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Economic and Efficiency Analysis of a New Converter Topology for Multifunctional AC/DC Hybrid Grids

Martim Machado[1], Sergio Coelho[1], Vitor Monteiro[1*], and Joao L. Afonso[1]

1 Department of Industrial Electonics, Centro ALGORITMI / LASI, University of Minho, Portugal

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

KEYWORDS

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ABSTRACT

The paradigm of smart grids has launched a precedent on the methods used to develop the new electrical power grids, related to their efficiency and overall cost. With that assessment in mind, this paper proposes an overhaul on the typical topologies related to the power electronics converters that are used to connect key technologies within a smart grid (i.e., a renewable and an energy storage system). Instead of the usual configuration, in which there is a set of power electronics converters for every technology connected to the AC power grid, it is suggested the use of a single power electronics converter (i.e., an AC/DC) to connect all the modules within the power grid and multiple DC/DC power electronics converters to connected native DC technologies, creating a DC-link and, consequently, a hybrid AC/DC power grid. This configuration aims to reduce the overall power consumption throughout the system, as well as to decrease the financial cost of the operation. Along the paper, the total cost of components will be compared between the two structures, as well as the efficiency of the system. The new topology proposed is presented, along with all the features and main differences that it includes, when compared to the traditional topology. Additionally, the main costs associated with assembling the proposed topology are estimated, as well as the demonstration of relevant comparisons between the new topology and the one already presented on the market.

INTRODUCTION

Nowadays, it is evident the growing interest, as well as the necessity, of producing energy from renewable energy systems (RES), with a special emphasis in solar photovoltaic, related to the consequences of global demand for electricity. The RES introduction into the power grid, both based on power plants or at residential level, brings a set of advantages, including the contribution to mitigate greenhouse gas emissions, and the contribution to decentralize the traditional centralized power grid [1][2][3]. Moreover, accompanied by this possibility, it is also included the active participation of the end-used in the energy market, which can provide a bidirectional power activity with the grid, i.e., by consuming and producing power. A thorough analysis on the impact of bidirectional converters can be found in [4]. The path of future grids will be followed in this direction, but not everything is an advantage, as there is an inconvenience associated with production from RES that cannot be ignored, and it is related to intermittency in production, leading to the need for developing systems capable of managing such demands, as the one found in [5]. Furthermore, in this sense, it may happen that production from RES does not coincide with the consumption needs of the power grid, which makes it difficult to manage the entire power production and consumption chain of the power grid. In [6] it is presented a control system to optimize the energy management of a grid connected with PV panels and batteries. As seen, it may be convenient to use energy storage systems (ESS), such as batteries, which to a certain extent can operate as energy intermediaries between power production from RES and the power grid, offering much greater flexibility in grid power management, while ensuring maximum power extraction from the RES [7][8].
Figure 1 represents the current topology present today. Supported by this figure, the aim of this paper is to propose another topology, more efficient and less financially costly, while ensuring the interface of the same technologies, namely the power grid, the RES and the ESS. Similar concepts have already been identified, mainly based on the way

in which all these different devices can interact from an efficiency perspective. A unified three-port topology for three-phase installations is proposed in [9], but without accounting for the overall cost of implementation. Another unified three-port topology is proposed in [10] , but in this case it is for single-phase installations. There are also papers identifying the possibility of interfacing RES through an active power filter, as is the case in [11][12]. A computer simulation of a multifunctional system also to interface a RES and an ESS is presented in [13], but in this case the ESS does not have a DC/DC converter connecting to the DC-link, which presents a disadvantage. Similarly, a computer simulation of a multifunctional system also to interface a RES and an ESS is presented in [14], but in this case the RES is connected to the DC-link without any DC/DC control converter.
Based on the analysis of the state-of-the-art, the main contributions of this paper can be distinguished as: (i) an overhaul of the typical topologies related to the power electronics converters used to connect renewables and energy storage systems into a smart grid, including the distinguished operation modes; (ii) proposed topology based on a single power electronics three-phase AC/DC converter, i.e., in the interface with the main AC power grid, but allowing to connect a renewable and an energy storage system with the power grid through a shared DC grid; (iii) proposed solution based on multiple DC/DC power electronics converters to connected native DC technologies (i.e., RES and ESS) and for creating a DC power grid; (iv) comparison of the proposed topology with the conventional solution in terms of total cost of components, as well as the efficiency of the system. The paper is organized as following. After the introduction, is presented the converter topology for multifunctional ac/dc hybrid grids. After that, it is presented all the details concerning the operation principle of the proposed converter topology, while the main achieved results are presented after. The paper is finalized with a set of conclusions.

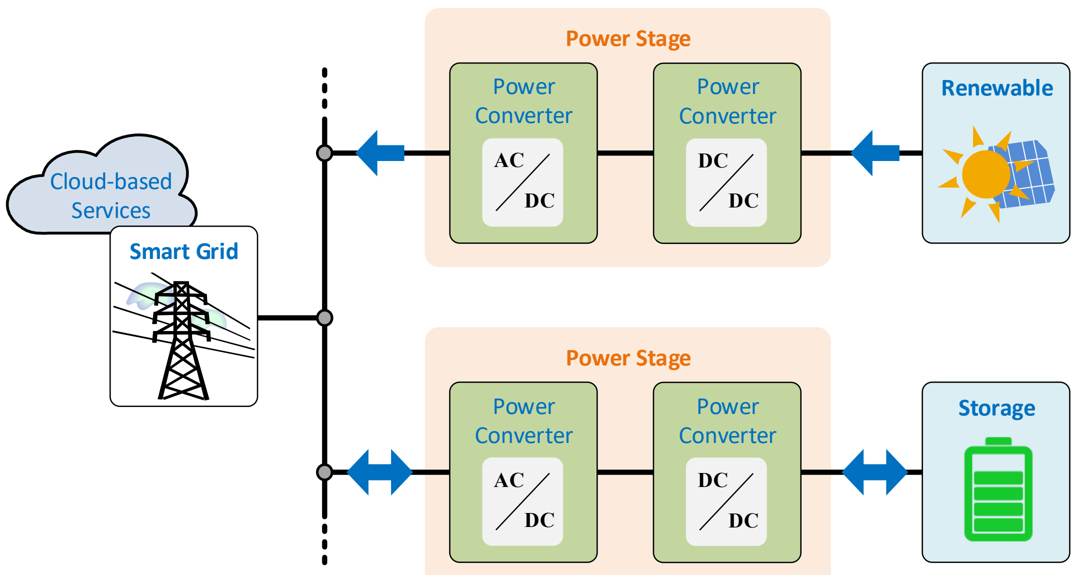

Figure 1. Traditional solution with multiple AC/DC power converters (electrical grid interface) and individual DC/DC power converters (RES and ESS interface).

CONVERTER TOPOLOGY FOR MULTIFUNCTIONAL AC/DC HYBRID GRIDS

This section presents the proposed converter topology for the multifunctional AC/DC hybrid grids, whose diagram can be observed in figure 2. As shown, in the DC grid is connected directly a RES and an ESS, namely solar PV panels and a set of batteries. Obviously, other DC technologies can be directly connected to such DC grid or connected by using a DC/DC power converter (independently of the mode of connection, is always avoided the need to additional AC/DC power converters in the interface with the main AC power grid). The AC grid-interface consists of a three-phase AC/DC bidirectional power converter, whereas the DC grid is comprised of several interfaces, of which it includes a unidirectional DC/DC power converter for the renewable energy source (RES) and a bidirectional interface for the energy storage system (ESS), among others, depending on the purpose of the DC interface. This unified topology, proposed in this paper, integrates all these interfaces with a common characteristic of having a single DC-link, without affecting the characteristics of an individual operation of each converter. The proposed converter topology for the multifunctional AC/DC hybrid grids operates in different operation modes according to the type of connection that needs to be established, i.e., according to the instantaneous power operation of each interface. In such circumstances are included, e.g., if the batteries are charging/discharging, or the energy produced by the solar PV panels is injected into the AC grid or into the DC grid for storing in the ESS for to be used by other DC loads.

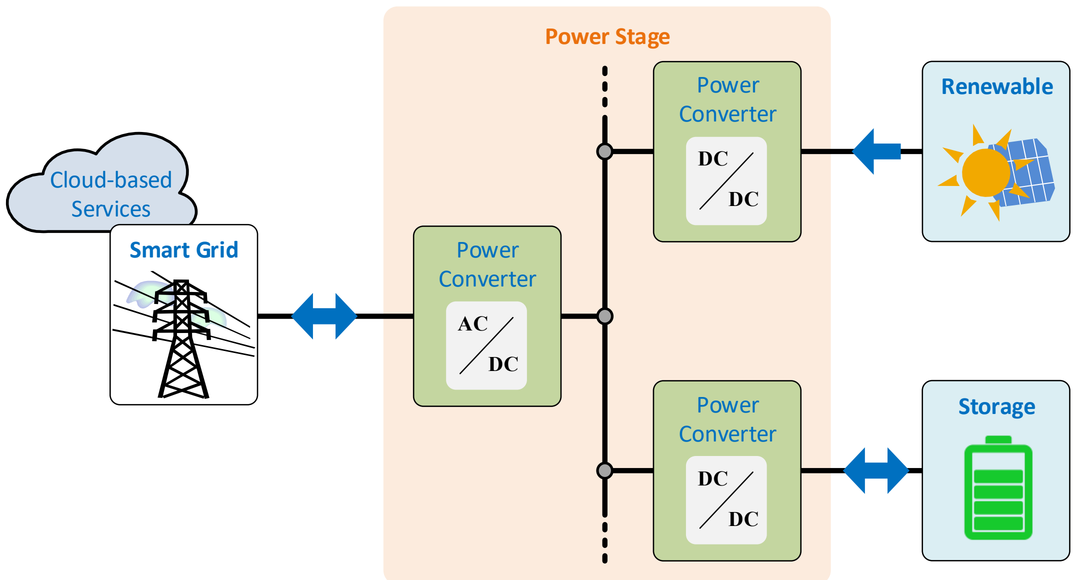

Figure 2. Proposed solution with a single AC/DC power converter (electrical grid interface) and multiple DC/DC power converters (RES and ESS interface).

I. AC Grid Interface

The AC/DC converter operates in bidirectional and it is responsible for controlling the AC grid interface in terms of current since the voltage is imposed by the AC grid, i.e., for ensuring sinusoidal currents in both bidirectional power operation, as well as balanced currents, which should be performed independently of the voltage conditions in terms of RMS values and unbalances (nevertheless, other power strategies can be considered for such purpose), as well as for ensuring the DC-link voltage, i.e., with a constant voltage for the correct operation of the DC/DC converters, as well as for the other loads or converters linked through the DC grid. The proposed topology brought forward in this paper permits the possibility of connecting the AC grid with a DC grid, where are the RES and the ESS. The power converters are constituted by IGBTs as switching devices, and by L coupling filters.

B. DC Grid Interface

Considering that the DC grid is the common point among the AC/DC and DC/DC power converters, the DC/DC power converters are designed to be adapted to the needs of the electrical component on the other end. For the ESS, the topology consists in the use of a bidirectional converter, with the intention of either charging the ESS (operating in buck mode with controlled voltage or current) or using it to feed energy into the DC grid, if the situation arises (operating in boost mode with controlled input current or injecting a constant power into the DC grid). For that reason, the use of a buck/boost converter, that can lower the voltage coming from the DC grid to match with the value of the ESS, or to raise the voltage to fit the needs of the AC grid, is the most adequate for the goal. For the interface with the RES, it is used a unidirectional boost converter, so that the voltage coming from the RES can be raised to match that of the DC grid. This converter is controlled with the main objective of guaranteeing that the maximum power available form the solar PV panels is in fact extracted and delivered to the DC grid.

OPERATION PRINCIPLE OF THE PROPOSED CONVERTER TOPOLOGY

With the context of the existing topology in mind, this paper proposes a new converter topology for multifunctional AC/DC hybrid grids integrating a RES (solar PV panels) and an ESS (batteries) through a common DC-link and with a single AC grid interface. The respective details of all power converters and the contextualization with the AC and DC grids is represented in Figure 3. The proposed converter topology for multifunctional AC/DC hybrid grids can operate as: (a) an active rectifier (absorbing power from the AC grid to the ESS); (b) a grid-tied inverter, injecting power from the RES to the AC grid; (c) a grid-tied inverter, injecting power from the ESS to the AC grid; (d) a converter directly from the RES to the ESS with an active power filter that can be combined with the operation as an active rectifier or as a grid-tied inverter.

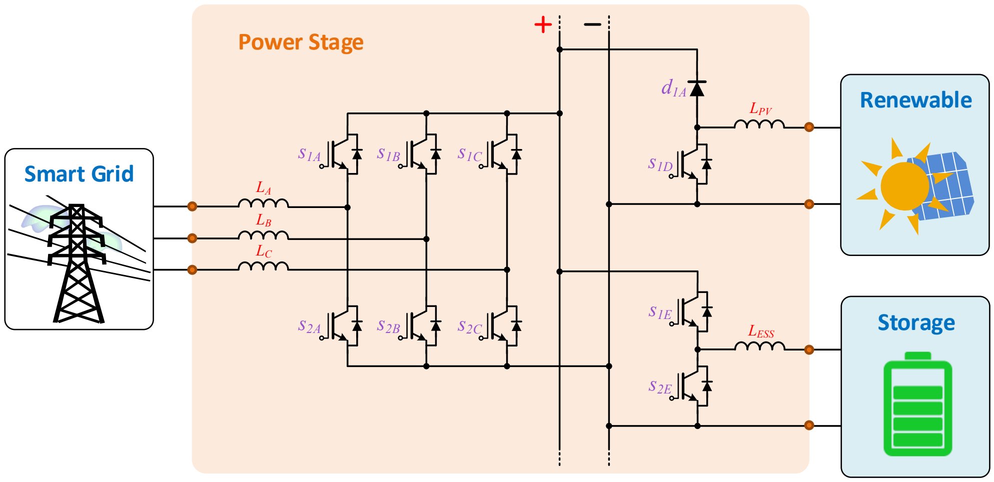

Figure 3: Operation Principle of the Proposed Topology

RESULTS

This section presents the results related to the efficiency and financial analysis concerning the proposed converter topology for multifunctional AC/DC hybrid grids.

A. Efficiency Results

Considering that one of the main aims of this paper is to study and compare the traditional solution available nowadays with the proposed solution about the possibility of reducing the number of semiconductors used in electrical grid interfacing (i.e., consequently a solution that permits reduce costs, while maintain the same features in terms of operation of the three power interfaces) and consequently increase the efficiency, it was performed an analysis about it in terms of simulation results. Thus, for the traditional solution, it was evaluated in simulations that the efficiency of the AC/DC power stages is around 90%, the efficiency of the DC/DC for interface the RES is around 93%, and the efficiency of the DC/DC for interfacing the ESS is around 92%. These values were considered for the power stages operating with the nominal power. Based on these values, when considering the traditional solution for interface RES, which is constituted by the two power stages DC/DC and AC/DC, the overall maximum efficiency is 83.7%. On the other hand, when considering this traditional solution for interface ESS, which is also constituted by the two power stages DC/DC and AC/DC, the overall maximum efficiency is 82.8%. The obtained values are almost similar since in both perspectives of interfacing the technologies of RES and ESS with the power grid using a three-phase interface are used two power stages. Moreover, for both cases, the AC/DC power stage is the same, which suggests redundancy in the use of the AC/DC power stage. In addition, the AC/DC power stage that interfaces the RES natively operates in bidirectional mode, which is not a requisite since it is only possible to inject power into the power grid and not the contrary. So, in the AC/DC it is possible to find an opportunity of optimizing this power stage. In this traditional solution, the difference lies in the DC/DC power stages, one operates in unidirectional mode (RES) and the other in bidirectional mode (ESS), meaning that the difference is just in the switching of an additional IGBT. However, it is important to highlight that the ESS interface only requires the switching of one IGBT in each mode, i.e., both IGBTs are note used at the same time, one is switched in buck mode (charging) and the other in boot mode (discharging). On the other hand, when considering the proposed solution, a single power stage for interfacing the grid is necessary, or for injecting power from the RES, or for injecting power from the ESS (discharging for the grid), or for absorbing power for the ESS (charging from the grid). So, in any kind of theses operation modes, it is expected around the same efficiency as for the traditional solution, i.e., 83.7% for the RES interface and 82.8% for the ESS interface. However, the main contribution in terms of efficiency analysis lies when considering the direct interface of the RES with the ESS, in other words, when the power production from the RES is stored directly in the ESS, meaning that all the power is stored for future purposes of the system and not injected into the power grid. In this possible scenario, if considering the traditional solution, firstly, the power production from the RES must be injected into the power grid (i.e., meaning the necessity of using the DC/DC and the AC/DC power stages) with an efficiency around 83.7% and, only after that the power is stored into the ESS (i.e., also in this case meaning the necessity of using the DC/DC and the AC/DC power stages) with an efficiency around 82.8%. As result, the overall efficiency for storing the power from the RES into the ESS is around 69.3%, where the power is not used by the power grid, but the grid was necessary for interfacing both RES and ESS technologies. Obviously, it is identified a possible contribution to increase the efficiency. With the proposed solution, the RES and ESS interface is almost direct, only realized by the DC/DC power stages with the shared DC-link. Moreover, depending on the electrical characteristic of the RES and ESS, can be used both DC/DC power stages or just of one of them. The most critical scenario is when considering the used of both DC/DC power stages, meaning an efficiency around 85.6%, which is much better that the traditional solution with an efficiency of 69.3%. Just considering this possibility, is obvious the achieved gain and the power grid is not used. However, as previously mentioned, depending on the instantaneous values of the voltage and current in both RES and ESS interfaces, as well as the required control in terms of the ESS charging optimization, a solution based on the operation of just of the DC/DC power stages can be considered. Thus, if just considering the DC/DC power stage used to interface the RES, the overall efficiency to charge the ESS from the RES is around 93%, while if just considering the DC/DC power stage used to interface the ESS, the overall efficiency to charge the ESS from the RES is around 92%. Based on these values, it is recognized the importance of the proposed solution, particularly, when all the power production from RES is stored in the ESS. Obviously, other hypothetical scenarios can be considered, i.e., when part of the power production from RES is stored in the ESS and the remaining injected into the power grid or when the ESS stores energy from the RES and from the grid. In such scenarios, obviously, the overall efficiency will decrease, but in the worst scenario for an efficiency always better than the traditional solution. The different cases are summarized in Table I.

Table I. Estimation of efficiency comparing the different scenarios
for the traditional solution and for the proposed solution.

	Used Power Converters	Traditional Solution	Proposed Solution
RES to electrical grid	DC/DC and AC/DC	83.7%	83.7%
ESS to electrical grid	DC/DC and AC/DC	82.8%	82.8%
RES to ESS	DC/DC / DC/AC and AC/DC / DC/DC	69.3%	-
RES to ESS	DC/DC and DC/DC	-	85.6%
RES to ESS	DC/DC (RES)	-	93%
RES to ESS	DC/DC (ESS)	-	92%

B. Financial Results

As for the other main purpose of this paper, it is to evaluate the financial advantages of the proposed topology in comparison to the topology currently used. As proved before that, for efficiency purposes, the new topology did indeed present some advantages by the reduced number of semiconductors being used and therefore less path losses throughout the device, it is now expected that the overall price of the proposed topology should be lower as well, presenting another advantage as to why it should be implemented. For this financial analysis, the semiconductors used for the AC/DC power stage are the SKM100GB12T4, model from Semikron, valued at €92.03 each [15], and with each containing 2 IGBTs. For the DC/DC converter, considering that it is only needed 1 IGBT per converter, it was used the SKM150GAL12T4, also from Semikron, valued at €84.26 each [16]. Firstly, it will be done a cost calculation on the existing topology. For this, it will be needed 6 dual IGBT modules (3 for each AC/DC converter), as well as 2 single IGBT modules (one for the RES interface, and another for the ESS interface). With these components, the total cost of the IGBT modules would be €720.70. For the new proposed topology, the total number of IGBT modules used would be 3 dual IGBT modules (for the AC/DC converter) and 2 single IGBT module (one for each DC/DC converter), with the total cost of the device being €444.61. This represents solely the comparison between the cost of the IGBT modules. For the entire device, the following table presents the price of every component used, as well as the overall cost[17], [18], [19], [20]. The estimation of prices is summarized in Table II.

Table II. Estimation of prices (individual and for the whole solution) comparing the different scenarios for the traditional solution and for the proposed solution, considering the key components.

	Price (unit)	Traditional Solution	Proposed Solution
SKM100GB12T4	€92.03	€552.18	€276.09
SKM150GAL12T4	€84.26	€168.52	€168.52
coupling filters	€76.44	€611.52	€382.20
DSP control board	€184.29	€184.29	€184.29
voltage sensors	€24.78	€247.80	€173.46
current sensors	€27.21	€217.68	€136.05
estimated total price		€1981.99	€1320.61

CONCLUSIONS

This paper presents a proposal for a new converter topology for multifunctional AC/DC hybrid grids, allowing the simultaneous interface of solar photovoltaic panels and batteries (energy storage system or an electric vehicle), through a DC interface with the AC power grid. The proposed topology is composed by three main power stages (one AC and two DC), each sharing the same DC-link, allowing for the power exchange between them. In addition, for all modes, it ensures high power quality on the AC power grid interface. Throughout the paper, it is presented the main structure of the topology, as well as the differentiating contribution, the main financial and efficiency advantages when compared to the one that currently exists (i.e., based on multiple interfaces with totally independent power electronics converters). It is proven that the proposed topology presents a decrease in the overall cost of the entire device. Based on the estimation of prices, for the traditional topology, the total cost would be €1981.99, while for the proposed topology, the total cost would be €1320.61, representing a reduction of around 33% on the traditional topology price. As for the efficiency results, supported by simulation results of the power converters, it is possible to conclude that, in the case of transferring power from the renewable to the storage system, the efficiency of the proposed solution offers an increase of around 16%.

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