5th International Conference on Energy and Environment: bringing together Engineering and Economics
Porto, Portugal
2-3 June, 2022

Smart Transformer: A Revolutionary Paradigm Toward Sustainable Power Grids

Vitor Monteiro,[1*], Sérgio Coelho[2], and João L. Afonso[3]

[1] Centro ALGORITMI, University of Minho, Portugal
[2] Centro ALGORITMI, University of Minho, Portugal
[3] Centro ALGORITMI, University of Minho, Portugal

* Corresponding author: vmonteiro@dei.uminho.pt, University of Minho, Campus de Azurem, Portugal

KEYWORDS
Sustainability, Energy Sustainable Technologies, Smart Grid, Smart Transformers, Solid-State Transformers.

ABSTRACT

Electrical power grids are evolving technologically from different perspectives, specifically, aiming to guarantee the sustainability of the power grid itself, the introduction of new and emerging technologies for the production and storage of energy, advanced communication systems, as well as higher levels of power quality for all sectors of activity (from production to consumption). Particularly, with special focus over the last two decades, power grids are undergoing a depth transformation, moving from a centralized and unidirectional architecture to a decentralized and bidirectional architecture, mainly due to the massive incorporation of new electrical engineering technologies. This change also presents an important aspect for the entire power grid: the possibility of energy storage and management according to the real-time needs. In this context, within the scope of this paper, the sustainability of power grids is considered, focusing on the new paradigms offered by the smart transformer and hybrid AC/DC power grids, including all the added value that can be established in terms of power management. Encompassed in a smart transformer context, the contextualization of the conceivable arrangements of solid-state transformers, and the various configurations of smart hybrid transformers, are evaluated from the point of view of offering advantages of improved efficiency and power quality. In addition to a theoretical introductory context, the paper presents computational validations and a comparison regarding the various configurations that can be obtained.

INTRODUCTION

Principally over the last decade, power grids have been the faced fundamental changes as a result of the massive incorporation of renewables, controllable electronic loads, electric mobility, energy storage systems, and lighting systems, as well as the resulting requirement of power management and the perspective of sustainable power grids (Vadari, 2020)(Kumari et al., 2020). Additionally, such changes are also aligned to ensure universal access to electricity (Deane et al, 2020). A future vision for the power grids is presented in (Kroposki et al., 2020) and in (Monteiro et al., 2021), considering the aspects of autonomy and managed incorporation of distributed energy resources. In fact, a great investment is also predictable for the next decades since the penetration of innovative technologies will continue to growth, as well as in the point of view of promoting to extenuating climate changes and offer sophisticated plans for the distribution management (Razon et al., 2019). In terms of energy production, the most important transformation is linked to the passage from a centralized production to a decentralized production (Smil, 2019)(Jiang et al., 2020). Consequently, the transformation from a unidirectional power flow to a bidirectional power flow contributes to the implementation of innovative solutions in terms of power electronics and power management (Rosso et al., 2021).

In the context of revolutionizing the power grid supported by power electronics technologies (Monteiro et al., 2021), as largely demonstrated, the smart transformer toward varied purposes in smart grids is seen as an growing technology as a compromise to substitute traditional low-frequency transformers, offering a set of advantages such as the improved power controllability, ancillary services, power management and flexibility, and power quality in the power grid and loads side (Ko et al., 2020)(Krishnamoorthy eta al., 2017). The predictable applicability of the smart transformer as a strategic element for power management in the actual and imminent distribution grids is presented in (Huber et al., 2019), emphasizing technical concerns and prospective restrictive issues. A review regarding the state of the art of smart transformer only concentrating on essential aspects as related to improved power electronics topologies, concerns of practical implementation, and up to date progress and challenges is presented in (Hannan et al., 2020). Moreover, with few improvements in terms of the smart transformer design, additional important features can be incorporated toward sustainability, including the assimilation of renewables, electric mobility, and storage systems. In this circumstance, an energy management plan by means of smart transformers is discussed in (Chen et al., 2017), a smart transformer interfacing dispersed renewables based on photovoltaic is presented in (Zhao et al., 2017), the perspective of using smart transformers for renewables based on wind power systems is presented in (Khadkikar, 2017), a new control algorithm aiming the efficiency optimization of a dc SST to interface renewables based on photovoltaics in presented in (Shi et al., 2020), the modeling and design of an SST for microgrid applications is studied in (Madichetty, 2017), and the applicability of the smart transformer for distribution systems, concerning a review of technologies, sustained functionalities, and construction aspects, is presented in (Saleh et al., 2019), while concerning the applications of smart transformer, the expansion challenges, and future perspectives to incorporate the smart transformer in distribution systems is presented in (Saleh et al., 2019).

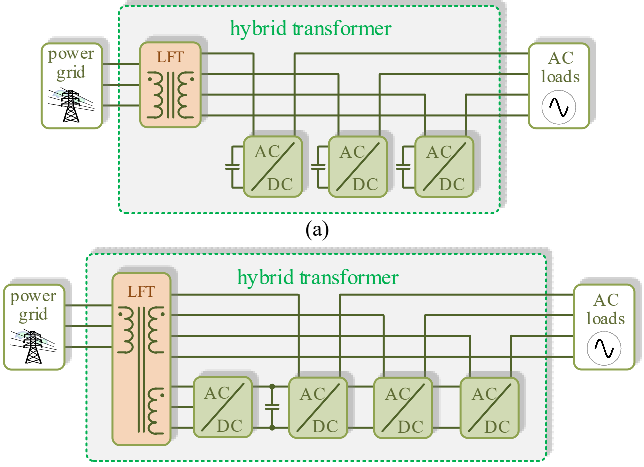
In this circumstances, it is clearly understood the crucial value of power electronics for the progress, modernization, efficiency, and sustainability of power grids (Bloemink et al., 2013). The position of power electronics in future power grids is evaluated in (Divan et al., 2016), considering a distributed integration permitting an economic methodology to control the grid with a variety of technologies. A new and futuristic evaluation concerning the use of power electronics in power grid is presented in (Boroyevich et al., 2013). Furthermore, considering the importance for future power grids in terms of sustainability, aspects related to power electronics, power quality, features for the power grid, efficiency, and reliability are analyzed in this paper. Moreover, the possibility of interfacing various areas in hybrid AC/DC power grids, such as renewables, electric mobility, and energy storage systems are also covered along the paper. All these topics are presented, encompassing the most pertinent and modern structures and characteristics that can be established, discussing them within a context of more sustainable power grids. Summarizing, this paper focus on the sustainability of power grids based on new paradigms offered by the smart transformer, hybrid AC/DC power grids, conceivable arrangements of solid-state transformers, configurations of hybrid transformers, and the importance of preserving power quality. After this introduction, a contextualization of the various topologies in a smart transformer context (conceivable arrangements of hybrid transformers and solid-state transformers) is presented, followed by the main results about the principle of operation, an analysis, and a detailed discussion and comprehensive comparison. The paper is finalized with the main conclusions.

SMART TRANSFORMER

The smart transformer concept is often presented as being the same concept as the solid-state transformer, i.e., purely based on power electronics and with a high-frequency transformer. However, the smart transformer, e.g., can be constituted by a low-frequency transformer and may only have intelligence from the point of view of communication and management of technological resources connected to it. Furthermore, on the other hand, the smart transformer can be composed of a hybrid structure, i.e., a base structure constituted by the structure of a low-frequency transformer, but with added power electronics systems to offer new valences in terms of improving power quality. In this context, depending on the final application for which the smart transformer application is intended, various configurations can be implemented.

In this context, from the load point of view, when the objective is to guarantee the energy supply with three sinusoidal and properly balanced voltage waveform, the smart transformer can be composed of three independent power converters on the secondary side, connected in series between the secondary windings of the low-frequency transformer and the respective phase of the load. This configuration is shown in Figure 1(a) and can be classified as a low-frequency transformer with a series active power filter on the secondary-side. The advantage of the power converters being independent is related to the fact that possible faults are not propagate between phases, however, it is not possible to ensure that the main power quality problems are compensated. In order to obtain a configuration that offers more possibilities of operation to compensate all power quality problems concerning voltages, it is necessary to supply or receive power through the DC interface of the power converters. Thus, as shown in Figure 1(b), other configuration can be implemented, requiring additional windings on the secondary-side of the low-frequency transformer. As it turns out, an extra bidirectional AC-DC power converter is required at the interface between the auxiliary winding of the low-frequency transformer and the DC-link of the power converters. In this way, it is possible to compensate for all power quality problems related to voltages on the secondary side of the smart transformer, i.e., three balanced and sinusoidal voltage waveforms are always applied to the loads, independently of the load characteristics and the steady-state or transient-state operation. As can be seen, the power electronics systems are connected on the secondary-side of the low-frequency transformer and have the sole purpose of guaranteeing sinusoidal and balanced voltages for the loads, regardless of the harmonic content and balance of the loads connected to the smart transformer. If the power electronics systems were connected on the primary-side of the smart transformer, due to the possible operation with non-sinusoidal currents and the impedances of the smart transformer windings, the voltages applied to the loads (i.e., the secondary-side of the smart transformer) would not be purely sinusoidal, presenting harmonic content as a function of the harmonic content of the currents consumed by the loads.

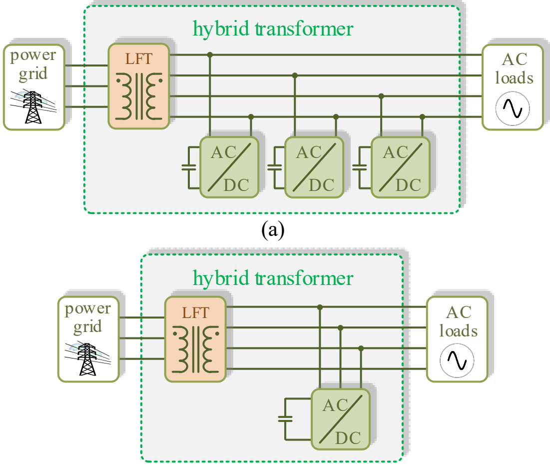
On the other hand, when the focus is on the power grid point of view, i.e., on ensuring that the currents are sinusoidal and balanced, it is important to add power electronics systems that allow this objective, being connected in parallel, rather than happens with series connections to compensate for voltage related problems. In this situation, three converters can be connected on the secondary side of the transformer, each one in parallel with the respective phase. This configuration has the advantages that the possible problems of one phase do not propagate to another phase. This configuration is shown in Figure 2(a). Another possibility is to use only one power converter with three legs, each one connected in parallel with the respective phase on the secondary-side of the low-frequency transformer. This configuration is shown in Figure 2(b). With this configuration, it is possible to compensate for all power quality problems arising from the currents consumed by the loads.



(a)

(b)

Figure 1: Configurations of hybrid transformers based on a: (a) low-frequency transformer and power electronics converters on the secondary-side connected in series; (b) low-frequency transformer with auxiliary windings on the secondary-side linked to the dc-link of the power electronics converters through a bidirectional AC-DC power converter.



(a)

(b)

Figure 2: Configurations of hybrid transformers based on a: (a) low-frequency transformer and power electronics converters on the secondary-side connected in parallel; (b) low-frequency transformer and a single power electronics converter on the secondary-side connected in parallel.

As can be seen, the power electronics systems are connected to the secondary-side of the low-frequency transformer and have the sole purpose of guaranteeing sinusoidal and balanced currents on the secondary-side of the smart transformer, regardless of the unbalances and the harmonic content of the loads. It is important to mention that if the power electronics systems were connected on the primary-side, the low-frequency transformer would operate with the currents consumed by the loads (i.e., with power quality problems), causing a wide range of problems for its operation, as well as accentuating the problems in the voltages applied to the loads. In this situation, the currents on the power grid side would be sinusoidal and balanced, but the smart transformer will operate with power quality problems, namely currents with harmonic content.

As mentioned, the choice of a certain configuration depends on the application where the smart transformer will be applied. In a generic perspective, it is possible to obtain configurations that allow to compensate for all problems, both in voltage and in current, being necessary to combine the configurations presented above. Such a combination can be carried out while maintaining the independence of the power converters, or it can be carried out ensuring the interface, through the DC-link, between the power electronics systems connected in series and connected in parallel. Figure 3 shows a shared configuration between the series and the parallel power electronics systems. This configuration, due to the possibility of power exchange between both systems, permitting to compensate for all power quality problems, specifically, it allows sinusoidal and balanced currents on the electrical grid side, as well as sinusoidal and balanced voltages on the load side.

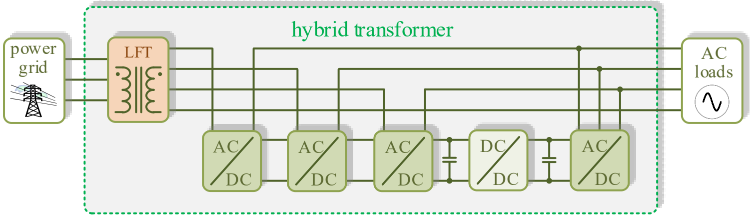
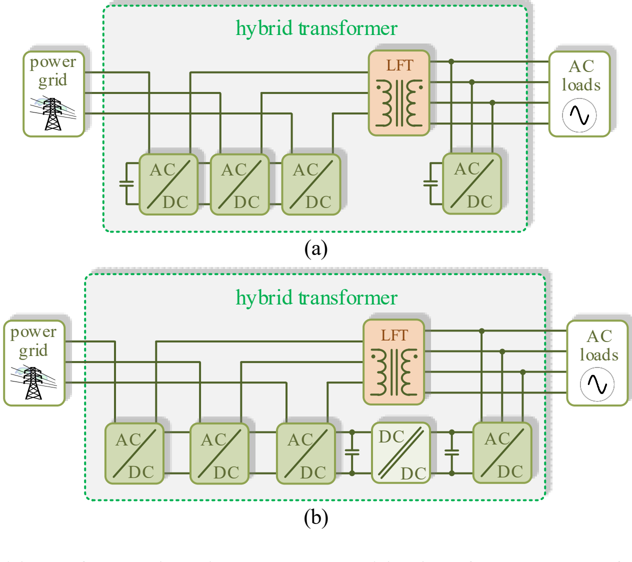


Figure 3: Configuration of hybrid transformer based on a structure with a low-frequency transformer and power electronics converters on the secondary-side connected in series and parallel.

As can be seen in the configurations presented, the power electronics systems are always connected on the secondary side, as they present more advantages, however, they force the low-frequency transformer to operate either with currents or with voltages with power quality problems, not being possible to optimize its operation from a general point of view. Thus, when the objective is to optimize the operation of the low-frequency transformer, allowing it to operate with sinusoidal and balanced currents and voltages, it is necessary to adopt another type of configuration, in which part of the power electronics is connected to the primary-side and the other part on the secondary-side. In this sense, the configuration that guarantees the best performance is the connection of the power electronics system in series on the primary-side, and the connection of the power electronics system in parallel on the secondary side. This configuration is shown in Figure 4(a). In this way, the low-frequency transformer operates with balanced and sinusoidal voltages and currents, where power quality problems are limited to the power grid and to the loads, not interfering with the operation of the smart transformer. However, not all power quality problems can be compensated, since the DC-link of both power electronics systems cannot receive or supply energy. To make this possible, a connection can be created between both DC-links, but as the systems are on the primary side and on the secondary side, it is necessary to guarantee galvanic isolation between both power electronics systems. The galvanic isolation can be guaranteed by using an isolated DC-DC converter. This configuration is shown in Figure 4(b). In this broader way, the smart transformer offers many advantages from the point of view of the electric system sustainability.



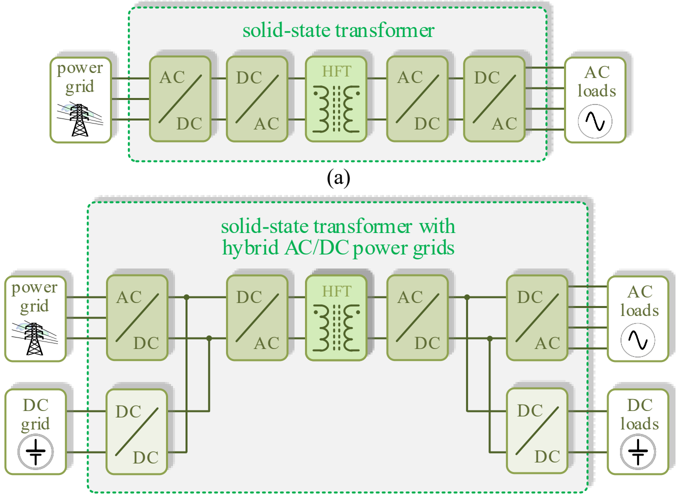
(a)

(b)

Figure 4: Configuration of hybrid transformers based on a structure with a low-frequency transformer and: (a) power electronics converters on the primary-side connected in series and power electronics converters on the secondary-side connected in parallel; (b) power electronics converters on the primary-side connected in series and power electronics converters on the secondary-side connected in parallel, but sharing the dc-link through a high-frequency DC-DC power converter.

Despite the advantages of a smart transformer, i.e., by incorporating a hybrid approach with a low-frequency transformer and power electronics systems, the fact is that a low-frequency transformer continues to be used. Thus, a more radical approach is to completely eliminate the low-frequency transformer, making necessary to use a high-frequency transformer. In this way, the power electronics systems presented above are no longer necessary for the specified functions and other power electronics systems are used to interface between the power grid, the high-frequency transformer and the loads. For this, the most common configuration regarding the primary side, consists of an AC-DC converter for interfacing with the power grid followed by a DC-AC converter for interfacing with the high-frequency transformer. On the other hand, on the secondary-side, the situation is very similar, using an AC-DC converter to interface with the high-frequency transformer and a DC-AC converter to interface with the AC loads. This configuration, identified as solid-state transformer, is shown in Figure 5(a). With this configuration, it is possible to guarantee the operation with sinusoidal and balanced currents on the power grid side and sinusoidal and balanced voltages on the load side, as well as the necessary galvanic isolation. Obviously, other configurations can be implemented, e.g., using direct or indirect AC-AC power converters on both sides, however, missing out on some extra functionality that this topology of solid-state transformer can offer. Additionally, *n* high-frequency transformers could also be used in parallel, with *n* power electronics converters, allowing to divide the operating power between them. On the other hand, mainly on the primary-side, multilevel or cascade type AC-DC power converters structures could be used (e.g., modular multilevel converter), allowing the operation with higher voltage ratings and reducing the stress of voltages and currents applied to the semiconductors of the power converter.

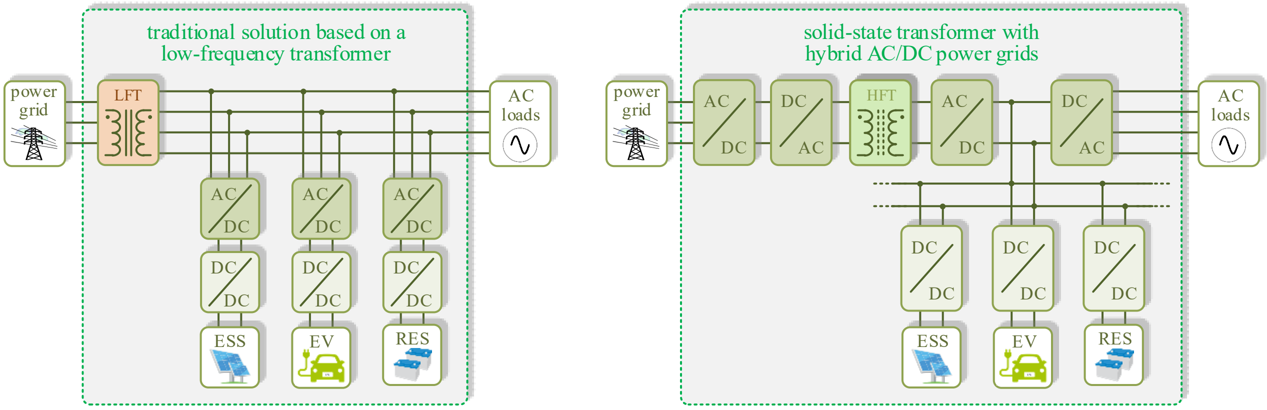
Analyzing this configuration in detail, it is possible to verify that on both sides, due to the connections of the AC-DC and DC-AC converters, a DC-link is created on each side of the solid-state transformer. These DC-links can be used for other purposes from the perspective of creating hybrid AC/DC power grids that facilitate the interface of technologies that operate natively on DC, such as renewable energy sources, charging systems for electric mobility, or energy storage systems. This possibility offers more flexibility toward the sustainability of the power grid since such technologies can be directly linked to the DC grid eliminating the need for AC-DC power converters and allowing the production, storage, and consumption of energy without the interference of the AC power grid (Monteiro et al., 2021). This is a very relevant point toward the sustainability of the power grid since the power production and consumption can be performed in the same local, avoiding the traditional solution based on multiple AC-DC power converters and centralized power production. Moreover, the creation of hybrid AC/DC power grids can be done on the primary-side only, on the secondary-side only, or on both sides, depending on the final application for which the solid-state transformer is intended, such as microgrids. Figure 5(b) shows a configuration of a solid-state transformer with hybrid AC/DC power grids on the primary side and secondary side. As can be seen, it is necessary to add, at least, one DC/DC converter to allow bidirectional operation, letting the power exchange between the DC power grid and the solid-state transformer. In this figure, specifically, in the secondary side, only the creation of a DC power grid is shown, but more than one DC power grid can be created, e.g., in order to create DC power grids with various voltage levels, requiring several DC-DC power converters. It is important to mention that the DC power converters must allow bidirectional operation, however, it is not essential that they have galvanic isolation. Figure 6 shows a comparison between a traditional grid with multiple AC-DC and DC-DC power converters (Figure 6(a)) and a grid based on a solid-state transformer and a hybrid AC/DC power grid (Figure 6(b)), where is considered the interface of energy storage system, electric vehicle and renewable energy source. With the topology presented in Figure 6(b), in addition to reducing the number of power converters to interface the mentioned technologies, it is possible to operate with high levels of power quality in both power grid (i.e., sinusoidal and balanced currents) and loads (i.e., sinusoidal and balanced voltages).



(a)

(b)

Figure 5: Configurations of smart transformers: (a) based on a traditional solid-state transformer; (b) based on a traditional solid-state transformer with the possibility of hybrid AC/DC power grids on the primary-side (HVDC) and on the secondary-side (LVDC).



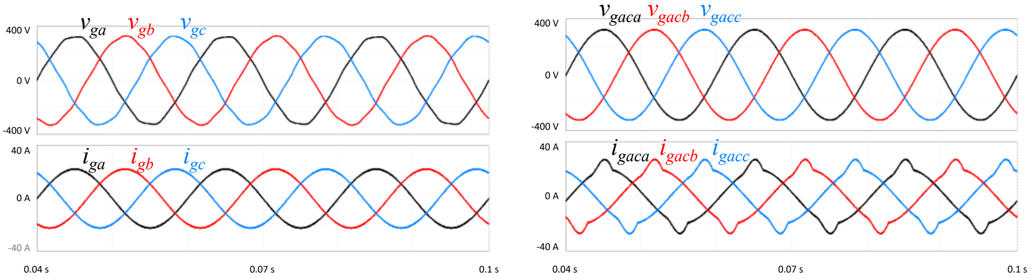
(a)

(b)

Figure 6: Considering the interface of energy storage system (ESS), electric vehicle (EV) and renewable energy source (RES), comparison between: (a) a traditional grid with multiple AC-DC and DC-DC power converters; (b) a grid based on a solid-state transformer and a hybrid AC/DC power grid for reduction the number of power converters to interface such technologies.

SMART TRANSFORMER: PRINCIPLE OF OPERATION

Figure 7(a) shows the principal results of a smart transformer based on a traditional solid-state transformer, validating the principle of operation in both primary-side and secondary-side, based on computer simulations. As shown in Figure 7(a), it is possible to visualize the three voltages on the main power grid, which present harmonic distortion, as well as the three currents consumed. It is possible to visualize that the currents are balanced and purely sinusoidal, which is extremely important in the perspective of contributing to the sustainability to the power grid. On the other hand, in Figure 7(b) it is possible to visualize the three voltages created on the secondary-side, as well as the three currents consumed by the loads. In this case, independently of the waveforms of the consumed currents, it is possible to visualize that the voltages are balanced and purely sinusoidal, which is extremely important in the perspective of contributing to the sustainability to the power grid.



(a) (b)

Figure 7: Principal results of a smart transformer based on a traditional solid-state transformer, validating the principle of operation in both primary-side and secondary-side: (a) voltages on the primary-side (v_{ga}, v_{gb}, v_{gc}) and currents on the primary-side (i_{ga}, i_{gb}, i_{gc}); (b) voltages on the secondary-side (v_{gaca}, v_{gacb}, v_{gacc}) and voltages on the secondary-side (i_{gaca}, i_{gacb}, $\mathrm{i}_{\mathrm{gaicc}}$).

ANALYSIS AND DISCUSSION

This section presents a brief analysis and discussion of the role of the smart transformer from a perspective of the sustainability of the power grid. Table I presents a comparative summary of the main configurations that are possible to implement. As can be seen, the solid-state transformer configuration is the one that presents the main advantages in a single configuration, also allowing the creation of hybrid AC/DC power grids on the primary side and secondary side. From the point of view of the the sustainability of the power grid, the creation of hybrid AC/DC power grids offers numerous advantages, which can be divided into two large groups: (i) from the point of view of the interface of other technologies using power electronic systems; (ii) from the point of view of power management control algorithms. These points are following discussed in more detail. Regarding the interface of other technologies, it is thus possible to substantially reduce the number of conversion stages (either AC/DC or DC/DC power converters) and thereby substantially increase the energy efficiency. For example, to make the interface between electric mobility and renewables, it is not necessary to use the AC power grid as an interface, contributing to the sustainability of the power grid. Regarding control algorithms, as the smart transformer is the key element in the interface of the power grid, loads, and the various technologies, it is possible to define power management algorithms in order to increase the efficiency and sustainability of the power grid. For example, it is possible to define optimized algorithms to store energy from renewables and use this energy strategically according to the needs of the hybrid AC/DC power grid. Combined both points of view, using the smart transformer with the solid-state transformer configuration, it is possible for the hybrid AC/DC power grid on the secondary-side to operate completely independently and isolated from the main power grid, which is a very important feature from the point of view of sustainability, optimizing the power production, storage and consumption, as well as allowing the hybrid AC/DC power grid to continue operating normally in the event of a failure of the main power grid. In addition, it is also possible to define advanced control algorithms from the power grid point of view, enabling its operation to offer additional services, e.g., reactive power compensation, voltage and frequency regulation per phase, production of current per phase.

Table I: Comparative summary of the main configurations.

	Figure 1(a)	Figure 1(b)	Figure 2(a)	Figure 2(b)	Figure 3	Figure 4(a)	Figure 4(b)	Figure 5(a)	Figure 5(b)
Compensation of voltage harmonics on the secondary-side	yes	yes	no	no	yes	yes	yes	yes	yes
Compensation of voltage imbalances on the secondary-side	no	yes	no	no	yes	yes	yes	yes	yes
Compensation of current harmonics on the primary-side	no	no	yes	yes	yes	yes	yes	yes	yes
Compensation of current imbalances on the primary-side	no	no	no	yes	yes	yes	yes	yes	yes
Galvanic isolation performed with a low-frequency transformer	yes	yes	yes	yes	yes	yes	yes	no	no
Galvanic isolation performed with a high-frequency transformer	no	no	no	no	no	no	yes	yes	yes
Transformer operates with power quality problems	yes	yes	yes	yes	yes	no	no	no	no
Power electronics systems are used to process all the power	no	no	no	no	no	no	no	yes	yes
Power electronics used only to compensate power quality	yes	yes	yes	yes	yes	yes	yes	no	no
Possibility of creating hybrid AC/DC power grids	no	no	no	no	no	no	no	no	yes
Possibility of operation offering services to the power grid	no	no	no	no	no	no	no	yes	yes

Figure 8 shows a comparison of the presented topologies in Figure 6 in the perspective of sustainable power grids. This comparison, based on a radar chart, is regarding the utilization of power electronics, the features in the perspective of the power grid (e.g., ancillary services for the main power grid), the efficiency that can be achieved, the reliability of the established power grid on the secondary side, and the power quality. Analyzing this figure, it is verified that the topology presented in Figure 6(b) is the most interesting topology toward sustainable power grids. It is verified that this topology is high dependent of power electronics, but such dependence is indispensable to ensure the other aspects.

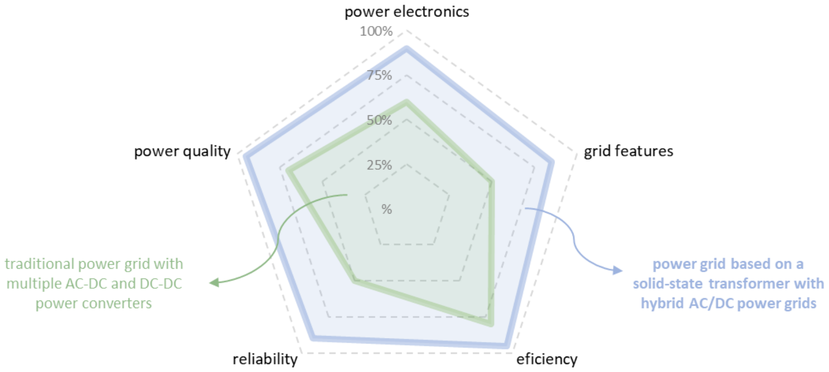


Figure 8: Comparison of the presented topologies in figure 6 in a perspective of sustainable power grids, regarding the aspects of power electronics, the features in the perspective of the power grid, the efficiency, and the reliability of the established power grid on the secondary-side, and the power quality.

CONCLUSIONS

Electrical power grids are growing in different perspectives, targeting to guarantee sustainability, introduction of new and emerging technologies, as well as higher levels of power quality for all activity sectors. Along with the paper, the contextualization of the conceivable arrangements of smart transformer is presented, highlighting the main diverse configurations of hybrid transformers and solid-state transformers. Particularly, in the point of view of offering more advantages for increasing the sustainability of power grids, the possibility of solid-state transformers with hybrid AC/DC power grids is evaluated. In terms of validating the principle of operation, in both primary side and secondary side of a solid-state transformer, the main results are presented. A comparative summary of the main configurations, as well as a specific comparison between a traditional grid with multiple AC-DC and DC-DC power converters, and a grid based on a solid-state transformer and a hybrid AC/DC power grid, are presented. Regarding the aspects of power electronics, the features in the perspective of the power grid, the efficiency, and the reliability of the established power grid on the secondary side, and the power quality, it was verified that the topology based on a solid-state transformer and a hybrid AC/DC power grid presents more relevant features in a perspective of sustainable power grids.

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