed, aiming at the integration of electric mobility applications. In [56,57], exhaustive reviews on power electronics converters dedicated to applications in DC grids are highlighted. In [58,59], extensive and detailed revisions regarding classifications related to topologies and control systems are discussed. To summarize, the advantages are very clear and unequivocal for leveraging hybrid AC/DC grids.

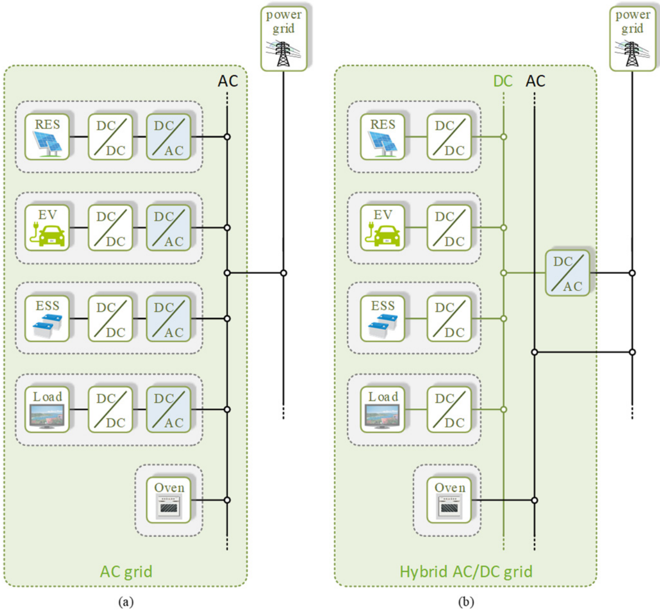

Figure 2. Exemplificative configuration of a hybrid AC/DC grid considering the interface of the same technologies, where the reduction of power converters can be verified: (**a**) Traditional AC grid; (**b**) Hybrid AC/DC grid.

As investigated in [60–62], hybrid AC/DC grids play a preponderant role in the residential sector, also contributing to the importance of smart homes as central to the development of future power grids. In this sense there are worldwide several projects, concluded or ongoing concerning hybrid AC/DC grids, permitting a greater attractiveness for power grids in the coming decades, e.g., as shown in [63–65]. In [66], the economic perspective of electrical appliances in a smart home is presented, discussing the viability of homes powered by a DC grid. In [67], a comparative analysis is presented for different power electronics topologies for DC supplied homes connected to the main AC grid. In [68], investigations are presented considering the behavior of non-linear loads when supplied in AC and DC grids. Despite all the advantages listed for DC grids and the rapid convergence of current grids to the new approach, there are still several challenges posed by DC grids. Some of these challenges are related to the standardization of voltage levels, network codes, and protection systems, as presented in [69–71]. In [72], the context of smart homes is presented, foreseeing the use of auxiliary services such as selective harmonics measurement for the main AC grid, while control solutions for power electronics converters in the interconnection of hybrid AC/DC grids are investigated in [73,74]. In [75], distinct applications and projects of DC grids are examined. Examining the structure of DC grids in detriment to AC grids or from a compromise perspective between both structures, it is essential to select suitable voltage levels as a compromise between efficiency and compatibility, as investigated in [76]. In [77], a distribution system based on a DC grid is presented, contemplating the interconnection of specific and complex electrical devices, while an innovative hierarchical control system particularly oriented towards DC grids with strong integration of renewables is proposed in [78]. In this context, other perspectives are identified for DC grids, such as the modes of operation in urban scenarios [79], the flexible control of power flow [80], the power flow regulation and management [81], and the multi-objective approaches for designing energy storage systems in scalable grids [82].

2.1. Unipolar and Bipolar DC Electrical Power Grids

With regard to possible structures to implement for DC grids, two main ones stand out: unipolar and bipolar [83,84]. Making a brief analysis of both structures, it is possible to conclude that, since it involves three wires, the bipolar structure is more complex in terms of control and hardware requirements. However, the bipolar structure has gained preponderance, due mainly to the advantage of supplying two voltage levels, representing an asset for the integration of DC technologies with different voltage levels. Furthermore, in case of the failure of one of the wires, the bipolar structure can, in exceptional situations, continue to operate, a feature that cannot be guaranteed by the unipolar structure. In [85], a broad evaluation related to emerging technologies and directly related to bipolar DC grids is presented. Despite the emphasis given to DC grids with a bipolar structure, they are susceptible to some problems such as the case of voltage imbalances, mainly due to imbalances in the loads or in the operating power for each of the levels. Thus, it is important to use power electronics converters with bipolar interfaces in the connection with the DC grid, ensuring that the consumption is properly balanced for the stability of the DC grid.

2.2. Structures of Hybrid AC/DC Grids

The structure of a hybrid AC/DC grid must consider some important characteristics for its correct functioning, regardless of the interconnected technologies, such as the guarantee of the power quality and the principle of hierarchy. Regarding the structure of a hybrid AC/DC grid, a distinction can be made between AC coupled and AC decoupled configurations, as shown in Figure 3.

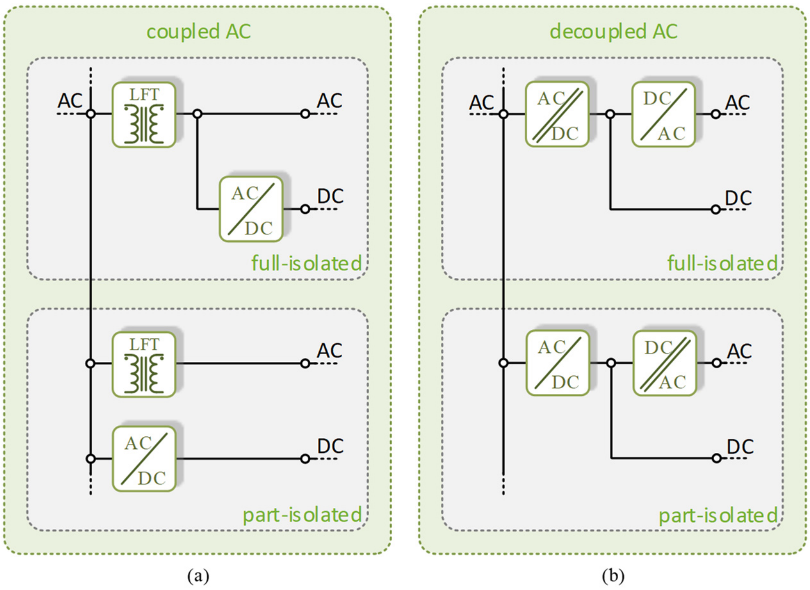

Figure 3. Comparison of full-isolated or part-isolated hybrid AC/DC grids: (**a**) Coupled AC configuration; (**b**) Decoupled AC configuration.

In the coupled AC configuration, a transformer is used to connect the AC grid of the hybrid AC/DC grid to the main AC grid, and a power electronics converter is used to create the DC grid. In this configuration, it is the low-frequency transformer that guarantees the galvanic isolation of the main AC grid. As the DC grid is established after the galvanic isolation, this configuration ensures that the hybrid AC/DC grid is fully galvanically isolated from the main AC grid. However, the DC grid can be established with the power electronics converter directly connected to the main AC grid, meaning that the hybrid AC/DC grid is only partially isolated from the main AC grid (i.e., only the AC grid is isolated). On the other hand, analyzing the AC decoupled configuration, it appears that at least one AC–DC and one DC–DC power electronics converter stage is required. For this reason, as the size of the AC–DC converter for managing the energy flow between the main power grid and the DC grid is larger, the costs associated with the AC decoupled grid are higher when compared to the AC coupled. However, in the AC decoupled configuration, the AC grid uses an AC–DC power stage and a DC–AC power stage in the AC connection to the AC main grid, ensuring that isolation and independent control algorithms are used in both grids. In this type of configuration, an SST can be used, guaranteeing the necessary galvanic isolation and the necessary control flexibility [86,87]. In the case of decoupled AC configurations, the AC grid and the DC grid are defined after the galvanic isolation, ensuring that the entire hybrid AC/DC grid is fully isolated from the main AC grid. However, galvanic isolation may not be guaranteed by the DC–AC converter, and therefore, the hybrid AC/DC grid is only partially isolated.

2.3. Problems to Be Solved

Despite the advantages listed for hybrid AC/DC grids, such as increased operating flexibility, a reduced number of power conversion stages compared to the traditional AC grid, and a greater power transfer capacity and technology interconnection, there are still many problems that need to be resolved with a view to widespread implementation. Currently, in addition to the technical requirements that the design of hybrid AC/DC grids requires, economic viability is also an obstacle to the wide implementation and development of these solutions as replacements for the currently available AC grids. New electricity metering systems, as well as new protection systems, are also needed for the effective implementation of hybrid AC/DC grids. These problems are also a reality even if the objective is to incorporate a new DC grid in the current AC grids, aiming at the implementation of hybrid AC/DC grids. Another problem is related to the definition of voltage values for the DC grid, which must be set to allow easy connection of common DC loads. Furthermore, it is also imperative that current electrical equipment is designed without the requirements of AC/DC converters at the front-end stage so that it can be directly connected to the DC grid. Despite these challenges that must be overcome, hybrid AC/DC grids are emerging and are predicted to be the next major evolutionary step in the evolution of electrical grids. To this end, the residential sector is identified as a first step towards the implementation of hybrid AC/DC grids, mainly due to the relative ease with which they can be developed and considered in the initial electrical project. This perspective assumes even more preponderance considering the integration, and often legislative obligation, e.g., installation of renewables (PVs), LED lighting systems, and EV charging systems. In the future, for the implementation of hybrid AC/DC grids, it is also important to take into account aspects such as control methodologies for the operation of hybrid AC/DC grids; dynamic operation and stability analysis; monitoring techniques; innovation in protection systems; dynamic and transient stability control; electromagnetic compatibility analysis; mitigation of operation problems between converters; advances in electrical equipment for interfacing with DC grids; control and operation in blackout situations; cyber security; islanding and dedicated control synchronization mechanisms; and standardization and regulation challenges.

3. Smart Transformer

Power electronics play a central role in establishing future directions for power grids, allowing for the interface with many different technologies. Since the emergence of power grids, the conversion of voltage levels at the transmission and distribution level was achieved by conventional low-frequency power transformers and century-old base technology. Nowadays, low-frequency transformers are still largely used. However, because of the large number of new technologies and players connected at the low voltage level, new challenges are also rapidly emerging, mainly with a focus on providing precise and fast controllability of the power grid. The importance of using power electronics technologies to respond to emerging challenges is clearly identified, where the possibility of replacing low-frequency transformers by smart transformers is extremely important, allowing for controllability and offering auxiliary services at the distribution/transmission as a fundamental new step of controllability for power grids, as demonstrated in [88].

3.1. Hybrid Transformer

Hybrid transformers are an alternative to low-frequency transformers, offering a set of benefits that allow for greater controllability of the power grids, as well as the increase in power quality standards. A hybrid transformer can be built with different configurations according to the connection of power electronics systems, as discussed in [89] and shown in Figure 4. In Figure 4a is presented an AC–DC converter connected to an auxiliary secondary winding for compensating for power quality problems related to currents. In Figure 4b is presented an AC–DC converter connected in series with the secondary winding for compensating power quality problems related with the voltages. On the other hand, Figure 4c presents AC–DC and DC–AC converters connected to an auxiliary secondary winding and in series with the secondary winding for compensating power quality problems related to currents and voltages. Figure 4d presents an AC–DC converter connected in parallel with the secondary winding for compensating power quality problems related to currents.

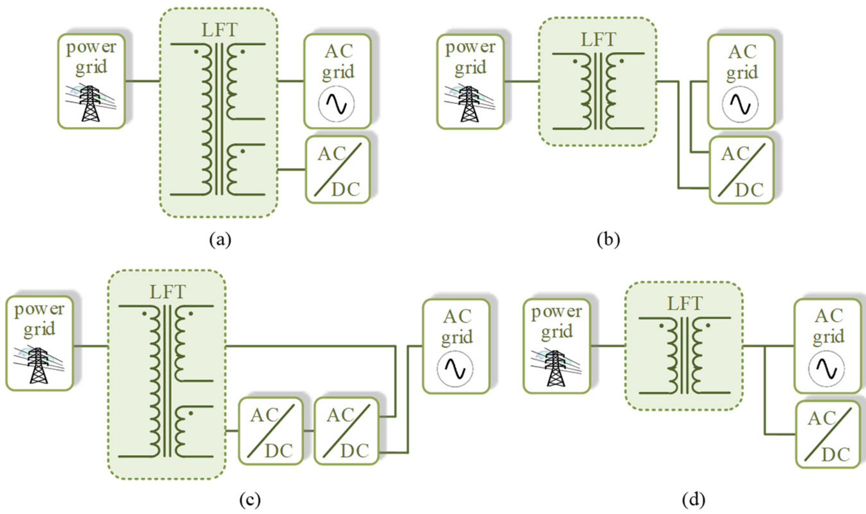

Figure 4. Possible configurations of hybrid transformers for different application scenarios and based on: (**a**) AC–DC converter connected to an auxiliary secondary winding; (**b**) AC–DC converter connected in series with the secondary winding; (**c**) AC–DC and DC–AC converters connected to an auxiliary secondary winding and in series with the secondary winding; (**d**) AC–DC converter connected in parallel with the secondary winding.

Briefly, a hybrid transformer rests on the base frame of a low-frequency transformer, but with an additional configuration where a power electronics converter is connected, which offers additional controllability, mainly for load voltages and currents on the main power grid. In [90], a control system composed of a hybrid transformer at the distribution level is proposed, consisting of two power stages that interconnect the primary and secondary sides in order to guarantee sinusoidal voltages on the secondary side and sinusoidal currents on the primary side. In [91], the design of a protection concept for a hybrid transformer is presented, showing the valences that it offers to power grids in terms of power quality and taking into account aspects of active protection.

3.2. Solid-State Transformer

In this context, even more promising and with many more advantages in terms of controllability, although much more demanding in terms of design, control, and protection, is the SST. In [92], the origin and technological advances related to the key concepts of the SST are detailed, presenting the main configurations in terms of power electronics and exemplary industrial projects. In [93], the SST is meticulously investigated in terms of its impact on the power grid, as well as the inherent technological challenges, covering control and communication functions and modular structures. On the other hand, in [94], an investigation is presented on the use of the SST for the regulation of frequency values in real time considering the control of the power consumed by the loads, allowing for a fast response. In fact, mainly over the last few years, SST technologies have undergone very relevant progress in terms of applications and topologies, where important projects were dedicated to SST development, showing that it is a key element at the distribution level.

The applicability of SST in future power grids, as well as in the actual power grids, is investigated in [95], highlighting the limitations of the SST for an immediate replacement to traditional transformers, the technological challenges of the SST and associated technologies, as well as the possible scenarios for SST applications. These investigations were conducted to show that the SST is seen as an answer to help to solve different challenges in the power grid. However, it was also identified that new challenges are emerging, where the SST design is a challenge in itself. In [96], the SST at the distribution level is analyzed with regard to constructive technologies and supported functionalities, and in [97], it is analyzed at the level of implementation challenges, taking into account the contribution to improve stability and reliability at the distribution level. Aligned with various areas in future power grids, the SST is seen with special focus on the application at the distribution level and in the residential sector. At the residential level, it is possible to use SSTs in smart homes (one per smart home), each one providing ancillary services for the main power grid when necessary, operating collaboratively between them and according to the availability of each one (e.g., in terms of operation with active and reactive power). As a contribution to solving the emerging challenges associated with the SST and giving it a future perspective on power grids, it is important to consider a multidisciplinary approach, with a special focus on the development and use of power electronics technologies such as the system control of power electronics. It is important to highlight that the SST configuration determines the services it can provide when applicable to specific installations, where aspects such as the analysis of technical requirements, harmony with power grid standards, and the identification of critical operating conditions influence the global SST project. Regarding the cost of SST, it is very dependent of the final application, the topology, and the nominal power (e.g., if the SST is for distribution power systems or for the residential sector). Nevertheless, the SST market, as presented in [98], was valued at USD 141.5 million in 2020 (where Europe accounts for the largest SST market) and the projection for 2028 is a value of USD 468.0 million, clearly demonstrating the importance of SST for future power grids. Figure 5 shows the main SST configurations for different application scenarios, considering the use of AC–AC power converters on both sides (a), indirect AC–AC power converters on both sides (b), and modular multilevel power converters with input-series output-parallel (ISOP) structure (c), and input-series output-series (ISOS) structures (d).

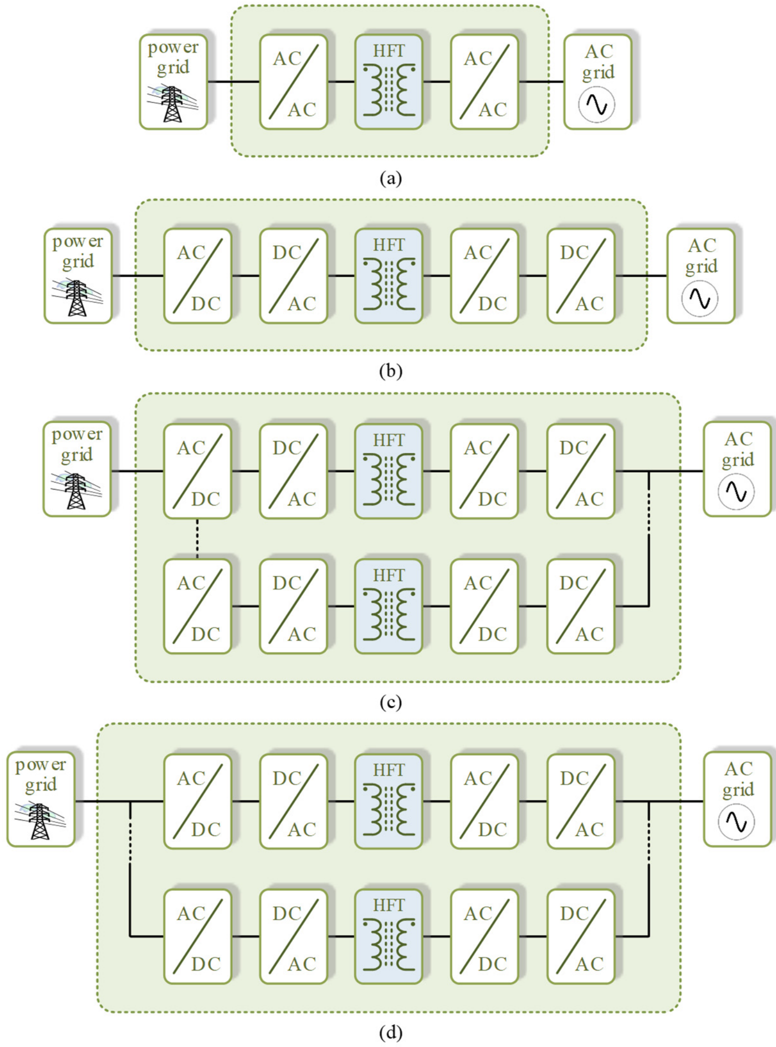

Figure 5. Possible configurations of SST for different application scenarios and based on: (**a**) Direct AC–AC power converters in both sides; (**b**) Indirect AC–AC power converters in both sides; (**c**) Modular multilevel input-series output-parallel (ISOP) structure; (**d**) Modular multilevel input-series output-series (ISOS) structure.

In terms of the structure of the power stages, as main characteristics that positively influence its development, it can be highlighted: (1) power electronics converters that best adapt to the SST requirements (e.g., use of multilevel topologies, mainly for the HV and MV); (2) emerging switching device technologies (WBG such as SiC and GaN) for all power stages, with the main focus on improving energy efficiency and increasing power density; (3) innovative magnetic elements designed to optimize the efficiency of power converters for a wide range of operating powers; (4) advanced capacitor technologies to increase system reliability, safety and lifespan of power converters; (5) new trends in programmable and more versatile digital platforms (e.g., DSPs and FPGAs); (6) innovative cooling systems in line with new switching devices; (7) new sensor/transducer technologies (e.g., including signal conditioning).

Considering the versatility that the SST allows in terms of configurations, the possibility of hybrid AC/DC configurations is also identified as an associated and very promising technology for future power grids. In fact, this context of using SSTs to establish hybrid AC/DC grids is perfectly in line with the development of hybrid AC/DC grids presented in Section 2. In this context, the SST gains even more preponderance since it can be developed to interact with technologies operating natively in DC, as is the case of renewable energies, storage systems, and electric mobility. Figure 6 shows examples of the use of SSTs within structures that allow for the creation of hybrid AC/DC grids. In Figure 6a an SST is used in the creation of a hybrid AC/DC grid at low voltage (LVAC and LVDC), while in Figure 6b, an SST is used in the creation of a hybrid AC/DC grid (hybrid AC/DC grid in LVAC and LVDC) and with a DC grid in HV (HVDC).

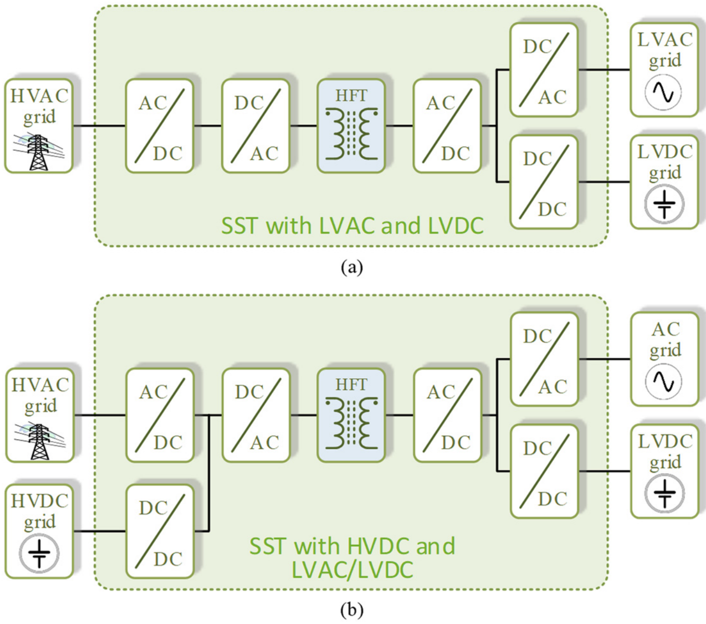

Figure 6. Application of a traditional SST structure to establish: (**a**) A hybrid AC/DC power grid with LVAC and LVDC; (**b**) A hybrid AC/DC power grid with LVAC and LVDC and with HVDC.

Aligned with the possibility of the SST for creating hybrid AC/DC grids, in [99], an SST is proposed that would allow for the configuration of hybrid AC/DC grids as a promising solution to obtain simultaneous control of power flow and voltage and consisting of a low voltage DC grid. In [100], a hybrid SST in an input-series output-parallel configuration is proposed that is suitable for connecting MVDC and LVDC distribution grids. In [101], a hybrid and modular SST is proposed, combining control flexibility and high operating efficiency, while problems related to modeling and control strategies are also discussed. In [102], a new modulation and control strategy is proposed for the multilevel and modular converter when applied to an SST, where the medium frequency isolation link, integrated with the modular converter structure, stands out, which translates into lower volume and higher power density.

Regarding the interface with other technologies, the SST represents an added value, mainly for the interface with renewables, energy storage systems, and electric mobility. In this context, in [103], the application of an SST in the interface with renewables, specifically with PV, is presented, proposing a modular configuration where the various panels are connected in a DC grid and the interface with the power grid is made through an SST. In addition to the renewables interface, in [104], a SST configuration is proposed that uses multiple DC–DC converters according to the number of panels, and the interface with the power grid is carried out by the SST. On the other hand, [105] proposes the use of a modular SST for fast charging applications for electric mobility, based on the concept of using multiple DC–DC converters according to the number of vehicles and requiring only one interface with the power grid, i.e., a DC grid is created with individual converters for charging EVs.

As mentioned, the design of an SST is a challenge in itself, as different topologies and power electronics technologies can be used. In this context, in [106], a modular SST built with SiC technology for MV applications is presented, highlighting the analysis of the problem, the control architecture, implementation design, and validation. In [107], the analysis, modeling, and control of multiple active high-frequency converters, which employ SiC technology, are proposed, aiming at a new generation of SST. In [108], active semiconductor control strategies for an SST are addressed, based on a single-stage structure, using soft-switching, and having as its main objective the reduction of conduction losses. In [109], a new high-frequency single-stage SST structure is proposed, with the objective of reducing the number of switching devices, based on a dual active bridge converter and a buck circuit that operates in an interleaved mode. The optimization of multi-physics and multi-objectives for high-frequency transformers (with core parameters and the number of turns as optimization variables) for SST applications, regardless of their configuration, is investigated in [110]. In [111], an SST based on a structure of a matrix-type power electronics converter on both sides of the SST is proposed, ensuring a single-stage and capacitor-free configuration and resulting in a large impact to increase service life and reduce weight and volume. In [112], an SST based on a three-level power module is proposed with the aim of connecting MVAC grids and LVDC grids, showing the importance of SSTs in a perspective of unique integration in DC grids. In [113], the application of an SST for power transmission systems based on HVDC as an interface for an offshore windfarm is presented. In this context of SST applications for future electrical grids, it is also very important to highlight that the SST research is aligned with a relevant market growth and with industrial players, including the presence of key companies such as Siemens AG, ABB, General Electric Company, and Schneider Electric SE. In addition, the SST market is expected to gain more attraction in the coming decades, where a gradual shift towards the implementation of SSTs is assumed.

Table 1 presents a summary of SST for applications of hybrid AC/DC grids. This summary is based on the analysis of the topology/structure and features/capabilities. It is important to note that the objective is not to establish a comparison between all the possible SST, as presented e.g., in [87], but limit the analysis to SST for applications of hybrid AC/DC grids. Specifically, a family of SSTs based on the modular multilevel converter for hybrid AC/DC grids is proposed in [114].

Table 1. Summary of SST for applications of hybrid AC/DC grids.

References	Topology/Structure	Features/Capabilities
[115]	Multi-stage based on three multilevel AC–DC (primary side), isolation based on DC–DC DAB, and three multilevel DC–AC and a multilevel DC–DC (secondary side)	LV AC at the primary side, and LV DC and LV AC at the secondary side for interfacing a hybrid AC/DC grid
[116]	Multi-stage based on a full-bridge AC–DC (primary side), isolation based on DC–DC DAB, and DC–DC and full-bridge DC–AC (secondary side)	MV AC at the primary side and MV DC, LV DC, and LV AC at the secondary side (three outputs)
[117]	Multi-stage based on modular multilevel converters (primary side), isolation based on DC–DC DAB, and full-bridge DC–AC (secondary side)	MV AC at the primary side and MV DC, LV DC, and LV AC at the secondary side (three outputs)
[102]	Multi-stage based on modular multilevel converters (primary side), isolation based on a magnetic integration without converter, and full-bridge DC–AC (secondary side)	MV AC at the primary side and LV DC at the secondary side, without intermediary DC–DC converter
[118]	Single-stage based on modular multilevel matrix converter (primary side), isolation based on three-phase three-port transformer, and by full-bridge DC–AC (secondary side)	MV AC at the primary side and two LV DC at the secondary side, formed from the two outputs of the transformer
[119]	Multi-stage with multilevel DC–DC, and isolation based on a DC–DC formed by an NPC (primary side) and by a full-bridge (secondary side)	MV DC at the primary side and LV DC at the secondary side, with DC operation in both sides
[120]	Multi-stage with full-bridge AC–DC (primary side), a bidirectional DC–DC, isolation based on dual stacked half-bridge DC–DC DAB, and DC–AC (secondary side)	LV AC at the primary side and LV DC and LV AC at the secondary side for interfacing a microgrid

Table 1. *Cont.*

References	Topology/Structure	Features/Capabilities
[121]	Multi-stage with cascade AC–DC (primary side), isolation based on a full-bridge DC–DC (four-winding topology), and individual DC–DC and DC–AC (secondary side)	MV AC at the primary side, and two LV DC and a LV AC at the secondary side formed through each output of the DC–DC
[122]	Multi-stage with full-bridge AC–DC (primary side), isolation based on DC–DC DAB, and for the hybrid AC/DC grid a full-bridge DC–AC and DC–DC DAB (secondary side)	MV AC at the primary side, and LV DC and a LV AC at the secondary side for interfacing a microgrid
[123]	Multi-stage with cascade full-bridge AC–DC (primary side), isolation based on DC–DC DAB, and full-bridge DC–AC (secondary side)	HV AC at the primary side, and LV DC (formed from the output of the DC–DC DAB) and a LV AC at the secondary side

4. Unified Multi-Port Systems

Today, with the escalation of smart grids, the controlled and dynamic integration of new technologies, with a particular focus on electric mobility, renewables, and energy storage systems, is increasingly predictable without neglecting power quality. To this end, as presented in previous sections, hybrid AC/DC grids and the SST will play a preponderant role in the integration of technologies such as these. Despite the rapid spread of electric mobility, for its integration into smart grids, it is absolutely essential to adopt adaptive control strategies for charging, as highlighted in [124], as well as to avoid power quality problems, as shown in the research results presented in [125]. Additionally, it is also necessary to take advantage of its use with the new paradigms of microgrids as analyzed in [126], and the power exchange in bidirectional mode through the grid-to-vehicle and vehicle-to-grid operating modes, as demonstrated in [127]. In particular, the benefits of the vehicle-to-grid mode to balance power demand in the context of smart grid are analyzed in [128] and the impact and challenges of vehicle-to-grid on the power grid are presented in [129]. In addition to these modes of operation, new opportunities and challenges for future smart grids arise in terms of new modes of operation, as investigated in [130].

As widely mentioned and investigated, in addition to the introduction of electric mobility, the massive introduction of renewables is also expected, with new opportunities and considering different conditions of the power grids. An integrated strategy aimed at power management considering the collaborative operation between electric mobility and power production from renewables is presented in [131], the impact of electric mobility and solar PV in terms of investment is presented in [132], and an innovative management strategy for cost minimization considering charging stations with renewables is proposed in [133]. However, the mentioned strategies are mainly based on control algorithms, e.g., maximizing the power supplied by renewables, maximizing the cost benefits to the utility company, energy balancing strategies, minimizing the charging time of electric mobility, or the programming to start and stop charging processes according to the power supplied by renewables. Moreover, even considering the highly diverse and very important contributions of these technologies, especially regarding the innovation in cooperative modes of operation, many individual power converters are needed for the interface with the power grid, contributing to global solutions with low efficiency. Therefore, with the natural evolution of smart grids, with the foreseeable increase of electric mobility and renewable solutions and considering the similarities between the power converters of these systems, opportunities have been identified for unified approaches, offering advanced control for future power grids, improving efficiency, and reducing costs, weight and volume.

Unified solutions can be classified in several ways, including the possibility of a single interface to the AC grids and multiple DC outputs (which can, for example, be isolated from each other or there may be a micro DC grid) or the possibility of a single interface with the DC grid and multiple DC outputs (which can be, e.g., isolated from each other or there may be a micro DC grid), as shown in Figure 7.

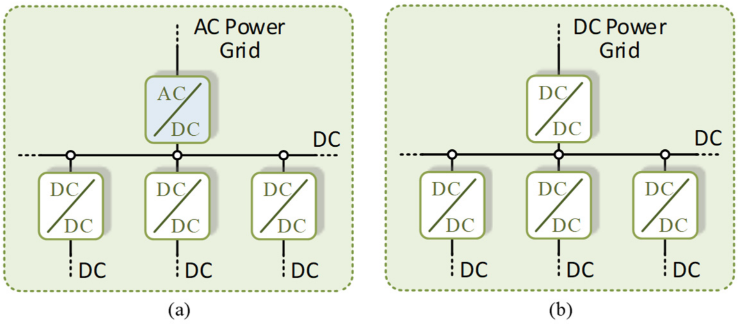

Figure 7. Unified multi-port systems when applied in: (**a**) AC power grids considering an AC–DC converter for a single AC interface and multiple DC–DC converters for multiple DC interfaces; (**b**) DC power grids considering a DC–DC converter for a single DC interface and multiple DC–DC converters for multiple DC interfaces.

Unified solutions are advantageous for interfacing two or more technologies with an AC or DC grid and can be applied in different contexts, including the residential sector. In this context, a new system based on a single-leg multimode power converter is proposed in [134] to control the power flow between DC systems, including renewables, but without the grid interface. A multi-port topology to deal with electric mobility, solar PV, and the power grid is presented in [135], but such a topology requires the use of two power converters to interface with the power grid, one operating as an active rectifier, and the other as a grid-tied inverter, representing a major disadvantage. In [136], a multi-port structure with DC–DC power converters is proposed, aiming at the integration between renewables and energy storage systems, which allows for integration into a DC grid and which is based on isolated converters sharing a DC link. In [137], a new multi-port structure is proposed for the applications of charging stations for electric mobility, also considering renewables and energy storage. In [138], a three-port DC–DC power converter is proposed for renewable energy applications that allows the integration of a DC grid with two inputs from two sets of solar PV panels connected with only one common point. In [139], a synthesis of DC–DC converters with a multi-input and multi-output structure is proposed, which presents as an innovative feature the fact that they do not have energy buffer stages, allowing the establishment of modular structures.

Figure 8 shows some comparative examples of the energy flow in traditional and unified solutions, considering renewables and energy storage. In Figure 8a, the comparison is made considering the interface with an AC grid. As can be seen, with the traditional solution, four conversion stages are required (two AC–DC and two DC–DC power converters) when the power flow is from the renewable to the storage system. On the other hand, with the unified solution, only two conversion stages are necessary in the same situation. In this case, only an interface with the AC grid is required, so it is necessary to use an AC–DC converter, but it is only used when it is necessary to inject power into the grid or charge the batteries from the power grid, i.e., when the power follows directly from the renewable to the storage system, the power grid is not used. In Figure 8b the comparison considering the interface with a DC grid is presented. As can be seen, with the traditional solution, two conversion stages (two DC–DC power converters) are needed when the power flow is from the renewable to the storage system, while only one conversion stage is needed in the same situation with the unified solution.

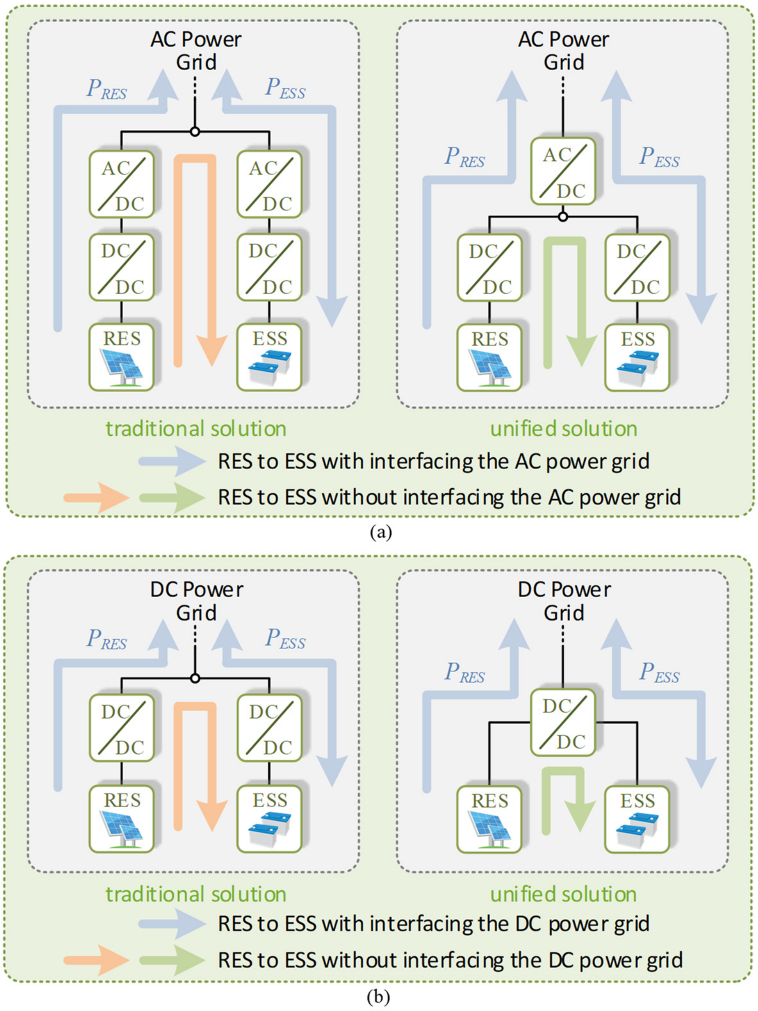

Figure 8. Exemplificative comparison of the power flow between traditional solutions and unified multi-port solutions, considering renewables and energy storage, when applied in: (**a**) AC power grids; (**b**) DC power grids.

5. Collaborative Vision of Technologies

In the previous sections, several technologies were presented, with a special focus on hybrid AC/DC grids, SSTs, and unified multi-port systems, highlighting the contributions of each of these technologies to the future power grids and, whenever appropriate, showing interconnections between them. The collaborative participation of these technologies in future power grids is obvious, and they can be considered for different application scenarios.

Figure 9 presents an example of a disruptive view of the future power grids supported by these technologies. As can be seen, a residential scenario is presented, showing that the concept of a smart home also involves the integration of the technologies addressed in this paper. A fully AC smart home that employs an SST is shown. Thus, from the point of view of traditional AC loads, they continue to be connected to the AC grid in the same way. On the other hand, unified solutions can be employed to reduce the number of converters to interface with the AC grid, e.g., integrating renewables and storage systems. In this scenario, the SST plays a fundamental role in ensuring the power quality, both in terms of the sinusoidal voltage available to the smart home, and in terms of the sinusoidal current consumed by the main AC grid. Furthermore, by employing an SST in each smart home, it is possible for each of them to provide additional services to the main AC grid, e.g., regarding the production of reactive power, voltage and frequency control, and the compensation of current harmonics. On the other hand, the figure also presents a scenario of a smart home, but where the SST is used to establish a hybrid AC/DC grid for the smart home. In this way, many of the loads can be directly connected to the DC grid (e.g., TV and light systems), significantly reducing the number of AC–DC converters. On the other hand, loads operating natively on AC can continue to be connected to the AC grid. In this situation of a smart home with a hybrid AC/DC grid, as shown, it is also possible to use unified multi-port systems, as presented in Section 4. Obviously, this same SST can be controlled to provide auxiliary services to the AC grid as the SST presented in the fully AC smart home scenario. Thus, these two SSTs can guarantee their operation for each of the smart homes independently but provide joint services for the main AC grid. An SST can also be used to interface an MVAC grid to create a hybrid AC/DC grid (LVAC and LVDC). In this DC grid (LVDC), several technologies can be connected, such as charging stations for electric mobility using a multi-port DC–DC power converter, as well as the interface of a multi-port DC–DC power converter for renewables, storage systems, and electric mobility.

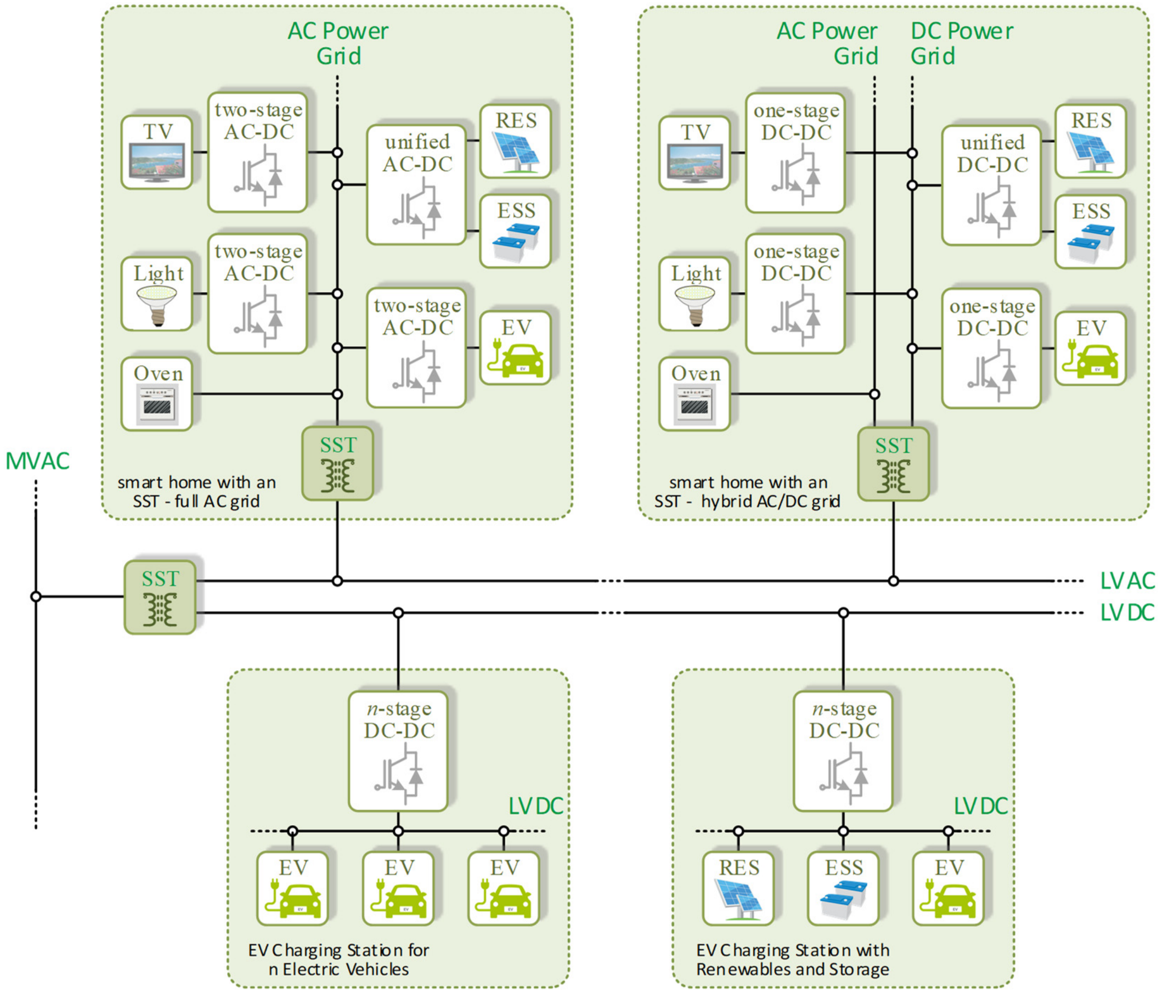

Figure 9. A disruptive vision of future power grids considering: A smart home with an SST (cf. Figures 5 and 6) and with a full AC grid; A smart home with a SST and with a hybrid AC/DC grid; An EV charging station for n EVs using an n-stage DC–DC (cf. Figures 7 and 8); An EV charging station with renewables and storage using an n-stage DC–DC.

In Figure 10 it is possible to verify the use of SSTs in the interface of the HVAC grid and the MVAC grid. In this figure, it is possible to verify an example of the application of a SST linked to the HVAC grid aiming to interface railway, hospital, and industry systems. Additionally, as shown, an SST can also be used to create a DC grid (LVDC). In this DC grid, several technologies can be connected, such as the interface of a multi-port DC–DC power converter for renewables, storage systems, and electric mobility. This figure also shows the use of an SST in the interface between an MVAC grid and an LVAC grid, where it is possible to verify, just as an example, the connection of industries, renewables, smart homes, storage systems, electric mobility, and offices. Obviously, many other scenarios will be considered in future power grids, but it is not possible to report all the possible configurations in this paper. The scenarios for the future vision of power grids encompass all the mentioned technologies, allowing us to unveil the evolution that culminates in the cooperative scope of these technologies.

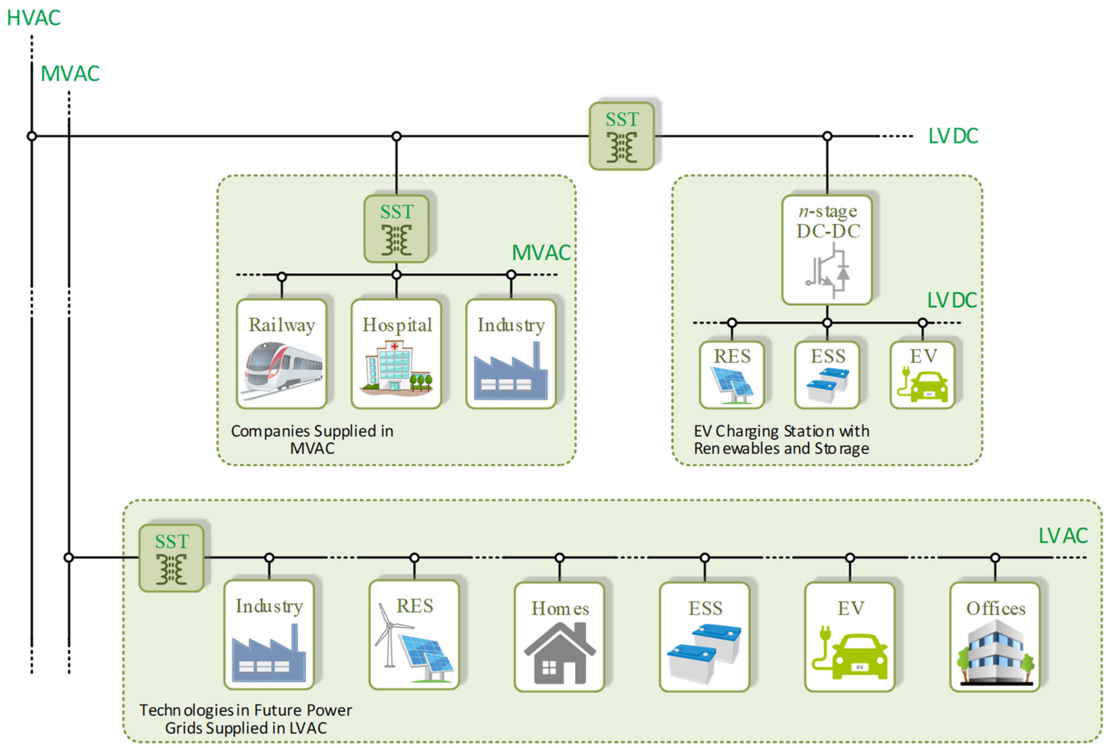

Figure 10. A disruptive vision of future power grids considering: A set of exemplificative companies supplied in MVAC through an SST; An EV charging station for n EVs using an n-stage DC–DC (cf. Figures 7 and 8); A set of technologies in future power grids supplied in LVAC through an SST.

6. Conclusions

New power grid architectures are emerging as alternatives to traditional AC grids, offering an interesting set of challenges and opportunities, where technological advances in the field of power electronics are fundamental. As demonstrated throughout the paper, convergence towards hybrid AC/DC grids is foreseeable, offering greater flexibility and improved efficiency for the future power grids, especially for those that operate natively in DC (since the AC–DC converters to interface the AC grid are dispensed). In this sense, the structures of the hybrid AC/DC grids and their coupling or decoupling with the main AC grid are presented in this paper, as well as viable options of unipolar and bipolar configurations (i.e., DC grids based on two-wire and three-wire, respectively). With the objective to respond to emerging challenges of power grids, the possibility of replacing traditional low-frequency transformers without any control by smart transformers is also presented, highlighting all the added value that this entails. In this context, several configurations of hybrid transformers are addressed, consisting of a low-frequency transformer combined with power electronics converters, with a series or shunt interface, aiming to provide additional functionalities to mitigate the power quality associated with voltages or currents. More prominently, the context of using the solid-state transformer (SST) is also presented, showing that it is an even more promising technology with many more advantages in terms of controllability in both the primary side and the secondary side, although much more demanding in terms of design, control, and hardware. Regarding the SST, the main configurations for different application scenarios regarding the use of power electronics converters (e.g., use of direct or indirect AC–AC converters and the use of single-stage or multi-stage) are presented, as well as different structures for framing with hybrid AC/DC grids (as presented, which can be performed in both sides of the SST). The use of the SST in future power grids is also presented, including the fact that the coupling side with the main AC grid can be used to provide complementary services for the power grids, e.g., allowing for collaboration in the production of reactive power or in the selective compensation of current harmonics. A specific and comparative analysis of SSTs for applications of hybrid AC/DC grids is also presented, which is based on the topology/structure and features/capabilities. This paper also presents the future vision of using unified multi-port systems for interfacing various technologies, both in AC and DC grids, which are foreseen to play an important role in future power grids (e.g., the unified interface of renewable energy sources and energy storage systems). The disruptive vision of new power grids supported by these technologies is presented throughout the paper, highlighting several application scenarios that encompass these technologies. In this context, summarizing, it is possible to unveil the evolution that culminates with the cooperative scope of these technologies: the convergence to hybrid AC/DC grids will allow technologies that operate natively in DC to be directly integrated into a DC grid (e.g., reducing the number of power converters and consequently maximizing the efficiency); unified multi-port systems will allow for a significant reduction of power conversion stages, both in AC and DC grids (e.g., a connection of a renewable energy source with an energy storage system can be performed through a single power converter and without the power grid as an intermediary); and the SST will allow the interconnection of voltage levels (e.g., HVAC to MVAC or MVAC to LVAC), and can also be designed for hybrid AC/DC grids, in both primary side or secondary side, as demonstrated in the paper, therefore comprising the possibility of DC grids in HV and LV. Despite the listed advantages, there are still many aspects that need to be resolved with the objective of widespread implementation of the technologies addressed in this paper, and in the full and simultaneous operation of all technologies, which is a challenge for power grids in the coming decades. Thus, it is not easy to predict when the complete revolution made possible by these technologies will take place, but, as the path is progressing, the initial steps are already well-founded and the decisive role of power electronics aiming at this transformation is absolutely guaranteed and is now in progress.

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