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Perspective

The Future of Electrical Power Grids: A Direction Rooted in Power Electronics

Vitor Monteiro * and Joao L. Afonso

ALGORITMI Research Centre/LASI, University of Minho, 4800-058 Guimarães, Portugal; jla@dei.uminho.pt
* Correspondence: vmonteiro@dei.uminho.pt

Abstract: Electrical power grids are changing with a focus on ensuring energy sustainability and enhanced power quality for all sectors. Over the last few decades, there has been a change from a centralized to a decentralized paradigm, which is the consequence of a large-scale incorporation of new electrical technologies and resultant equipment. Considering the foreseeable continuation of changes in electrical power grids, a direction rooted in power electronics with a focus on hybrid AC/DC grids, including the support of solid-state transformers and unified systems, is presented in this paper. Converging on hybrid AC/DC grids, DC grids (structured as unipolar and bipolar) and coupled and decoupled AC configurations are analyzed. On the other hand, in the context of solid-state transformers, feasible structures are analyzed, including the establishment of hybrid AC/DC grids, and the assessment of gains for boosting power quality is presented. Unified power electronics systems are also of fundamental importance when contextualized within the framework of future power grids, presenting higher efficiency, lower power stages, and the possibility of multiple operations to support the main AC grid. In this paper, such subjects are discussed and contextualized within the framework of future power grids, encompassing highly important and modern structures and their associated challenges. Various situations are characterized, revealing a gradual integration of the cited technologies for future power grids, which are also known as smart grids.

Keywords: future power grids; hybrid AC/DC grids; smart grids; solid-state transformer; power quality; power electronics

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1. Electrical Power Grids

With the aim of ensuring worldwide access to electrical energy, power grids are in a state of constant evolution in different areas of actuation, including the sectors of production, transport, and distribution. This evolution has been more evident over the last few decades. Despite initial efforts to design distributed power grids, the fact is that centralized power grids achieved predominance [1]. Since the beginning, and along with the natural evolution of power grids, real-time stability in the production and consumption stages was always viewed as a priority. In this sense, during various decades, efforts were focused on controllability, reliability, reduced costs, and efficiency; however, sophisticated technologies are emerging for a sustainable and resilient future of power grids [2]. Moreover, various technologies have appeared and are assuming predominance, promoting a set of pertinent synergies among diverse areas [3]. A review on multilevel power management systems for future power grids is presented in [4], wherein benefits, drawbacks, challenges, and limitations are discussed. A forthcoming concept of power grids that includes a large-scale integration of distributed energy resources, ensuring autonomy and controllability in the production and consumption stages, is analyzed in [5]. The importance of blockchains, machine learning, and deep learning technologies for future power grids is presented in [6–8], demonstrating the importance of subjects such as security, cyber-physical attacks, and defense approaches. These concerns are interconnected with power grid management, and from a certain point of view, should be considered a priority since radical changes concerning the large-scale incorporation of technologies in power grids are sought (concerning, e.g., electric mobility, renewables, controllable electronic loads, and storage systems) [9]. Therefore, the transformation of power grids is a dynamic process that is expected to be heavily invested in over the next few decades to support the growing penetration of modern technologies. Indeed, the transformation from centralized to decentralized production is now underway, which is identified as a new and significant radical change in power grids [10]. Together with such changes, there is also an ongoing revolution in terms of power flow, with bidirectional operation being increasing utilized to realize modern solutions, not only regarding management, but also in terms of power electronics systems [11,12]. Specifically, a perspective on the use of power electronics to facilitate the incorporation of renewables is presented in [13]. A review on power grid solutions, infrastructure, and challenges for the comprehensive integration of renewables in offshore conditions is presented in [14]. Such topics will be extensively explored in the following decades, and highly successful attempts to manage the progress of power electronics technologies are found in [15–17]. From this scenario of constant evolution to deliver more intelligent power grids arise the commonly designated "smart grids" and, moreover, so-called "future smart grids" are also experiencing notoriety. In such a context, final users are assuming active participation, offering new perspectives for the power grid in terms of consumption, storage, and supply, which is a paradigm generally classified as "prosumers" [18].

With the integration of more and more technologies, power grids are moving from a centralized to a decentralized approach. In this context, microgrids are also gaining predominance, permitting the incorporation of local distribution systems with production, storage systems, and controlled loads. Moreover, microgrids also offer the possibility of operating with a coordinated and controlled approach, so they can operate via being linked to the main power grid or, on the contrary, they can operate independently, ensuring fully autonomous operation [19,20]. An analysis concerning microgrids is offered in [21], highlighting robustness, resilience, and energy efficiency, as well as opportunities and challenges. A wide-ranging analysis of power electronics algorithms and control plans for AC/DC microgrids is given in [22]. Based on this perspective, specific control approaches and synchronization methods also presume a pertinent dominance for various purposes, including remote microgrid synchronization [23], adaptive methods of synchronization [24], and sophisticated synchronization controllers among power converters [25]. Thanks to new power electronics technologies, conventional substations are also changing, along with upcoming DC power grids. An evaluation of multilevel converters designed for grid-tied systems is presented in [26], demonstrating the crucial contribution of power electronics.

Figure 1 presents a set of technologies that will be available in future power grids, highlighting the interface maintained by hybrid AC/DC power grids, which are established by solid-state transformers (SSTs). The emphasized technologies are categorized into groups, including renewables (e.g., solar PV panels and wind turbine technologies) in onshore and offshore conditions, energy storage systems, electric mobility (e.g., on-board and off-board chargers allowing bidirectional operation controlled by the user and grid management technology), hydroelectric systems, and factories and homes (conventional and smart factories and homes). Numerous papers focusing on hybrid AC/DC power grids, as well as the role of the SST, are available in the current literature; nonetheless, a comprehensive paper concentrating on the definitive role of future power grids is missing. The most relevant references available in the literature are appropriately described and referenced in this paper, wherein a context for future power grids is presented.

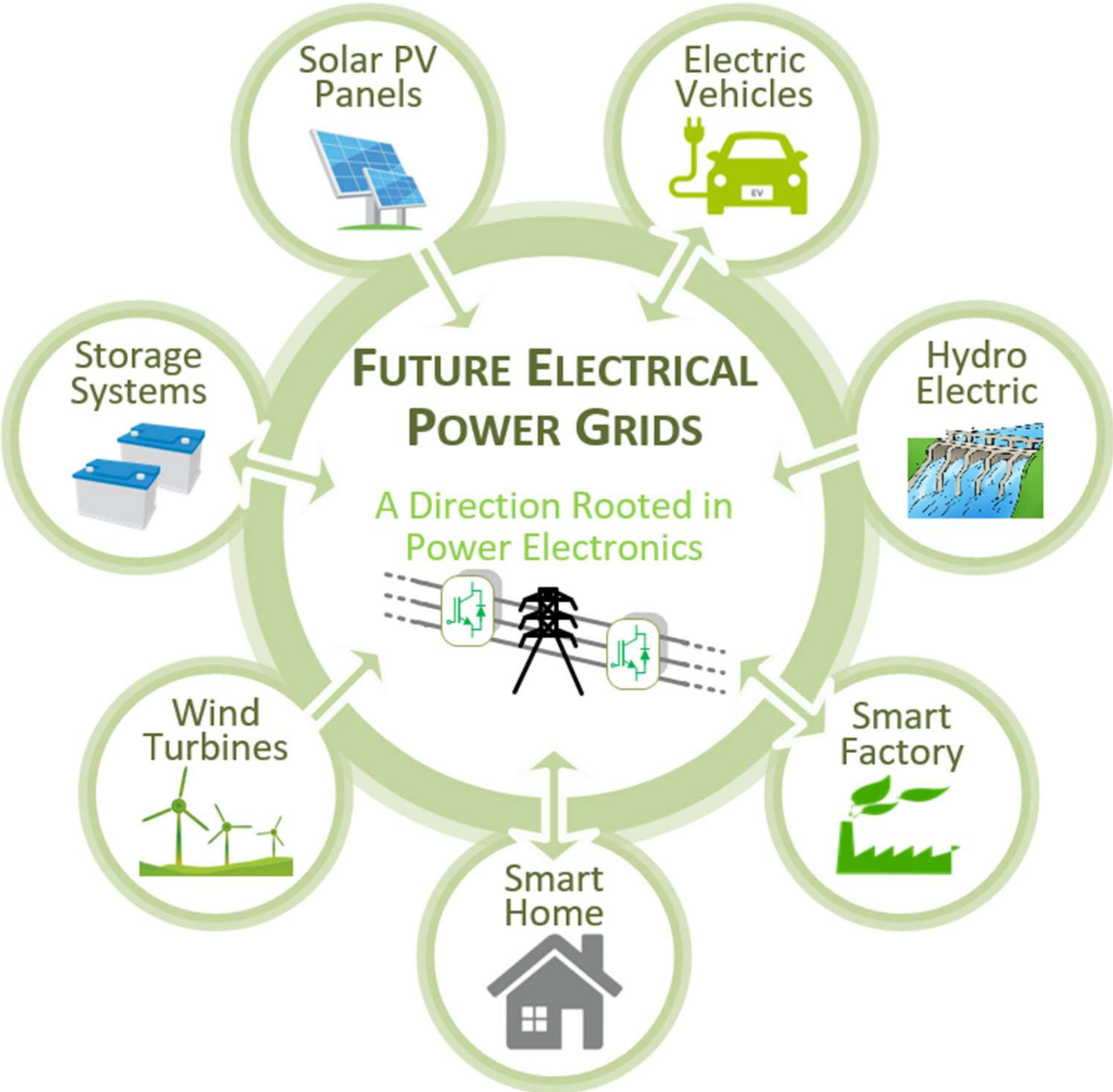

Figure 1. Technologies present in future electrical power grids.

This perspective paper has as its central contribution the depiction of a direction rooted in power electronics for future power grids, fundamentally concentrating on a direction supported by hybrid AC/DC grids and SSTs. Throughout the paper, such technologies are contextualized individually regarding their role in future power grids and concerning the relationship between them. Section 2 describes the relevance of hybrid AC/DC power grids, including key challenges and design structures. Section 3 introduces the applicability of SSTs for establishing hybrid AC/DC power grids, showing their definite value in the context of future power grids. Section 4 presents the importance and contextualization of unified power electronics systems with multiple operations for future power grids, permitting their optimization in terms of functionalities, while reducing the number of power converters, namely AC-DC. Section 5 summarizes the main conclusions.

2. Hybrid AC/DC Power Grids

As an alternative to the traditional AC grids, new power grids based on DC are emerging, presenting important challenges and opportunities. AC grids date back to the 19th century, as evidenced by the debate between Edison and Tesla/Westinghouse. Thanks to the use of power transformers, which simplify changes in voltage levels, AC grids succeeded, facilitating power transmission and distribution. This advantage still prevails, since most electrical equipment is designed to operate in AC. Nevertheless, considering the technological innovations in power electronics, and that nowadays several technologies function in DC, DC grids are expected to continue to gain preponderance. Technologies such as renewables (mainly supported by solar PV), energy storage systems (principally supported by batteries), and electric mobility systems require a DC interface; therefore, DC grids are a viable solution for establishing a direct connection. DC grids are a feasible solution, mainly due to that fact that (i) solar PV is progressively present in diverse sectors; (ii) batteries are frequently employed as storage applications; (iii) lighting systems are generally based on LED technologies; (iv) electric mobility systems use batteries as storage systems; (v) power quality problems are alleviated; (vi) the power stages based on power electronics are radically diminished; (vii) passive AC-DC rectifiers are removed; (viii) control systems are simpler; (ix) DC grids can operate independently of the AC grid. However, a drastic move from AC to DC grids is not possible; consequently, the integration of AC and DC grids is welcome. This has been accomplished for various circumstances, being labeled as "hybrid AC/DC grids". A review of power electronics converters committed to meeting the demands of DC grids is provided in [27]. In summary, the benefits of hybrid AC/DC grids are obvious and indisputable, and they can also perform an essential role in the residential sector (e.g., smart homes); thus, their role in future power grids is evident [28]. Worldwide, various projects involving hybrid AC/DC grids have been completed or are ongoing, indicating the significant attention they will receive in the coming decades. Notwithstanding the benefits of DC grids and the quick transformation to a new system, there are still challenges caused by DC grids, mainly due to their standardization, grid codes, and protection procedures.

Regarding possible structures of DC grids, the two main possibilities are identified as follows: unipolar and bipolar. The bipolar structure requires three wires and is more complex, with regard to both control and hardware, but presents the possibility of an operation based on three voltage levels, which is relevant to the assimilation of DC technologies natively operating with distinct voltage levels. Additionally, if a malfunction occurs in one wire, it is possible to maintain the operation; likewise, a unipolar DC grid, since it is just a part of the grid, will be affected by the malfunction. A comprehensive assessment of promising technologies linked to bipolar DC grids is given in [29]. However, issues related to voltage imbalances caused by imbalanced loads can occur in bipolar DC grids, and therefore, power electronics converters are fundamental for guaranteeing balanced power consumption, ensuring the bipolar DC grid's stability.

The configuration of a hybrid AC/DC grid needs to be designed to accomplish crucial attributes, with consideration of the linked technologies. Figure 2 displays a configuration of a hybrid AC/DC grid. Concerning the structure of hybrid AC/DC grids, the principal difference is whether the grid is AC-coupled or AC-decoupled. Considering the example of a coupled AC, a transformer is used to link the main AC grid to the AC grid internally, which is performed by the hybrid AC/DC grid. In this case, the utilization of power electronics converters is imperative for forming the DC grid. Considering the example of a decoupled AC, at a minimum, a single AC–DC and a single DC–DC power converter are necessary. In this case, linking the AC to the AC main grid is accomplished through AC–DC and DC–AC power stages, guaranteeing isolation in both AC and DC grids.

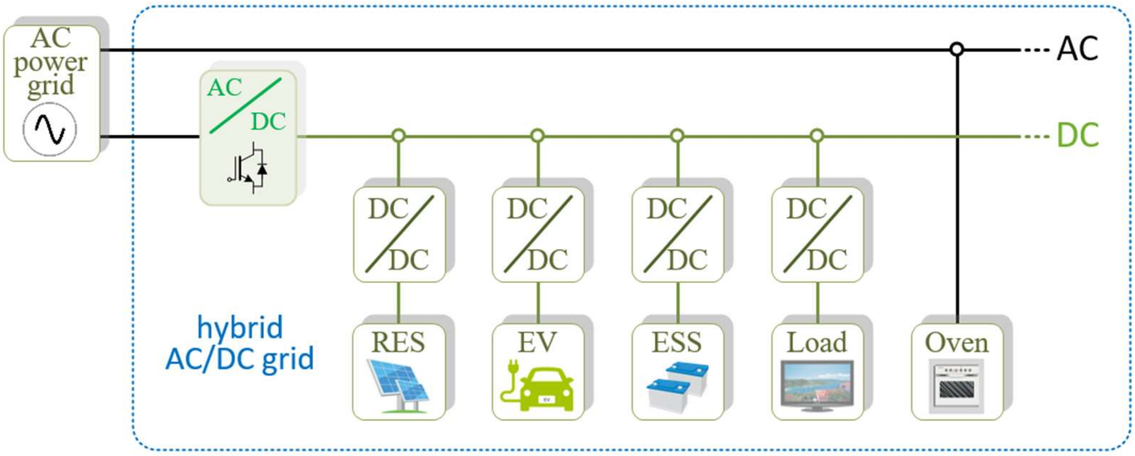

Figure 2. Composition of a hybrid AC/DC grid.

3. Solid-State Transformer

Low-frequency power transformers originate from AC power grids and are still used at the transmission and distribution level. Nevertheless, considering the increasing number of technologies and players linked to power grids, new challenges regarding providing precise and fast controllability are emerging. In this context, the relevance of power electronics in consideration of growing technological requirements is obviously recognized, bearing in mind that the opportunity offered by substituting low-frequency transformers with SSTs is very significant, as it offers controllability and support for supplementary services, both at the transmission and distribution levels [30]. Over the last few years, SSTs have experienced very pertinent growth concerning topologies and applications, demonstrating that they will form a crucial part of future power grids. Considering the adaptability offered by the SST, the prospect of hybrid AC/DC grids being supported by SSTs is additionally recognized in the context of future power grids. The possibility of using an SST to generate additional features, such as hybrid AC/DC grids, demonstrates the ability that it has for interacting with technologies based on a native DC operation. An SST developed for forming hybrid AC/DC grids, which allows synchronized control of power and voltage, is presented in [31]. A hybrid SST for linking MVDC and LVDC grids is proposed in [32]. A novel modulation and control strategy for an SST designed with a modular converter configuration is suggested in [33]. An SST for interfacing renewables from PV panels through DC interfaces is proposed in [34]. A modular SST specially built for EV battery-charging stations is proposed in [35]. The deployment of an SST has been revealed to be an interesting challenge, since it requires numerous power electronics technologies. The development and management of high-frequency converters based on SiC power devices for the next generation of SSTs are proposed in [36]. Effective control methodologies specifically developed for SSTs, using soft-switching approaches, are proposed in [37]. A novel high-frequency SST design with a decreased quantity of switching devices is shown in [38]. An SST based on matrix power electronics converters is proposed in [39]. Regarding SSTs' purpose in future power grids, the alignment of relevant industrial players and market growth is highly beneficial, with a special focus on companies like ABB, Siemens AG, and Schneider Electric SE. Furthermore, the SST market will achieve further value in the next few decades, considering the ongoing evolution of the SST. Comprehensive reviews detailing qualitative and quantitative analysis of traditional solutions and SST solutions are presented in [40,41], and a framework for an SST operating with virtual synchronous machines functionalities is presented in [42–44]. Figure 3 presents an SST used to link high-voltage AC (HVAC) and high-voltage DC (HVDC), as well as low-voltage AC (LVAC) and low-voltage DC (LVDC), permitting hybrid AC/DC grids to be established.

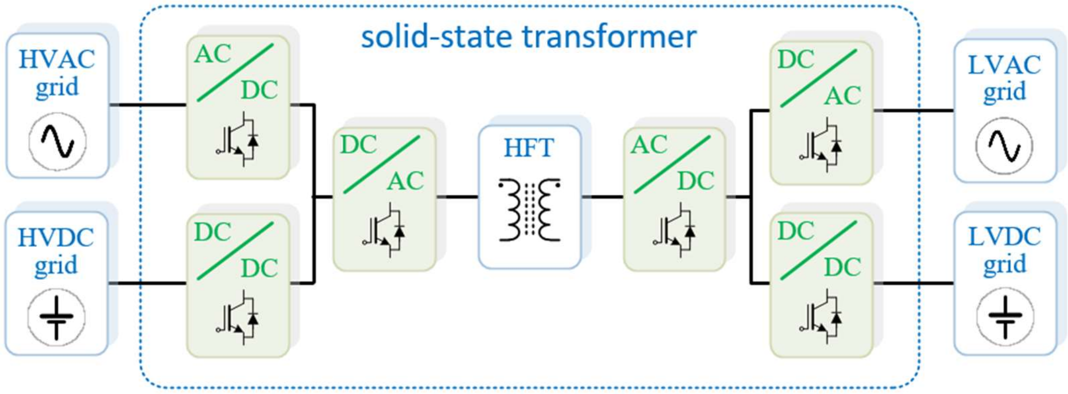

Figure 3. An SST used to link AC and DC grids at high-voltage levels (HVAC and HVDC) and AC and DC grids at low-voltage levels (LVAC and LVDC), permitting the creation of hybrid AC/DC grids.

4. Unified Power Electronics Systems with Multiple Operations

As stated earlier, power grids are shifting toward the integration of more controlled technologies, but other technologies can also be considered, such as power conditioners. Thus, unified control strategies for power electronics are essential to diminish disturbances in the power grid [45]. The mutual support among electric mobility systems and renewables facilitates revolutionary circumstances in terms of power management, where using the batteries of electric vehicles for controlled energy storage, and the use of such energy when it is convenient for the grid and for the user, is recognized to be significant for power grid sustainability and stabilization [46]. Therefore, focused control approaches dedicated to both electric mobility and renewables are of the utmost importance, with regard to various power profiles, the costs, and the power quality impact. Such points of view are notorious, but on the other hand, the role of power electronics cannot be negated, since new radical practices can be implemented in terms of hardware structure, without jeopardizing the individual operation of electric mobility systems or renewables, and providing new opportunities for the power grid. Hence, technologies for integrating battery chargers and renewables specifically dedicated to such interfaces have already been identified, allowing the integration of storage technologies and decreasing the number of power stages in AC and DC conversion, with inherent advantages, such as reducing costs and increasing efficiency [47,48]. In examining these vectors, we find relationships between the AC-DC converters, allowing for the evolution of power converters toward unified power electronics topologies with natural attributes including increased efficiency, and reduced costs, weight, and volume. The focus on unified power electronics topologies with multiple operation interfaces is an important topic of research for future power grids, involving power quality enhancement [49], a direct interface of renewables to the DC link without power converters [50], and a unified topology with multiple power converters for optimizing each interface and compensating for all power quality problems related with current [51]. Thus, with the focus on the future of power grids, it is expected that unified power electronics with multiple operations will ensure a single interface of power grids, in single-phase or three-phase connections, involving technologies of electric mobility, renewables, and features of power quality; four-quadrant active/reactive power operation on the AC side; unidirectional/bidirectional power operation on the DC side, even without the AC interface (e.g., direct connection from the renewables to the electric mobility); and power grid support through voltage/frequency services. A diagram showing unified power electronics with multiple operations for future power grids is illustrated in Figure 4, where Figure 4a demonstrates the shared operation of power grids, electric vehicles, and renewables, allowing or prohibiting the improvement in power quality; Figure 4b demonstrates the direct linkage of power grids and electric vehicles, allowing, or prohibiting, the improvement in power quality; Figure 4c demonstrates the direct linkage of power grids and renewables, allowing or prohibiting the improvement in power quality; Figure 4d demonstrates the direct linkage of electric vehicles and renewables; Figure 4e demonstrates power quality improvement based solely on the unified system, i.e., excluding the linkage of electric vehicles or renewables.

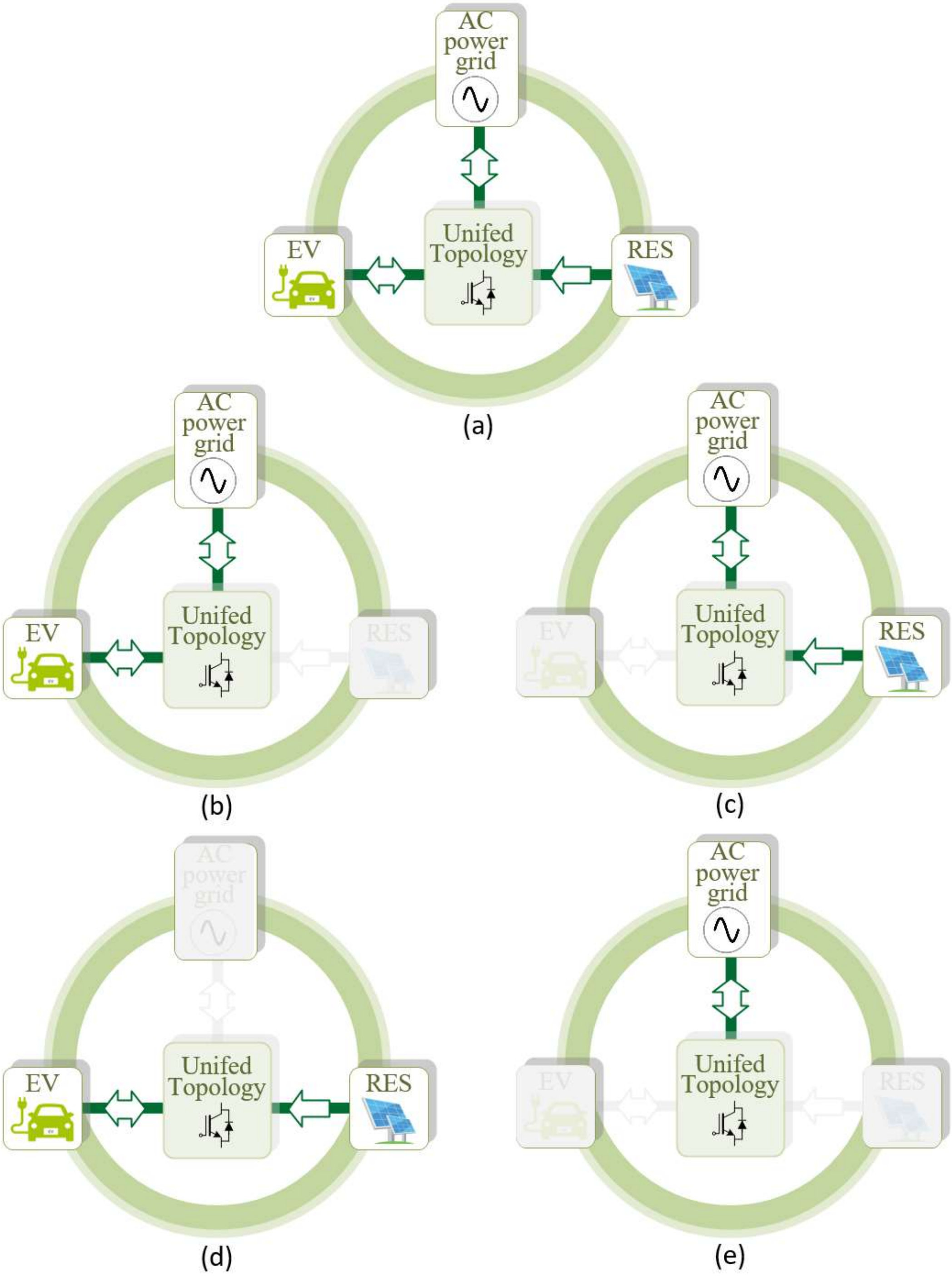

Figure 4. Diagram of unified power electronics with multiple operations for future power grids: (**a**) Shared operation of power grids, electric vehicles, and renewables, allowing or prohibiting the improvement in power quality; (**b**) direct linkage of power grids and electric vehicles, allowing or prohibiting power quality improvement; (**c**) direct linkage of power grids and renewables, allowing or prohibiting the improvement in power quality; (**d**) direct linkage of electric vehicles and renewables; (**e**) power quality improvement based solely on the unified system (excluding the linkage of electric vehicles or renewables).

5. Conclusions

New perspectives are arising as alternatives to conventional power grids gain traction, proposing attractive opportunities supported by technological innovations in power electronics. The integration of hybrid AC/DC grids is a forthcoming contribution able to improve flexibility and efficiency in the context of future electrical power grids, particularly with regard to the technologies natively operating in DC. Coupling and decoupling structures in hybrid AC/DC power grids are introduced as well in this paper, demonstrating viable alternatives to the traditional solutions, as well as the possibility of having unipolar or bipolar DC power grids, which are solutions, respectively, based on two-wire or three-wire systems. Additionally, considering the advances in power electronics, and aiming to address the emergent challenges of power grids, an SST is also presented, which is a viable solution for replacing low-frequency power transformers. SSTs can support technologies with various benefits concerning controllability on both sides (primary and secondary), but with additional demanding hardware and control. The contextualization of SSTs within the framework of hybrid AC/DC grids is also presented in this paper, including perspectives of SSTs' ability to offer additional services, such as collaboration to produce reactive power or selective current harmonics. As presented throughout the paper, technologies based on unified power electronics systems will represent an asset for future power grids, offering a reduced number of power converters and thus improving efficiency, and adding multiple operations to strengthen the main AC grid management. Summarizing, it is feasible to reveal the evolution of power grids toward hybrid AC/DC grids supported by an SST. Notwithstanding the advantages, various issues should be solved for the widespread implementation of such future power grids. It cannot be foreseen when the whole transformation will occur; however, the vital contribution of power electronics in terms of new power devices, topologies, and control algorithms is ongoing.

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