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A Novel Front-End Multilevel Converter for Renewable Energy Systems in Smart Grids

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Abstract:

The integration of renewable energy systems into smart grids requires dc-to-ac power electronics converters for adapting the voltage levels of both sides. In this context, a novel topology of front-end multilevel dc-to-ac converter is proposed in order to enhance the integration of renewable energy systems into smart grids, preventing power quality problems. The proposed converter is designed to operate as a grid-tied inverter, imposing controlled sinusoidal grid currents in phase opposition with the power grid voltage, and establishing five distinct voltage levels to improve the current waveform. The dc side is suitable to be connected directly to a set of photovoltaic solar panels with an appropriated voltage level, or to an external dc-to-dc intermediary converter used to interface other renewable energy sources. An entire analysis of the hardware design and the operation principle is presented, including the adopted control strategy for the proposed front-end converter in conditions of current control. An accurate computational validation under realistic operating conditions for a significant operating power range is presented using a dedicated power electronics simulation software, where the obtained results show the advantages and the convenience of the proposed front-end converter in detriment of the classical solutions.

Keywords:

Renewable Energy Systems, Smart Grids, Multilevel Converter, Power Quality

1. Introduction

European Union has committed to reduce greenhouse gas emissions by 80% by 2050 and plans to set intermediate targets for 2030 [1]. As a contribution to achieve such objective, an increasing share of renewable energy systems is fundamental, even considering the discontinuous production of energy from wind and solar [2][3]. The introduction of smart and flexible electrical loads, monitored and remotely controlled by information and communication technologies, also represents a challenge for this new paradigm of energy [4]. Combining all of these scenarios, results in a smart power grid, where new challenges and opportunities for technological developments are emerging [5][6]. As example, a vision and framework for smart transmission grids considering of environmental, market, infrastructure, and innovative technologies challenges is presented in [7], and an overview about key players and pilot projects for smart grids and smart homes is presented in [8].

The emerging reality of smart grids promotes a set of advantages to the global energy management at the distribution and transmission levels, as well as to the end-user, since it can operate as an energy consumer or producer [5][9][10]. Increasingly, this new paradigm for the electrical sector stimulates the energy microgeneration through the integration of renewable energy sources (RES) and contributes to improve the energy efficiency in the transmission and distribution levels. The future perspectives for RES is presented in [11], the RES operation and optimization in microgrids is presented in [12], and the integration of RES in a smart grid scenario is presented in [13]. In this context, the collaborative management with electric vehicles and energy storage systems (ESS) also represents a new opportunity for RES integration into power grids [14][15][16]. Considering these three strands, a demand-side energy management is proposed in [17], an optimization for economic deployment is proposed in [18], an integrated management is proposed in [19], a multifunctional converter interfacing RES and electric vehicles is proposed in [20], and a review about ESS for mitigating the RES variability is presented in [21]. Nevertheless, the RES integration into the power grid requires the use of power electronics in order to convert the energy extracted from RES according to the requirements of the power grid. A review about power electronics converters for RES is presented in [22], RES with modularity in power electronics presented in [23], and a review focusing converters for RES based on photovoltaic (PV) modules is presented in [24].

Along the last decades, as a result of advances in power electronics, including new technologies of devices and digital control platforms, a large variety of solutions can be adopted to interface RES with the power grid [25]. In this circumstance, two main approaches can be adopted: Single stage dc-to-ac converter (front-end); Double stage consisting in a dc-to-dc converter (back-end) followed by a dc-to-ac converter (front-end). In the scope of this paper, a novel topology of dc-to-ac converter operating as a front-end converter is proposed. Since the voltage is imposed by the power grid, the front-end converter controls the current in order to inject a sinusoidal current with adjustable amplitude and in phase opposition with the power grid voltage [26]. This is more relevant considering power quality issues in smart grids [27]. When the front-end converter is operating as a grid-tied inverter (injecting energy into the power grid), the voltage established by the converter affects directly the waveform of the current injected into the power grid. The classical front-end converter to integrate RES into the power grid allows the establishment of three distinct voltage levels and, with a passive filter, it is possible to control the injected current into the power grid. Improving the voltage established by the front-end converter, for instance, by increasing the number of voltage levels, results in a more accurate controlled current. Theoretically, the number of voltage levels can be undefined, but the practical implementation and commercialization limits the number of voltage to few levels. This limitation is imposed by the requirements in terms of hardware components as power semiconductors, gate-drivers and sensors. Typically, the front-end converters with capability to establish more than three voltage levels are classified as multilevel converters (MLCs) [28]. The use of MLCs is especially relevant for applications with a dc-link composed by a series of voltage sources, as, for instance, occurs with the interface of PV panels [29]. A review and detailed comparison about the different MLC referenced in the literature is presented in [30], and a more comprehensive review about the main single-phase and three-phase MLC, including a discussion about power control theories and applications, is presented in [31]. Associating in series or parallel a set of MLCs results in a new family of converters identified as modular or cascade MLCs. A review about the operation, control and applications of modular MLCs for medium or high-power systems is presented in [32], a review of modular MLCs for high-voltage dc transmission systems is presented in [33], and the control of a cascaded MLC for PV systems is presented in [34].

In this context, this paper proposes a novel topology of front-end converter based on a five-level MLC. Contextualizing the proposed topology in smart grids, the more relevant advantages are: Reduced number of semiconductors in comparison with the state-of-the-art topologies of MLCs; Improved efficiency in comparison with the state-of-the-art topologies of MLCs; Possibility to operate in bidirectional mode, which is especially useful to interface ESS in the same dc-link; Flexibility to accommodate the variations of energy production from RES; Controlled grid currents and operation with high-levels of power quality. These advantages are established as a comparison with the main state-of-the-art topologies and are contextualized with the presented references. A new five-level topology is proposed in [35], however it requires two independent dc-links, representing the main disadvantage for front-end MLCs used in RES interface. The same disadvantage is presented in the cascade nine-level MLC proposed [36]. New structures of MLC are proposed in [37], [38], and [39], but only for unidirectional systems, i.e., they cannot be used for applications of RES (injecting energy into the power grid). A new five-level MLC is proposed in [40], but it requires more capacitors and controlled semiconductors than the topology proposed in this paper. A flexible five-level cascaded MLC is proposed in [41], and a five-level MLC based on multistate switching cell is proposed in [42], but, in both cases, the high number of controlled semiconductors is the main drawback compared with the proposed topology in this paper.

A clarification about power electronics converters in smart grids is presented in section 2. The proposed MLC is presented in section 3, illustrating its principle of operation and the proposed control structure. The proposed MLC operating as interface of RES in smart grids considering an analysis of power quality aspects is presented in section 4, and the main conclusions are discussed in section 5.

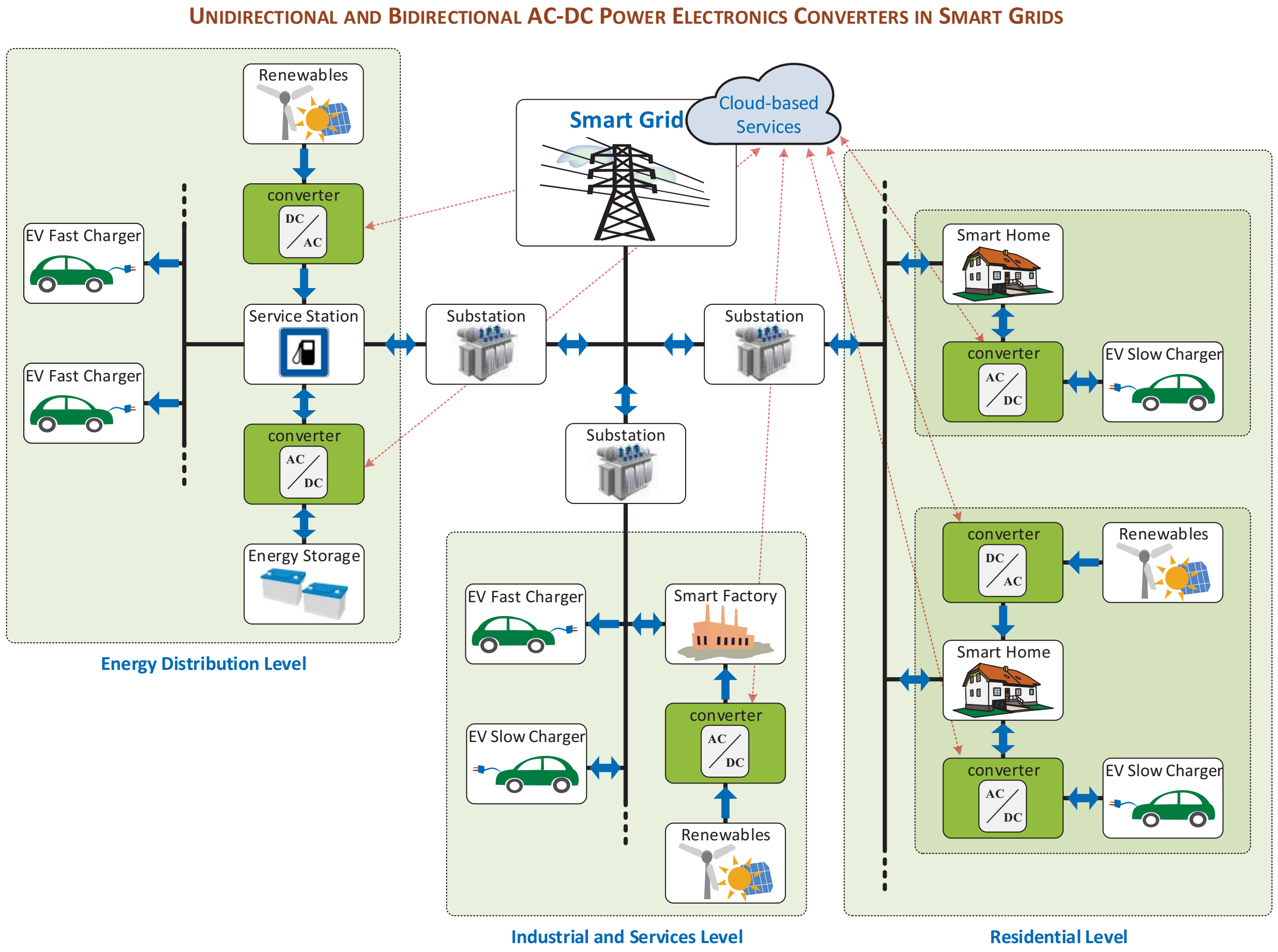

Fig. 1. Application of power electronics converters for renewable energy systems (RES) and energy storage systems (ESS) in smart grids.

2. Power Electronics Converters in Smart Grids

Fig. 1 shows the application of power electronics converters for RES and ESS in smart grids. Concretely, this figure shows the application of unidirectional and bidirectional dc-to-ac power electronics converters, illustrating their use as interface between RES (both from PV panels and wind turbines) and ESS (from batteries) with the power grid. As it can be seen, dc-to-ac power electronics converters are required for three fundamental levels of energy in smart grids: energy distribution; industrial and services; residential. At the distribution level, large scale of RES and ESS can be integrated with the power grid, where its controllability and quality of service is directly performed and guaranteed by distribution system operators (DSOs) or even by transmission system operators (TSOs) toward a demand response (DR) control. At the industrial level, RES can be integrated in order to reduce the energy consumption from the power grid and to minimize energy costs, where the DSO can play a management role in smart grids. At the residential level, RES and ESS can be integrated in small-scale with the purpose of minimizing the energy costs of the final energy user, as well as of contributing to define management strategies for DR, allowing to establish a distributed scenario of RES. Taking into account the aforementioned three energy levels, and aiming a smart grid operation with a DR management by a DSO, the power electronics converters identified in Fig. 1 should be equipped with a communication interface to establish a bidirectional communication with a cloud-based service. This communication interface can be used to define the status of the converter (controlled as an on-off electrical appliance), to report power quality problems and to define set-points of operation, as well as to communicate the values about energy transactions.

Unidirectional converters are used when the energy follows from an energy source to the power grid, where the integration of RES is the main application for such converters. In this case, the voltage and current levels in the dc-side are adjusted in order to inject a sinusoidal current in phase opposition with the power grid voltage, guarantying a high-level of power quality. Depending of the operating power level of RES, a single dc-to-ac converter can be applied to interface the power grid, however, a dc-to-dc back-end stage can also be used as intermediary between the dc-to-ac front-end and the power grid. On the other hand, bidirectional converters are used when the energy flows from an energy source to the power grid and from the power grid to an electrical appliance, where the integration of ESS is the main application for such converters in a smart grid context. It is relevant to highlight that a bidirectional power electronics converter can also be applied as an on-board or off-board battery charger for electric vehicles. As explained for the unidirectional converters, a single dc-to-ac converter can be used, as well as an intermediary dc-to-dc converter. Taking into account the indispensable necessity of dc-to-ac converters for the smart grids growing, in the scope of this paper, a novel front-end MLC for application of RES is proposed. However, it should be noted that the proposed converter can also be applicable for ESS, since it can operate in bidirectional mode.

3. Proposed Front-End Multilevel Converter

In order to interface RES (a set of PV panels) with the power grid, power electronics converters are required. A classical approach consists in use a back-end converter to interface the PV panels and a front-end converter to interface the power grid, both sharing a common dc-link. In this context, Fig. 2 shows the proposed MLC operating as front-end converter for RES integration in smart grids. It is composed by eight controlled semiconductors (metal oxide semiconductor field-effect transistor - MOSFET), by an inductor (L) ac-side passive filter, and by a capacitor (C) dc-side passive filter. The ac-side is directly connected to the power grid, and the dc-side is connected to a back-end converter, which is connected to a set of PV panels. Controlling the state of each MOSFET with a fixed frequency, the proposed MLC can establish five distinct voltage levels, i.e., the voltage between the points a and b before the L passive filter. Besides the level 0, this voltage can assume the values of $+v_{dc}$ and $+v_{dc}/2$ during the positive half-cycle, and the values of $-v_{dc}$ and $-v_{dc}/2$ during the negative half-cycle. It is relevant to note that classical front-end converters for RES only allow the voltage levels of $+v_{dc}$, 0, and $-v_{dc}$.

3.1. Principle of Operation

Taking into account that the proposed converter is evaluated for applications of RES, i.e., the injected current is in phase opposition with the power grid voltage, the analysis is performed in two quadrants highlighted in Fig. 3. When the power grid is positive ($v_g > 0$), the voltage established by the MLC can assume the values of 0, $v_{dc}/2$ and v_{dc}. In order to establish the voltage levels of 0 and $v_{dc}/2$, MOSFET s_1 is ON, MOSFETs s_2, s_5, and s_6 are OFF, and MOSFETs s_3, s_4, s_7, and s_8 are switched. To establish the voltage levels of $v_{dc}/2$ and v_{dc}, MOSFET s_1 is ON, MOSFETs s_2, s_3, s_4, and s_5 are OFF, and MOSFETs s_6, s_7, and s$_8$ are switched. When the power grid voltage is negative ($v_g < 0$), the voltage established by the MLC can assume the values of 0, $-v_{dc}/2$ and $-v_{dc}$. In order to establish the voltage levels of 0 and $-v_{dc}/2$, MOSFETs s_1, s_5, and s_6 are OFF, MOSFET s_2 is ON, and MOSFETs s_3, s_4, s_7, and s_8 are switched. To establish the voltage levels of $-v_{dc}/2$ and $-v_{dc}$, MOSFETs s_1, s_3, s_4 and s_6 are OFF, MOSFETs s_2 is ON, and MOSFETs s_5, s_7, and s_8 are switched.

Table 1 summarizes all of the aforementioned states in both positive and negative half-cycles of the power grid voltage.

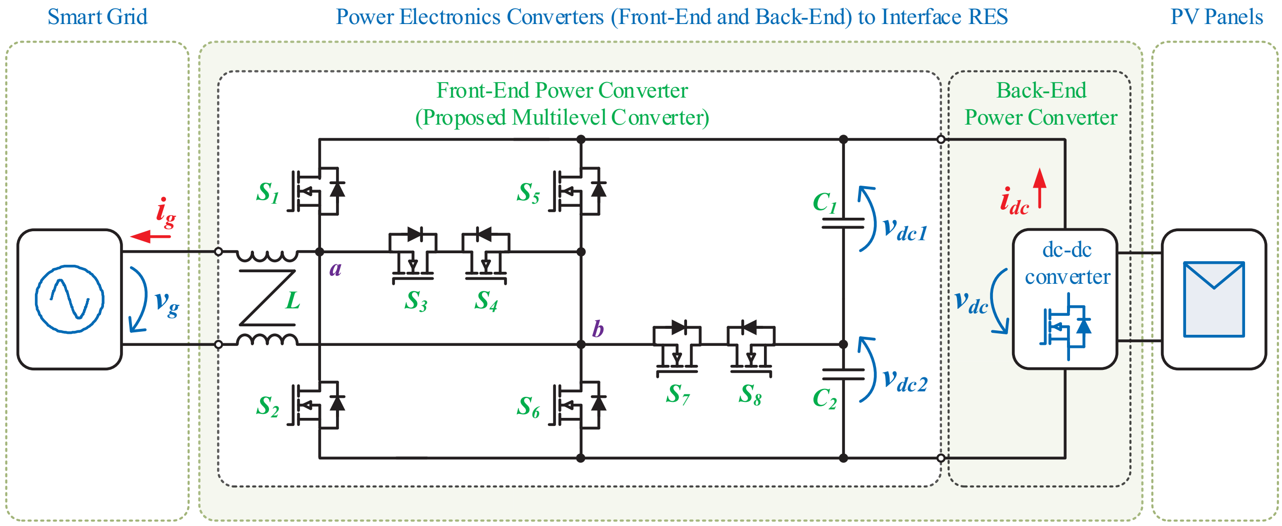

Fig. 2. Proposed front-end multilevel converter for the integration of renewable energy systems in smart grids.

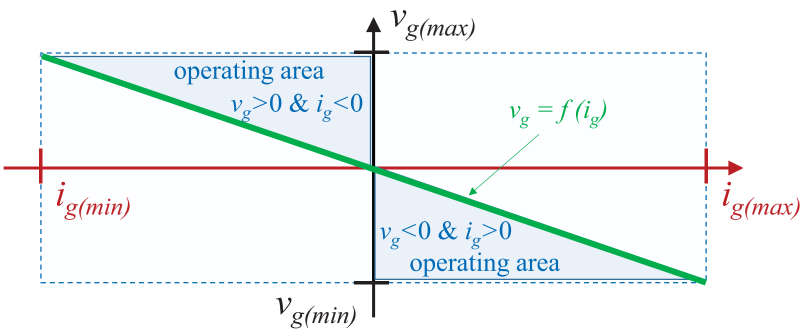

Fig. 3. Quadrants of operation for the proposed front-end multilevel converter.

Table 1. MOSFETs state in both positive and negative half cycles of the power grid voltage.

		s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	v_{ab}
$v_g > 0$	$0 < v_{ab} < v_{dc}/2$	ON	OFF	ON	ON	OFF	OFF	OFF	OFF	0
		ON	OFF	OFF	OFF	OFF	OFF	ON	ON	$+v_{dc}/2$
	$v_{dc}/2 < v_{ab} < v_{dc}$	ON	OFF	OFF	OFF	OFF	OFF	ON	ON	$+v_{dc}/2$
		ON	OFF	OFF	OFF	OFF	ON	OFF	OFF	$+v_{dc}$
$v_g < 0$	$0 < v_{ab} < -v_{dc}/2$	OFF	ON	ON	ON	OFF	OFF	OFF	OFF	0
		OFF	ON	OFF	OFF	OFF	OFF	ON	ON	$-v_{dc}/2$
	$-v_{dc}/2 < v_{ab} < -v_{dc}$	OFF	ON	OFF	OFF	OFF	OFF	ON	ON	$-v_{dc}/2$
		OFF	ON	OFF	OFF	ON	OFF	OFF	OFF	$-v_{dc}$

3.2. Proposed Control Structure

Fig. 4 shows the proposed control structure for the MLC, which is composed by three main parts: power theory; grid current control; PWM. The power theory block receives the variables acquired from the ADC (v_g, i_g, v_{dc1}, v_{dc2}, i_{dc}) and establishes the current reference (i_g*) for the power grid current. The dc-link voltage is regulated in this block using a proportional-integral (PI) controller, which produces a power component that is added to the dc-side power (determined with the variables v_{dc} and i_{dc}), resulting in the value of the instantaneous power for MLC operation. Using the value of this power, and the root mean square (rms) and instantaneous values of the power grid voltage, it is determined the instantaneous value for the power grid current reference (i_g*). The current control block receives the grid current reference (i_g*), the measured grid current (i_g), and the power grid voltage (v_g) as inputs, and using the values of the ac-side passive filter (L) and the sampling frequency (f_s) (in the scope of this paper, a sampling frequency of 200 kHz was used), defines the instantaneous voltage reference (v_{ab}*) that the proposed MLC must establish in order to obtain the five distinct voltage levels. The PWM block receives the instantaneous voltage reference (v_{ab}*) and establishes a set of control signals for each MOSFET, which are compared with a triangular carrier to define the ON and OFF state of each MOSFET. In the scope of this paper, a switching frequency of 100 kHz was used. Taking into account the aforementioned control strategy, the PWM can be optimized with only four individual PWM signals, representing an attractive strategy mainly considering that the classical converter (full-bridge three-level) also requires four individual PWM signals.

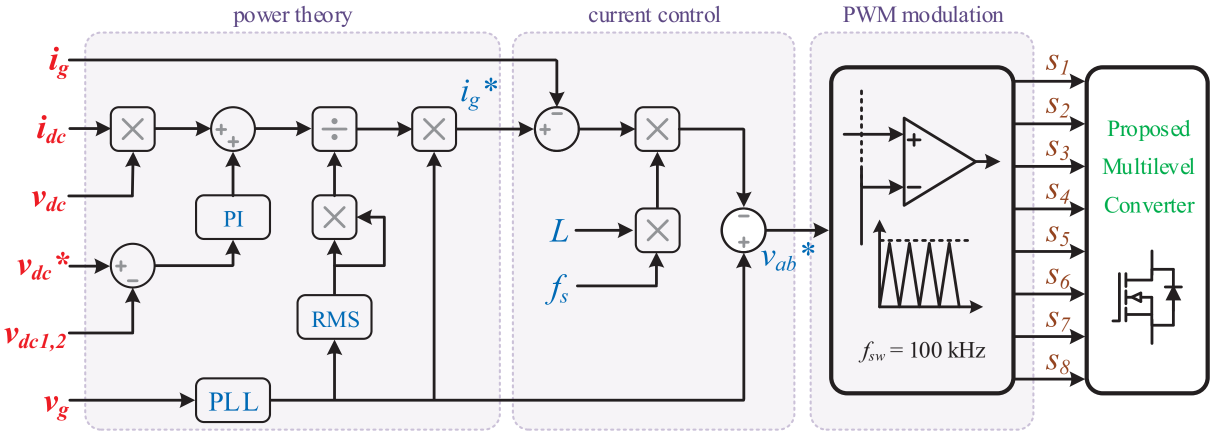

Fig. 4. Proposed control structure for the front-end multilevel converter.

4. Proposed MLC Operating with RES in Smart Grids

This section introduces the proposed MLC operating as interface of RES in smart grids. For such purpose, a detailed simulation model was implemented in the dedicated power electronics software PSIM. The main parameters and requirements of the proposed MLC are listed in Table 2.

Fig. 5 shows the results obtained with the proposed MLC operating in steady-state with the nominal power of 3.5 kW. The injected current (i_g) is in phase opposition with the voltage (v_g), presents a total harmonic distortion (THD%) value of 2.5%, and is sinusoidal even with a THD% value in the voltage of 3.5%. As highlighted, the five distinct voltage levels established by the proposed MLC are clearly identified (v_{ab}), proving the proper action of the proposed power theory, current control and PWM. This figure also shows the state of each MOSFET during the positive and negative half-cycles of the power gird voltage. As shown, MOSFETs s_1 and s_2 are switched at the power grid frequency (50 Hz), representing an important advantage of the proposed MLC. Besides, only MOSFETs s_7 and s_8 are always switched during all the time in both half-cycles.

Table 2. Main parameters and requirements of the proposed MLC.

Parameter	Label	Value	Unit
Power Grid Voltage	v_g	230	V
Power Grid Voltage THD (maximum)	THDv	3.5	%
Power Grid Frequency	f_g	50	Hz
Grid Current (@ full power)	i_g	15	A
Grid Current THD (@ full power)	THDi	2.5	%
Rated Power	P_g	3.5	W
Power Factor (@ full power)	PF	0.99	-
Dc-link Voltage	v_{dc}	200 + 200	V
MOSFETs Switching Frequency	f_{sw}	100	kHz
Sampling Frequency	f_s	200	kHz
L Passive Filter (ac-side)	L	300	µH
C Passive Filter (dc-side)	C_1, C_2	2.2	mF

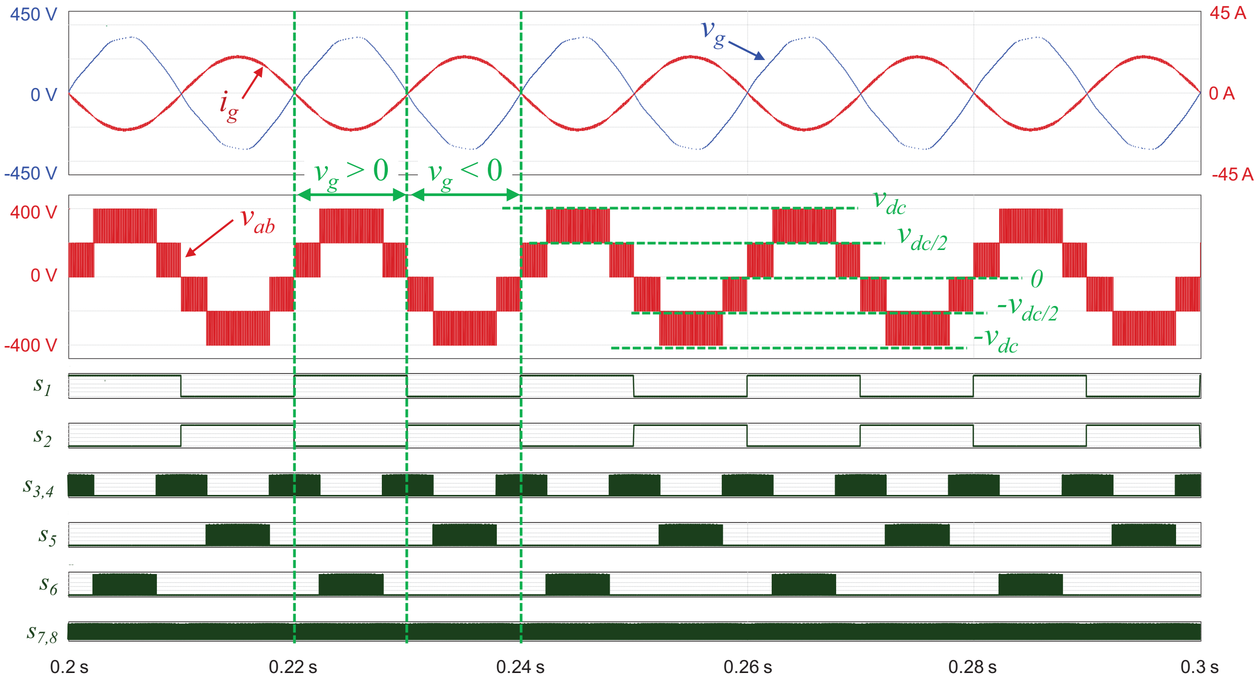

Fig. 5. Proposed multilevel converter operating in steady-state with nominal power of 3.5 kW.

Fig. 6 shows the dynamic operation of the proposed MLC in accordance with the energy extracted from the simulated PV panels. This simulation result was obtained during four distinct periods of operation, illustrating the performance of the proposed MLC and respective control strategy, as response to the variations of the energy extracted from the PV panels. During the first period, the operating power increases from 0 until a maximum of 3.5 kW without sudden variations and during a time period of 0.17 s. During the second period, the operating power is maintained with a value of 3.5 kW during a time period of 0.13 s. During the third period, the operating power decreases from 3.5 kW until a minimum of 2 kW, also without sudden variations in the injected current. During the fourth period, the operating power is maintained with a value of 2 kW during a time period of 0.15 s. The injected current is always sinusoidal and in phase opposition with the voltage during all the four periods, validating the proposed MLC for applications of RES. Moreover, this figure also shows a detail about the grid current (i_g) and grid voltage (v_g) crossing the zero value, and a detail about the comparison between the reference for the grid current (i_g*) and the measured current (i_g). No power quality issues can be identified in these detailed figures, representing an important requisite for the RES integration into smart grids.

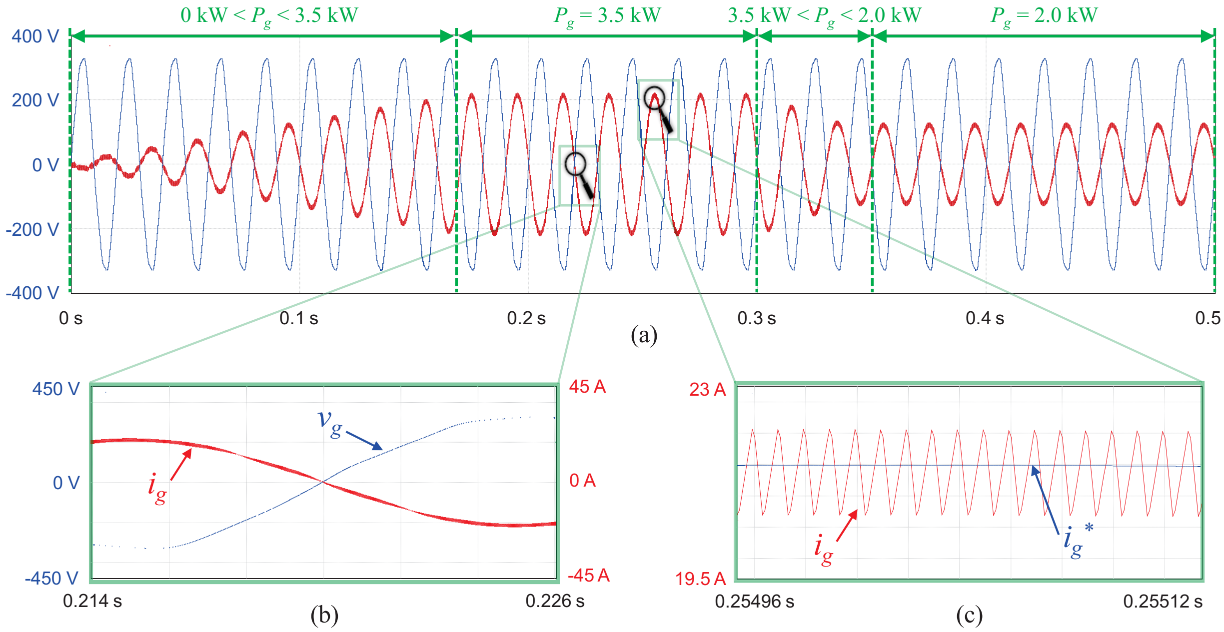

Fig. 6. Dynamic operation of the proposed multilevel converter in accordance with the energy extracted from the PV panels for four distinct operating levels: (a) Power grid voltage (v_g) and grid current (i_g) waveforms; (b) Detail about the grid current (i_g) and grid voltage (v_g) crossing zero value; (c) Detail about the comparison between the grid current reference (i_g) and the measured current (i_g).*

Fig. 7 shows a comparison between the proposed multilevel converter and the classical converter (three-level full-bridge converter) used to integrate RES with the power grid.

In Fig. 7(a) and Fig. 7(b) are presented, respectively, the topology of the proposed multilevel converter and the topology of the classical converter. For both topologies, the grid current (i_g) and the voltage levels (v_{ab}) are presented in Fig. 7(c) and Fig. 7(d), respectively. As shown, the proposed topology permits to establish five distinct voltage levels while the classical topology allows only three levels, representing an important advantage of the proposed MLC against the classical topology.

A comparison of both topologies in terms of total harmonic distortion is presented in Fig. 7(e), allowing to identify the contribution of the proposed MLC to increase the power quality levels in smart grids. The proposed MLC has lower values of total harmonic distortion for all the operating powers. The difference is more expressive for low values of operating power, representing an attractive solution for RES, mainly considering the uncertainty of energy production.

A comparison in terms of estimated efficiency for different power levels is presented in Fig. 7(f). The results for such comparison were obtained using the thermal module available in the PSIM software, where the dynamic behaviour of the semiconductors is considered in order to estimate the switching and conduction losses. In the simulation model were considered the MOSFETs STW45NM50 from ST Microelectronics (drain-source voltage of 550 V and drain current of 45 A), an upper level of gate voltage of 15 V, a lower level of gate voltage of -15 V, turn-on and turn-off gate resistances of 5 Ω, and a drain-source resistance of 0.08 Ω.

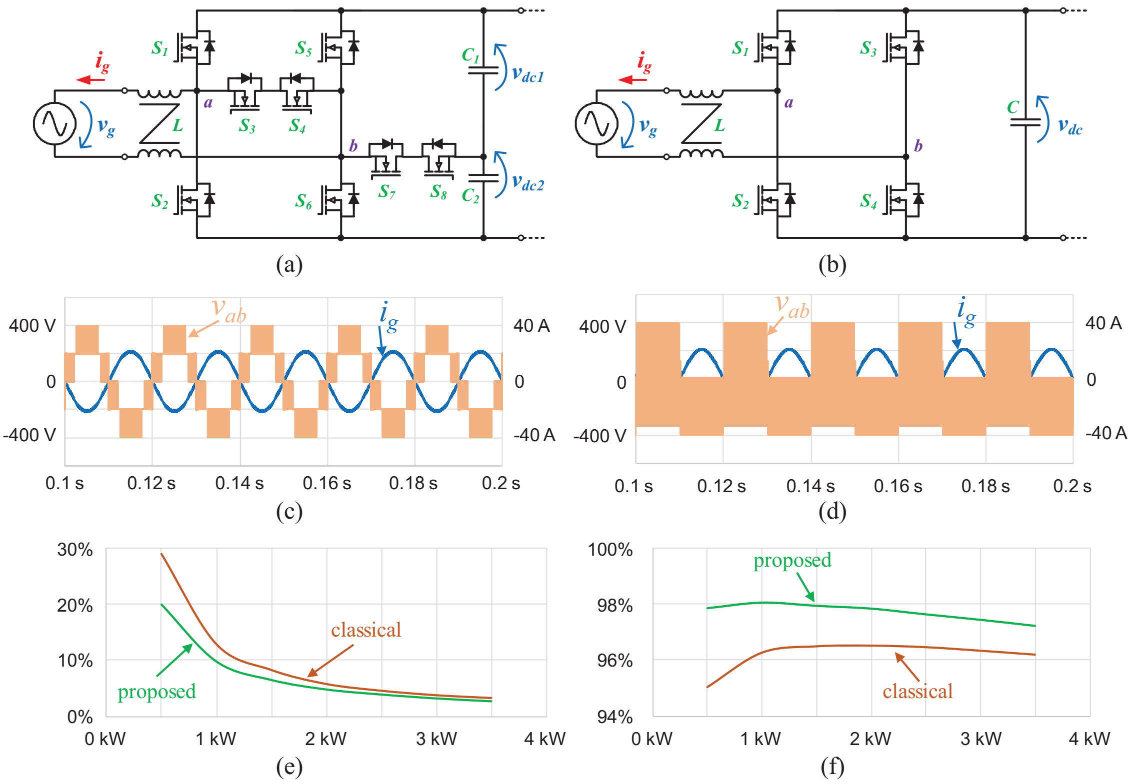

Fig. 7. Comparison between the proposed multilevel converter and the classical converter used to integrate RES with the power grid: (a) Topology of the proposed multilevel converter; (b) Topology of the classical converter; (c) Grid current (i_g) and voltage levels (v_{ab}) of the proposed multilevel converter; (d) Grid current (i_g) and voltage levels (v_{ab}) of the classical converter; (e) Comparison in terms of total harmonic distortion for different power levels; (f) Comparison in terms of estimated conversion efficiency for different power levels.

5. Conclusions

Power electronics converters are fundamental for the integration of renewable energy systems (RES) into smart grids. Therefore, front-end converters for interfacing the power grid and back-end converters for interfacing RES are used in order to adapt the voltage levels of both sides. In this context, a novel topology of front-end converter is proposed, where the multilevel characteristic with reduced number of semiconductors and optimized control strategy are the main advantages, in comparison with other multilevel converters in the literature. Moreover, the proposed converter operates with high-levels of power quality, imposing a controlled sinusoidal grid current in phase opposition with the power grid voltage. Along the paper, the proposed front-end multilevel converter (MLC) is presented in detail, highlighting the main features, and illustrating the principle of operation and the proposed control structure. The paper also presents an analysis based on simulation results about the integration of RES into smart grids considering the proposed MLC, and a comparison in terms of total harmonic distortion (power quality) and estimated efficiency for different power levels, between the proposed MLC and the classical converter used to integrate RES with the power grid. The simulation results were obtained under realistic operating conditions for a significant operating power range, allowing to validate the superior performance of the proposed MLC when compared to the classical solution.

Acknowledgments

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Abbreviations

RES	Renewable Energy Sources
MLC	Multilevel Converter
THD	Total Harmonic Distortion
PWM	Pulse-Width Modulation
ADC	Analog-to-Digital Converter
PI	Proportional-Integral

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