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A NOVEL CONVERTER TOPOLOGY FOR APPLICATIONS IN SMART GRIDS: TECHNICAL AND ECONOMICAL EVALUATION

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Smart Grids; Power Converters; Power Quality.

ABSTRACT

Technological advances in smart grids significantly contribute to an energy sustainability paradigm, assisting to diminish harms associated with global warming. Some of the key challenges in smart grids are linked with power electronics applications for renewable energy sources (RES), electric mobility (EM), energy storage systems (ESS) and power quality (PQ). These applications for smart grids have a common feature: the requirement to use the full-controlled grid-side power converters. Thereby, this paper aims to contribute with a technical and economical evaluation about a novel topology of the grid-side power converter for applications in smart grids. In terms of technical features, the proposed converter is classified as: (a) Bidirectional, allowing a bidirectional power flow with the electrical grid; (b) Symmetrical, allowing the operation with two distinct applications in the dc-side (e.g., RES, ESS, or EM); (c) Multilevel with nine levels, allowing high levels of PQ for the grid-side. With the objective to establish an accurate case-study, throughout the paper, the technical and economical evaluation is also performed based on the comparison between the proposed topology and the conventional ones. Considering an economical evaluation, the paper presents a cost estimation study concerning the implementation costs of the proposed topology, assuming realistic conditions of operation for applications in smart grids. Based on the entire evaluation for a real operating power range, the obtained results show the operational convenience of the topology in accordance with different applications in smart grids.

INTRODUCTION

As an involvement for reducing the greenhouse gases emissions, European Union has agreed to emission reduction for 2050 by 80% and some intermediate plans for 2030 (Ackermann et al. 2015). Therefore, it will be a crucial growing of renewable energy sources (RES) (Martinez et al. 2017)(Yan et al. 2017), new solutions for the transport sector reinforced by electric mobility (EM) (Boulanger et al. 2011)(Dallinger, Link, and Büttner 2014), and the introduction of energy storage systems (ESS) for supporting demand response (Beaudin et al. 2014)(Castello, LaClair, and Maxey 2014). Besides, aspects of power quality (PQ) for the grid-side, flexible electrical appliances, local or remotely controlled also represent new challenges for the new paradigm of energy (Kulkarni, Lewis, and Dave 2014)(Tushar, Zeineddine, and Assi 2017). In this sense, with the emergent reality of these technologies, the end-users can participate as active agents in the energy management, operating as a power producer or consumer (Liu et al. 2015)(Bragard et al. 2010). New opportunities for RES integration with the cooperative management of EM and ESS are demonstrated in (Monteiro, Exposto, et al. 2016), and (Monteiro, Pinto, and Afonso 2016). These technologies can be contextualized in terms of demand-side management (Gao et al. 2014), or in terms of multifunctional power converters (Monteiro et al. 2015). For the power grid interface, all of these technologies require grid-side power electronics converters: RES interface the power grid in an unidirectional mode to inject energy according to the production; ESS interface the power grid in a bidirectional mode, independently of the storage technology, to store energy form RES or from the power grid; and EM interfaces the power grid also in a bidirectional mode, prospecting the grid-to-vehicle (G2V) and vehicle-to-grid (V2G) modes. As a consequence, advanced single-stage topologies are emerging s in different areas of power electronics, interfacing RES, ESS, or EM into the power grid with high-levels of PQ.

In the scope of this paper, a novel topology of grid-side power converter for applications in smart grids, is presented. The proposed topology can be employed in different scenarios, e.g., considering a combined integration of RES and ESS, or RES and EM, or EM and ESS. Independently of the combination, PQ aspects are preserved for the grid-side. Analyzing the paper as a whole, the main contributions are: (a) Technical evaluation of the proposed topology, considering a comparison with the state-of-the-art power converters, the bidirectional operation, the symmetrical feature allowing distinct applications in the dc-side, and the multilevel feature allowing high-levels of PQ; (b) Economical evaluation about the proposed topology, considering a cost estimation about the implementation for different applications in smart grids. These contributions are supported by a comparison with the main state-of-the-art strategies contextualized with the presented references.

PROPOSED TOPOLOGY EMPHASIZING SMART GRIDS

The transition from the traditional power grids toward smart grids has been supported by a diversity of factors, including power electronics technologies for different sectors and applications. For instance, sustainability in the transport sector is supported by EM (Su et al. 2012)(Chan, Bouscayrol, and Chen 2010), but its massive introduction must consider PQ aspects for an effective use of the power grid (Lopes, Soares, and Almeida 2011), the collaboration with electrical appliances (Paterakis et al. 2015), and the integration in control paradigms of smart grids (Kisacikoglu, Kesler, and Tolbert 2015). In this perspective, occasions for the combination of EM with RES are also emerging (Weckx and Driesen 2015), where the power production from RES can be used by the EM, alleviating the power requirements from the power grid (Zhao et al. 2012)(Chaudhari et al. 2018). However, the integration of RES, EM, and ESS is performed considering independent power converters, where for each case two power converters are required: (i) Power grid is interfaced by an ac-dc converter; (ii) RES, EM or ESS is interfaced by a dc-dc converter. With these solutions, the power grid is always used as the middle energy point. For instance, when a power is necessary for the EM (for charging the batteries) from RES, firstly, the power is injected into the power grid, and then, the EM is charged from the power grid. In order to overcome this disadvantage, integrated topologies can be employed, both for large- or small-scale integration of RES, EM, and ESS. Figure 1 presents a comparison between the traditional solution and the integrated solution. Based on integrated solutions, in the literature can be found relevant proposals, both in terms of control and topologies of hardware. A simple overview, without discussing hardware or software, for an integrated interface of RES with EM is introduced in (Traube, Lu, and Maksimovic 2012). An interesting structure established by a multimode single-leg for controlling the interface of RES with ESS is presented in (Park and Kim 2013), but without the grid interface. A control optimization for the integration of RES, EM, and ESS in a three-phase microgrid is proposed in (Lu et al. 2014). A solution for interfacing RES, EM, and the power grid is presented in (Gamboa et al. 2010), but it is based on two converters, indicating a pertinent disadvantage. Integrated topologies, but only considering the EM interfacing the power grid in unidirectional mode is presented in (Hamilton et al. 2010). A relevant proposal considering RES and EM in bidirectional mode is experimentally verified in (Monteiro, Pinto, and Afonso 2018), but employing a single converter for the grid interface. Summarizing, in the aforementioned references, PQ aspects are not considered as an applicable issue, contributing for evidencing the significance of the power topology proposed in this paper. Moreover, an economical evaluation is not presented and never discussed in any reference.

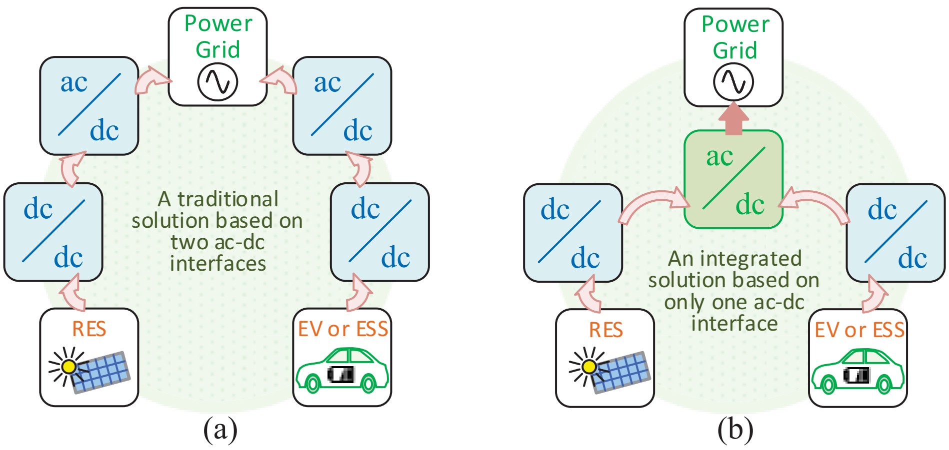

Figure 1: Power grid interface comparison between: (a) A traditional solution based on two ac-dc interfaces; (b) An integrated solution based on only one ac-dc interface.

Figure 2 shows the main options for interfacing RES, ESS or EM into the power grid. As shown, the main focus is on the ac-dc converter, where the traditional solution based on two interfaces in the grid-side is presented in Figure 2(a), a single grid-side interface structure is presented in Figure 2(b), but for a three-level structure, a multilevel (five-levels) single grid-side interface structure is presented in Figure 2(c) and the proposed multilevel (nine-level) single grid-side interface structure is highlighted in Figure 2(d). It is imperative to note that by increasing the voltage levels from five to nine, advantages and disadvantages are identified. In terms of advantages, it is possible to obtain a significant reduction of the total harmonic distortion in the grid-side current (adding improvements in terms of PQ) while maintaining the same coupling passive filters. On the other hand, in terms of disadvantages, four additional power semiconductors are necessary, representing a total of twelve semiconductors facing the eight semiconductors in the five-level structure (Figure 2(c)). For the dc-dc converters diverse topologies can be employed, unidirectional or bidirectional, in the domain of this paper, it is not established a complete description about such topologies. Relating with the state-of-the-art, the foremost contributions of the proposed ac-dc converter are: Single ac-dc converter for interfacing two technologies for smart grids (RES, EM, or ESS), employing a bidirectional multilevel (nine-level) topology; Opportunity for charging the batteries (EM or ESS) directly from RES, i.e., without the power grid as energy-buffer, which is more relevant in case of power outages; Operation with high-levels of PQ, i.e., sinusoidal current and unitary power factor in all functioning approaches.

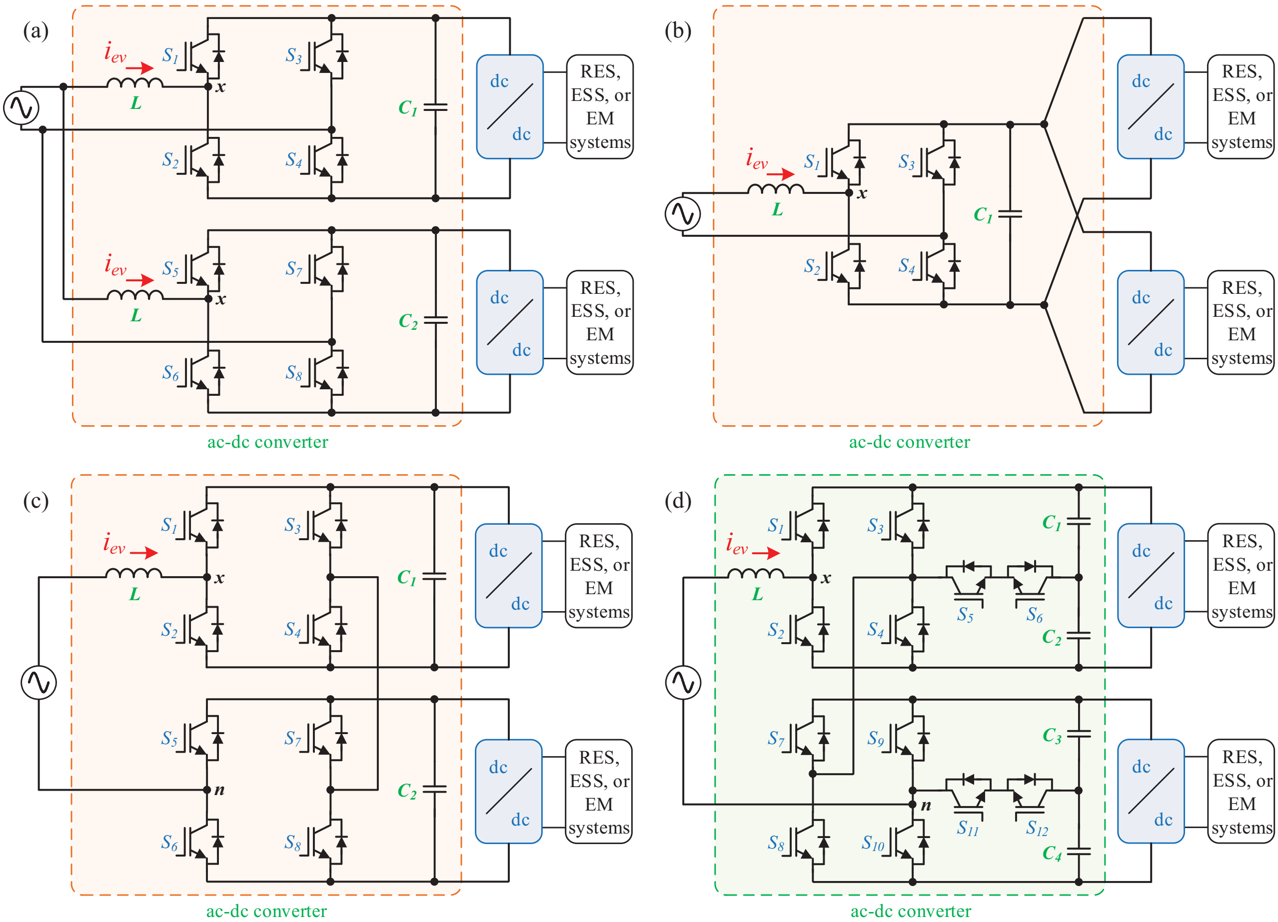

Figure 2: Main options for interfacing RES, ESS or EM into the power grid: (a) Traditional solution based on two interfaces in the grid-side; (b) Single grid-side interface structure with three-levels; (c) Single multilevel grid-side interface structure with five-levels; (d) Proposed single multilevel grid-side interface structure with nine-levels.

PROPOSED TOPOLOGY: COMPUTATIONAL VALIDATION

The proposed topology was introduced in the previous section (Figure 2(d)). Concerning the control algorithm, a phase-locked loop structure is applied to allow the control of the consumed or injected current into the power grid with a sinusoidal waveform, independently of the grid voltage waveform. This aspect is relevant as a compromise to prevent PQ problems. The current on the ac-side is defined according to the created voltage, i.e., as the proposed converter operates with nine voltage levels, a low harmonic distortion can be achieved for the current waveform. A fixed switching frequency predictive scheme is employed for defining the control state of each semiconductor. The dc-link voltages, interfacing the proposed ac-dc and the two dc-dc converters, are controlled by PI controllers. In terms of computational validation, the main results are presented in Figure 3. In more detail, the stage #1 of this result presents the current and voltage waveforms when power is consumed from the grid. In this case, the power grid provides energy for charging the ESS and the RES are not producing energy. Framed in a smart home perspective, this situation can occur, for instance, during the night, where the energy price from the grid is lower, convenient for charging the ESS, and it is not produced any energy from the RES (PV panels). During the day, the stored energy can be injected into the smart home (depending on the RES production and the defined energy management) or as a supporting compromise with the power grid (e.g., supplying other smart homes). Aiming to provide a simulation as realistic as possible, a grid voltage with PQ problems of harmonics was considered. As demonstrated by this result, the current presents a sinusoidal waveform, however it is in phase with the fundamental component of the voltage (unitary power factor), where the proposed converter is operating in the first and third quadrants (i.e., when the voltage is positive the current is also positive and vice-versa). In this figure, it is also presented the distinctive multilevel characteristic of the proposed converter, characterized by the nine voltage levels (the level zero, four levels in the positive half-cycle and more four levels, but in the negative half-cycle). This voltage is measured between the grid voltage and the filters, as identified in Figure 2(b) through the points x and n. Similarly, stage #2 of Figure 3 presents the current and voltage waveform, but when energy is injected into the grid. In this particular case, the current is not in phase with the voltage, meaning that energy is injected into the grid. In this second case, the power grid receives energy from the RES and the ESS is not charging or discharging. Analyzing this case in a smart home perspective, it can occur, for instance, when the ESS is completely charged and it is not necessary to provide energy for the electrical appliances in the home. Therefore, the produced energy from RES can be injected into the grid, benefiting the power grid management (e.g., supplying industries near the installation or supplying other smart homes). As verified by this result, the current presents a sinusoidal waveform, however, the proposed converter is operating in the second and fourth quadrants (i.e., when the voltage is positive, the current is negative and vice-versa). In this second stage are also presented the nine voltage levels, meaning that the proposed converter operates with a multilevel characteristic, independently if it is consuming or injecting energy into the grid.

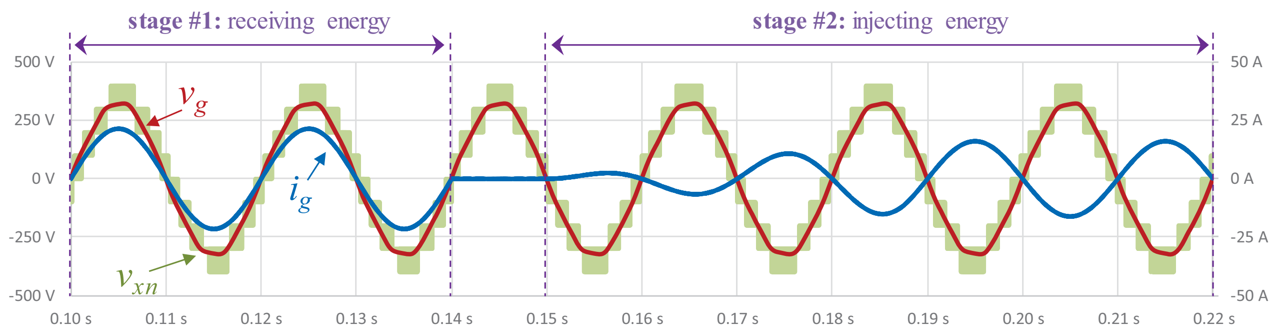

Figure 3: Computational validation when the proposed converter receives energy from the power grid (stage #1) and when it provides energy to the power grid (stage #2).

TECHNICAL AND ECONOMICAL EVALUATION

A technical and economical evaluation concerning the proposed converter is presented, where a comparison was established in terms of hardware implementation costs, neglecting the final cost considering the industrialization process of the equipment. In Figure 4 is presented a comparison between the four structures present in Figure 2.

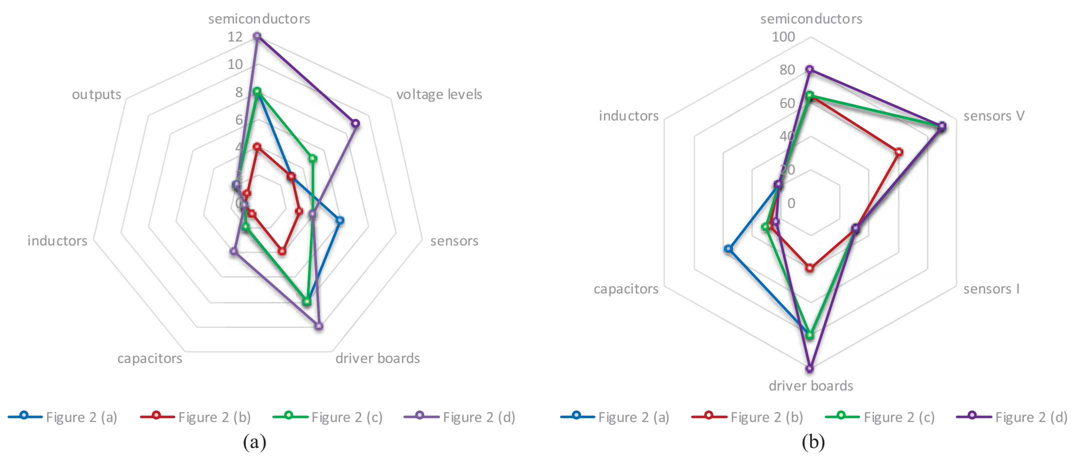

Figure 4: Comparison between the four structures presented in Figure 2 concerning: (a) The required number of components for the hardware implementation; (b) The cost implementation.

In more detail, Figure 4(a) presents the comparison in terms of the required hardware for implementation of these four solutions, taking into consideration: The number of controlled semiconductors; The number of voltage levels (distinct voltages); The number of sensors (current and voltage); The number of driver boards for controlling the semiconductors; The number of capacitors (filters for the dc interface); The number of inductors (filters for the grid interface); The number of independent outputs (for dc systems). Besides the mentioned parameters, it is important to evidence that each solution has a single digital control platform, where are encompassed the signal conditioning and the microcontroller. Consequently, this parameter was not considered in the established comparison. In Figure 4(b) is presented a comparison based on the four solutions, but considering an economic perspective in terms of the cost estimation for the implantation of each solution. For this comparison were considered commercial prices for each parameter identified in Figure 4(a), and was also considered the price of the digital control platform. In this figure, it is also possible to identify the total cost associated with each solution. By analyzing the obtained results in Figure 4 based on currently commercial values, the solution presented in Figure 2(b) is identified as the cheapest solution (246 €), whereas the proposed converter presented in Figure 2(d) is identified as the most expensive solution (347 €), but with very acceptable costs compared with the solutions presented in Figure 2(a) (344 €) and in Figure 2(c) (318 €). However, when comparing the four solutions in terms of PQ aspects related with total harmonic distortion for the grid-side current, the proposed converter presents the better results for all the range of operating powers. Figure 5 presents the obtained results about the total harmonic distortion when the operating power varies from 500 W to 3500 W.

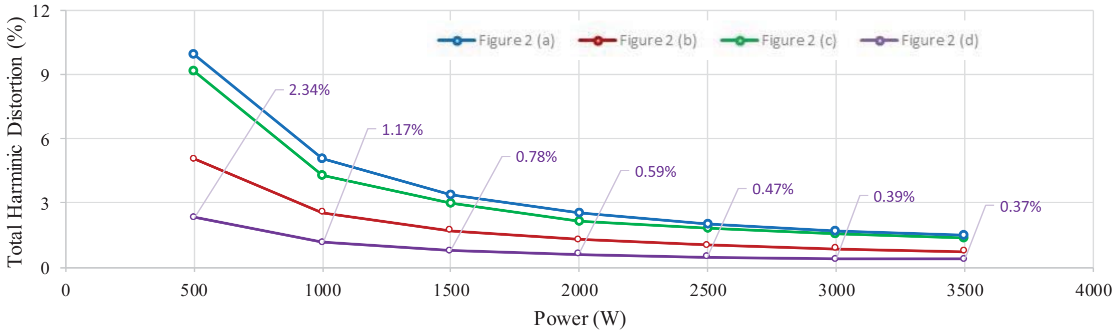

Figure 5: Comparison between the four structures presented in Figure 2 concerning total harmonic distortion for a range of power from 500 W to 3500 W.

CONCLUSIONS

With the introduction of smart grids driven by renewable energy sources (RES), electric mobility (EM), energy storage systems (ESS) and power quality (PQ), new technological advances are required in terms of power electronics applications. Therefore, advanced single-stage topologies are emerging as result of the developments in different areas of power electronics, representing a pertinent advantage when compared with the multi-stage topologies for interfacing the power grid. Along this paper, a novel converter topology for applications in smart grids is presented, highlighting the main features related with a symmetrical, bidirectional and multilevel topology. The multilevel feature is the most distinctive feature, since with the produced nine-levels, it is possible to improve the power quality at the grid-side. Within the target of establishing a comparison between the most conventional solutions, a technical and economical evaluation is presented, where the obtained results show that the proposed nine-level converter has a slightly higher cost (about 1.2% more than the most conventional solution based on independent interfaces with the power grid), but presents better results concerning PQ aspects (low total harmonic distortion of the grid-side current) for all the range of operating power. Therefore, the obtained results permit to conclude that the proposed converter has innovative and advantageous features, representing a relevant solution for different applications in smart grids.

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