

Article

## Single DC-Sourced 9-level DC/AC Topology as Transformerless Power Interface for Renewable Sources

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**Abstract:** This paper introduces an advanced transformerless multilevel hybrid-conversion topology intended for the interconnection of renewable DC sources at small-scale. The most important contribution presented in this paper is the generation of two isolated DC sources from a single DC source without the use of any type of transformer. The DC sources feed a nine-level DC/AC hybrid cascade multilevel converter. This advanced topology is achieved by redesigning the conventional DC/DC Buck topology, attached to the multilevel converter, and embedding a suitable switching strategy along with a Field Programmable Gate Array (FPGA)-based control. The advantages of the proposed structure, when compared to other proposals in the literature, are higher efficiency, reduced number of power switches, and high power density derived of transformerless characteristic. As a way to highlight differences and advantages of this converter over other options recently available in the literature, this paper carries out a quantitative evaluation comparing the number of voltage levels and the number of elements involved in the structure of DC/AC multilevel converters. The mathematical model and control strategy of the converter are explained and analyzed by means of simulations. Finally experimental results, obtained from a laboratory-scale prototype, show the performance of the system and demonstrate its relative advantages.

**Keywords:** multilevel converters; buck converter; cascaded cells; transformerless; micro-grids; FPGA control

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## 1. Introduction

Today, the power electronics converters are one of the essential elements for electrical energy transformation and interconnection of renewable DC power sources to today's electrical power grids.

On the pursuit of modernization of distribution networks, the participation of novel power-electronics technologies is required. These technologies, mainly based on DC/AC topologies, require continuous improvements in features, such as higher efficiency, higher power density, controllability and reduction of total voltage and current harmonic distortion [1]. These features can be met by the implementation of DC/AC multilevel converters.

The multilevel converters have gained widespread acceptance for medium and high voltage applications [2]. The main advantages of DC/AC multilevel converters are: (i) low harmonic distortion at the output voltage; (ii) low voltage stress on their switching devices; and (iii) operation at low switching frequencies [3]. The multilevel converters were initially engaged in high voltage grids and power train applications but afterwards these were included in renewable energy converters as part of utility-scale plants, in which they are still largely employed [4,5].

In small scale, or residential applications, there are several well-known disadvantages regarding the use of transformers for DC/AC converters such as: size, weight and frequency limitation. Due these limiting factors, there is a growing interest in developing cutting-edge efficient and flexible transformerless topologies. The high number of voltage levels of DC/AC converters greatly helps to minimize the total harmonic distortion of the current injected into the electrical grid and to reduce the size of Inductor-Capacitor (LC filters).

A comparison of characteristics among various recently proposed DC/AC multilevel converters—based on a single DC source—is shown in Table 1. These converters are mainly proposed for renewable power sources applications in which the power flows unidirectional from a DC source to the AC power grid [6–15].

It is noticeable in Table 1 that the elimination of the galvanic isolation is a relevant topic for new designs of DC/AC multilevel topologies. Therefore, the techniques presented in [8] and [15], are not considered as a viable option compared to transformerless techniques, such as the ones in [6,7,9–14].

Specifically, in [15], the voltage waveform is constructed with four H-Bridges, 16 Insulate-Gate bipolar transistor(IGBT), and four line-frequency transformers (50 or 60 Hz). The square-shaped voltage fed to all four transformers involves the presence of harmonics. This condition stresses the transformers and increases significantly losses due to the skin effect. Out of [8] and [15], most of the proposals analyzed in Table 1 have output voltage waveforms with fewer than nine levels [7–14].

From other point of view, the technique shown in [8] has some advantages over the one in [15]. For instance, the former uses only one transformer. However, this feature can be considered a disadvantage if compared to [7,11,12,14]. This is because the latter proposals have the same number of voltage levels (seven) than the one in [8] but without using any transformer. Moreover, it should be noted that proposals in [9–14] perform the balancing of DC voltages by means of its multilevel modulation scheme, in which the charge and discharge of its capacitors is defined by angles and switching tables.

The topologies shown in [16] and [17] need more than one DC source at input. These options are in disadvantage, compared to those presented in Table 1, because they need extra circuitry for the purpose of implementing multiple DC voltages from a single DC source.

**Table 1.** Comparison for recent proposal DC/AC multilevel converters based on single DC source.

Publications	Year	No. Levels	No. Transformers	No. IGBTs	No. Capacitors	No. Inductors	No. Diodes
Proposed Topology	2014	9	0	12	2	2	4
[6]	2014	9	0	11	3	1	4
[7]	2014	7	0	10	4	1	0
[8]	2014	7	1	8	3	2	5
[9]	2013	5	0	8	1	0	0
[10]	2012	5	0	8	2	0	0
[11]	2011	7	0	7	4	1	10
[12]	2011	7	0	14	3	1	11
[13]	2009	5	0	8	1	0	0
[14]	2009	7	0	8	1	0	0
[15]	2009	9	4	9	0	0	0

Moreover, the technique presented in [6] shows an acceptable performance in the task of generating a nine-level voltage waveform, free of transformers. It also requires only one power source and a floating capacitor, similar to [9]. However, this technique uses two cascaded cells and three extra semiconductor switches. In addition, this proposal implements a rather complex algorithm to support its operation, making it difficult for applications in grid-integrated renewable energies environments.

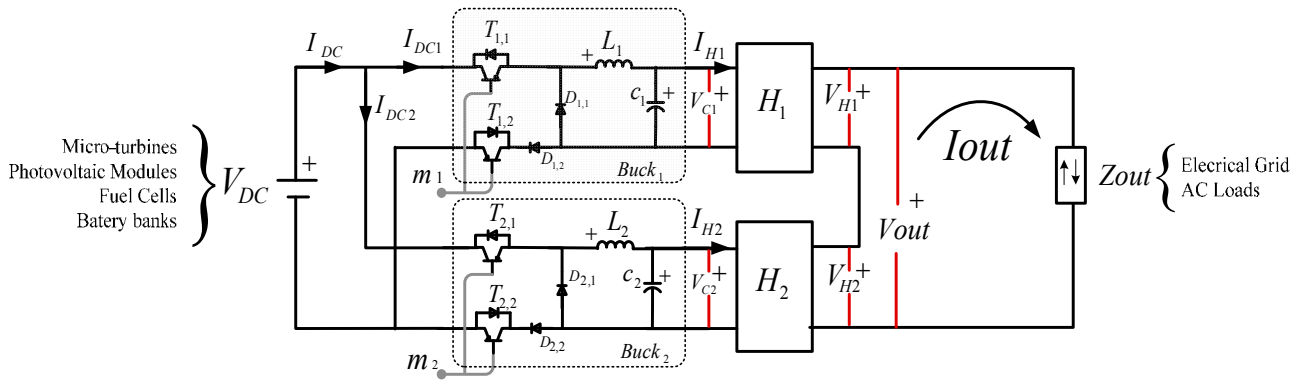
This paper introduces a novel hybrid multilevel conversion topology. This structure puts together two modified basic topologies, a DC/DC Buck converter and a DC/AC Multilevel hybrid cascaded cell, into a single nine-level DC/AC structure. The new single-phase, two-stage converter uses 12 power-switches only and a single DC input. Finally, this structure does not require switching tables or complex control algorithms to balance the capacitors. Significant advantages are obtained, based only on a single DC source at input, over all recent techniques of multilevel converters analyzed in Table 1. This research, in general, pursues to further improve the efficiency and power density of transformerless architectures as well as its reduction in complexity and costs.

## 2. Operation Principle of Proposed Converter

The main objective of this proposal is the generation of two isolated DC sources, named  $V_{C1}$  and  $V_{C2}$ , from a single power supply  $V_{DC}$ , without use of transformers. These isolated DC sources are required for the proper performance of 9-levels DC/AC cascaded cells topology.

To achieve this goal, this paper proposes a modification in the structure of conventional DC/DC Buck Converter, without changes in the operating principle.

The proposed modification consists on a time-lapse high impedance generation between each Buck converter and  $V_{DC}$  power supply, to achieve the continuous high impedance states between  $V_{C1}$  and  $V_{C2}$  voltages generated by the Buck converters. Using the converter  $Buck_1$  shown in Figure 1, the proposed modification is described. It consists on adding a power switch ( $T_{1,2}$ ) with the task of opening the ground path of the  $V_{DC}$  source. The diode  $D_{1,2}$  is connected in series to  $T_{1,2}$ . This connection ensures the unidirectional current flow from the collector to the emitter of  $T_{1,2}$ .



**Figure 1.** Single DC nine-level DC/AC hybrid proposed topology.

The power supply,  $V_{in}$ , is the input voltage of the proposed converter.  $V_{in}$  can be a renewable DC source, such as a solar PV array, a low-voltage wind, or a battery bank. It must be noted that the voltage DC source,  $V_{in}$ , must have a value greater than the peak value of the output voltage,  $V_{out}$ . The recommend range is  $1.2 \times |V_{out}| < V_{in} < 1.5 \times |V_{out}|$ .

The output voltage,  $V_{out}$ , can be connected to low–medium-voltage power grids or to off-grid AC loads. Since the proposed structure does not need a transformer for any conversions, process, or interconnection, it has advantages, such as higher power density, higher efficiency, lower cost and reduction of total harmonic distortion at output.

### 2.1. Isolated Bucks Converters

As shown in the  $Buck_1$  converter of Figure 1, the commutation states of the switches  $T_{1,1}$  and  $T_{1,2}$  are controlled in parallel by the control pulse  $m_1$ , while  $T_{2,1}$  and  $T_{2,2}$  are controlled by  $m_2$ , on  $Buck_2$  converter. The PWM pulses,  $m_1$  and  $m_2$ , are generated based on the magnitude comparison between  $D_1$  and  $D_2$  modulation signals and  $carry_1$ , and  $carry_2$ , ramp signals. The latter signals have a constant  $180^\circ$  phase shift and use the switching frequency,  $FC_{Buck}$ . Equations (1) and (2), shown the comparison rules for  $m_1$  and  $m_2$ :

$$m_1 = \begin{cases} 1 & \text{when } D_1 > Carry_1 \\ 0 & \text{when } D_1 < Carry_1 \end{cases} \quad (1)$$

$$m_2 = \begin{cases} 1 & \text{when } D_2 > Carry_2 \\ 0 & \text{when } D_2 < Carry_2 \end{cases} \quad (2)$$

From Equations (1) and (2) it can be deduced a number of topological combinations between  $Buck_2$  and  $Buck_1$  converters, as shown in Table 2. These states are obtained considering that switching variables  $m_1$  and  $m_2$  do not take state 1 at the same time instant, which has been termed as a prohibited state for this application.

**Table 2.** Topological states for buck converters.

Topological State	$m_1$	$m_2$	$I_{L1}$	$I_{L2}$	$I_{D1,1}$	$I_{D1,2}$	$I_{D2,1}$	$I_{D2,2}$	$I_{DC}$
(i)	0	0	$\Delta I_{L1off}$	$\Delta I_{L2off}$	$\Delta I_{L1off}$	0	$\Delta I_{L2off}$	0	0
(ii)	1	0	$\Delta I_{L1on}$	$\Delta I_{L2off}$	0	$\Delta I_{L1on}$	$\Delta I_{L2off}$	0	$\Delta I_{L1on}$
(iii)	0	1	$\Delta I_{L1off}$	$\Delta I_{L2on}$	$\Delta I_{L2off}$	0	0	$\Delta I_{L2on}$	$\Delta I_{L2on}$
	1	1	Prohibited						

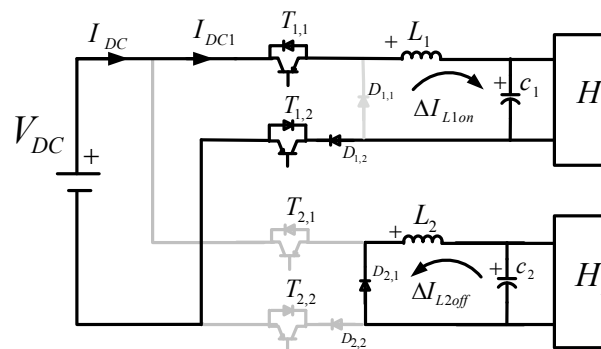
Figures 2 and 3 show the main topological states proposed for the Buck converters. Figure 2 shows specifically the topological state (ii) of Table 2, which meets the switching state  $m_1 = 1$ , and the *Buck*<sub>1</sub> converter takes the  $\Delta I_{L1on}$  current state, which is dependent on the potential difference between  $V_{DC}$  and  $V_{C1}$  as shown in Equation (3):

$$\Delta I_{L1on} = \frac{1}{T} \int_0^{t_{1on}} \frac{V_{DC} - V_{C1}}{L_1} \cdot dt + I_{L1}^\circ = \frac{(V_{DC} - V_{C1})}{L_1} \cdot \frac{t_{1on}}{T} + I_{L1}^\circ \tag{3}$$

From Figure 2, it can be deduced that current  $I_{DC1}$  flows from the power supply  $V_{DC}$ , from collector-emitter of  $T_{1,1}$  switch, followed by the inductor  $L_1$  to the capacitor  $C_1$ , closing the circuit to ground by  $D_{1,2}$  and the extra switch  $T_{1,2}$ . It is noted that for this current mesh, the diode  $D_{1,1}$  is not polarized. Parallel to this process it is noted in *Buck*<sub>2</sub> converter, the current state  $\Delta I_{L2off}$ , where this current is only dependent of voltage  $V_{C1}$ , and initial condition  $I_{L2}^\circ$ , as described in Equation (4):

$$\Delta I_{L2off} = \frac{1}{T} \int_0^{t_{2off}} \frac{-V_{C1}}{L_2} \cdot dt + I_{L2}^\circ = -\frac{V_{C1}}{L_2} \cdot \frac{t_{2off}}{T} + I_{L2}^\circ \tag{4}$$

In Figure 2, referring to *Buck*<sub>2</sub> converter, it can be seen that the  $T_{2,1}$  and  $T_{2,2}$  switches are in open condition, due to  $m_2 = 0$ . In this way, a high impedance state is generated between the positive and negative source terminals  $V_{DC}$  and the level of voltage  $V_{C2}$ , where the current  $I_{L2}$  flows from the positive terminal of the inductance to the cathode of the diode  $D_{1,1}$  to the negative terminal of the capacitor  $C_2$ .



**Figure 2.** Topological state (ii),  $m_1 = 1$ ,  $m_2 = 0$ .

Note that in this commutation state, the  $V_{DC}$  power supply is directly connected to the voltage  $V_{C1}$ , but in a high impedance state with  $V_{C2}$  voltage. We concluded that there is no direct connection between  $V_{C1}$  and  $V_{C2}$ .

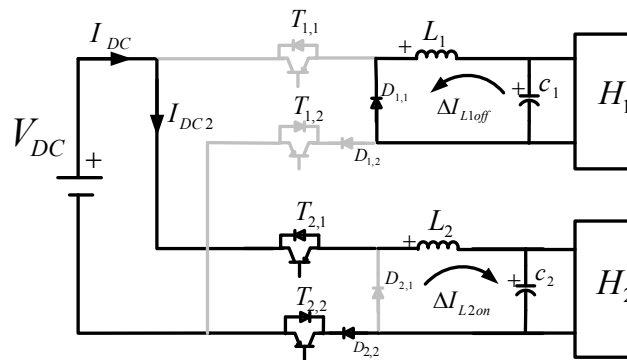
Moreover, Figure 3 shows the next commutation stage (iii) of Table 2. It can be seen that the converter *Buck*<sub>1</sub> is in current state  $\Delta I_{L1off}$ . This current depends only on voltage  $V_{C1}$ , and the initial condition  $I_{L1}^\circ$ , as described in Equation (5):

$$\Delta I_{L1off} = \frac{1}{T} \int_0^{t_{1off}} \frac{-V_{C1}}{L_1} \cdot dt + I_{L1}^\circ = -\frac{V_{C1}}{L_1} \cdot \frac{t_{1off}}{T} + I_{L1}^\circ \tag{5}$$

Parallel to this process, the current  $I_{DC2}$  in the *Buck*<sub>2</sub> converter flows from the power supply  $V_{DC}$  to the collector-emitter of  $T_{2,1}$  switch, then to the  $L_2$  inductance and afterward toward the capacitor  $C_2$ , closing the circuit to ground through  $D_{2,2}$  and finally to emitter-collector of switch  $T_{2,2}$ :

$$\Delta I_{L2on} = \frac{1}{T} \int_0^{t_{2on}} \frac{V_{DC} - V_{C2}}{L_2} \cdot dt + I_{L2}^\circ = \frac{(V_{DC} - V_{C2})}{L_2} \cdot \frac{t_{2on}}{T} + I_{L2}^\circ \tag{6}$$

It is observed that in this trajectory the diode  $D_{2,1}$  is not polarized, so the topological state described ( $\Delta I_{L2on}$ ) is fulfilled by Equation (6).

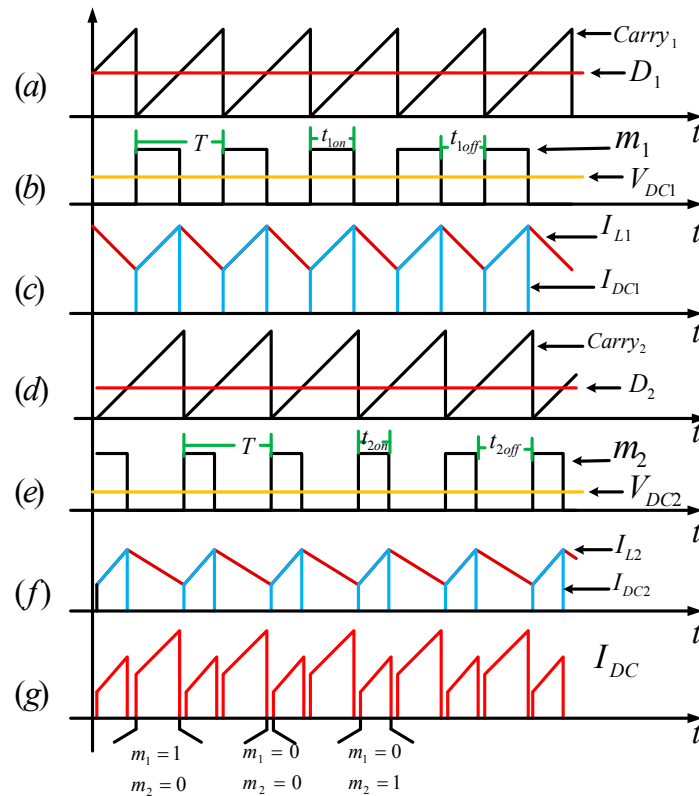


**Figure 3.** Topological state (iii),  $m_1 = 1, m_2 = 0$ .

Note that this switching state is complementary to state (ii) in Table 2. The  $V_{DC}$  power supply is directly connected to the voltage  $V_{C2}$ , but in a state of high impedance is connected to  $V_{C1}$ . It can be concluded again, that there is not direct connection between  $V_{C1}$  and  $V_{C2}$ .

Finally, the topological state (i), of the switching Table 2, can be considered as a dead time and there is no connection between the power supply  $V_{DC}$  with the  $V_{C1}$  and  $V_{C2}$  voltage, where the *Buck*<sub>1</sub> and *Buck*<sub>2</sub> converters acquired a complementary behavior ( $\Delta I_{L1off}$  and  $\Delta I_{L2off}$ ), as Indicated in the Equations (4)–(6). Figure 4 shows the main waveforms involved in the process of DC/DC conversion, to generate two isolated voltage sources ( $V_{C1}$  and  $V_{C2}$ ) based on single DC source at input.

The *carry*<sub>1</sub> and *carry*<sub>2</sub> variables are displayed in Figure 4a,d, respectively. In this figure it can be observed 180° of constant phase shift between the control pulses coming from the magnitude comparison between the *carry*<sub>1</sub> and *carry*<sub>2</sub> signals with  $D_1$  and  $D_2$ . The variable modulation technique is shown in Figure 4b,e, in which it can be seen a complementary behavior and a dead time between the rising and falling edges. The generation of control pulses  $m_1$  and  $m_2$  is based on Equations (1) and (2). These pulses are applied directly to control circuit breakers, being  $T_{1,1}$  and  $T_{1,2}$  controlled by  $D_1$  and  $T_{2,1}$  and  $T_{2,2}$  controlled by  $D_2$ , as previously indicated.



**Figure 4.** Main waveforms for buck<sub>1</sub> and buck<sub>2</sub> converters (a) *carry*<sub>1</sub> and *D*<sub>1</sub>; (b) *m*<sub>1</sub>; (c) *I*<sub>L1</sub> and *I*<sub>DC1</sub>; (d) *carry*<sub>2</sub> and *D*<sub>2</sub>; (e) *m*<sub>2</sub>; (f) *I*<sub>L2</sub> and *I*<sub>DC2</sub>; (g) *I*<sub>DC</sub>.

Currents *I*<sub>L1</sub> and *I*<sub>L2</sub> in the inductances are shown in red in Figure 4c,f. In these, it can be observed a continuous conduction mode behavior. In the same figure, in blue color, there are shown the waveforms of currents *I*<sub>DC1</sub> and *I*<sub>DC2</sub> generated in each Buck converter, which are dependent of the product of the inductance current and the control drive variable *m*<sub>1</sub> and *m*<sub>2</sub>, as is stated in the Equations (7)–(8):

$$I_{DC1} = I_{L1} \cdot m_1 \tag{7}$$

$$I_{DC2} = I_{L2} \cdot m_2 \tag{8}$$

Finally, the instantaneous sum of the *I*<sub>DC1</sub> and *I*<sub>DC2</sub> currents is shown through the *I*<sub>DC</sub> variable in Figure 4g. This represents the total current supplied by the voltage source *V*<sub>DC</sub>, and is calculated by means of Equation (9):

$$I_{DC} = I_{DC1} + I_{DC2} \tag{9}$$

The voltages *V*<sub>C1</sub> and *V*<sub>C2</sub> are depending of the inductors currents and the H-Bridges currents, defined as:

$$V_{C1} = \int (I_{L1} - I_{H1}) \cdot dt \tag{10}$$

$$V_{C2} = \int (I_{L2} - I_{H2}) \cdot dt \tag{11}$$

Currents  $I_{H1}$  and  $I_{H2}$  are detailed in the next section. After analyzing the topological states of the Buck converters and by noting the connection and disconnection of alternating  $V_{DC}$  voltage source and also by noting a state of continuous high impedance between  $C_1$  and  $C_2$ , we conclude that it is possible to feed the DC/AC multilevel cascaded hybrid cells from a single power supply.

2.2. DC/AC Nine Levels Cascaded Cell Topology

A hybrid, two-bridges, multilevel structure with asymmetrical sources has key advantages over the VSC-NPC and flying capacitor VSC. For instance, it can provide a higher number of voltage levels with fewer switches. In addition, the hybrid topology has no need of capacitors or transformers for its basic operation. As a consequence, using the latter configuration, a sine waveform can be reproduced with lower harmonic distortion than with other multilevel topologies.

The generation of different voltage levels in  $V_{out}$ , from the cascade cell converter, is shown in Figure 5. This voltages are obtained based on the algebraic sum of voltages  $V_{C1}$  and  $V_{C2}$  as shown in Table 3, where  $H_1$  and  $H_2$  bridges generate combinations independent of voltage versus time, being  $V_{H1} \in \{+V_{C1}, 0, -V_{C1}\}$ ; and  $V_{H2} \in \{+V_{C2}, 0, -V_{C2}\}$ ; respectively.

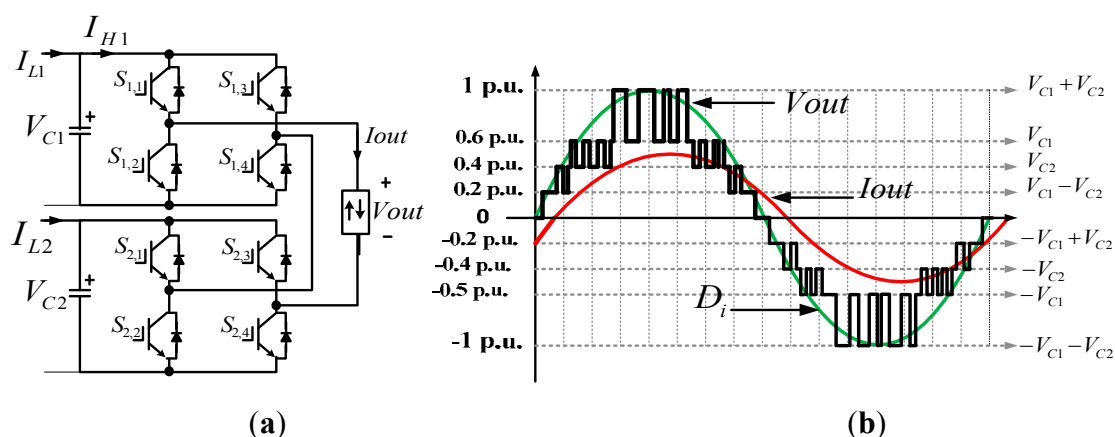


Figure 5. Nine levels DC/AC cascaded hybrid converter (a) topology; (b)  $V_{out}$  waveform.

Table 3. Switching states and respective voltage levels.

Vout Level	$H_1$				$H_2$			
	$S_{1,1}$	$S_{1,2}$	$S_{1,3}$	$S_{1,4}$	$S_{2,1}$	$S_{2,2}$	$S_{2,3}$	$S_{2,4}$
$V_{C1} + V_{C2}$	1	0	0	1	1	0	0	1
$V_{C1}$	1	0	0	1	1	0	1	0
$V_{C2}$	1	0	1	0	1	0	0	1
$V_{C1} - V_{C2}$	1	0	0	1	0	1	1	0
0	1	0	1	0	1	0	1	0
$-V_{C1} + V_{C2}$	0	1	1	0	1	0	0	1
$-V_{C2}$	1	0	1	0	0	1	1	0
$-V_{C1}$	0	1	1	0	1	0	1	0
$-V_{C1} - V_{C2}$	0	1	1	0	0	1	1	0



Finally, the magnitude and phase shift of  $I_{out}$  depend on the type of load connected to converter, which can be an independent load or a distribution electrical grid. The voltages of each H-bridge converter ( $V_{H1}$  and  $V_{H2}$ ) can be defined by Equations (12) and (13) as:

$$V_{H1} = V_{C1} \cdot [S_{1,1} - S_{1,3}] \tag{12}$$

$$V_{H2} = V_{C2} \cdot [S_{2,1} - S_{2,3}] \tag{13}$$

The currents of each H-bridge converter ( $I_{H1}$  and  $I_{H2}$ ) can be defined by Equations (14) and (15) as:

$$I_{H1} = I_{out} \cdot [S_{1,1} - S_{1,3}] \tag{14}$$

$$I_{H2} = I_{out} \cdot [S_{2,1} - S_{2,3}] \tag{15}$$

Figure 5 shows the nine levels DC/AC cascaded hybrid topology implemented in this research. It should be mentioned that for the topology employed specifically here, the voltage levels  $V_{C1}$  and  $V_{C2}$  have to satisfy the following ratio:

$$V_{C1} = \frac{3}{2} V_{C2} \tag{16}$$

where  $V_{C1} \approx V_{in} \cdot D_1$  and  $V_{C2} \approx V_{in} \cdot D_2$ . Based on Equation (16) it is possible to calculate the duty cycle  $D_1$  and  $D_2$ , applied in Buck<sub>1</sub> and Buck<sub>2</sub> converters, respectively. It is noteworthy to mention that if the voltage ratio between  $V_{C1}$  and  $V_{C2}$  is different from that stated in Equation (16), then  $V_{out}$  results with deformations and, as a pertinent consequence, some harmonics can be injected to the power grid. The harmonic distortion due to the imbalance of DC sources in DC/AC cascade-cell converter has been already studied [18]. As  $V_{C1}$  and  $V_{C2}$  depend of  $D_1$  and  $D_2$ , a larger or shorter of the latter will deform  $V_{out}$ . The generation of voltage levels  $V_{out}$  is performed based on switching states in Table 3. To obtain the correct control pulses to be applied to inverter power switches connected in cascade is necessary to implement a multilevel modulation Sine-Pulse Width Modulation (SPWM) process, discussed in next section.

### 2.3. Nine-Level SPWM Modulation

The multilevel modulation process employed for the topology, and shown in Figure 6, is obtained from a magnitude comparison between eight modulating waves  $carry^-_j$  and  $carry^+_j$  where  $j \in (1,2,3,4)$  and a sine modulating signal  $D_i$ .

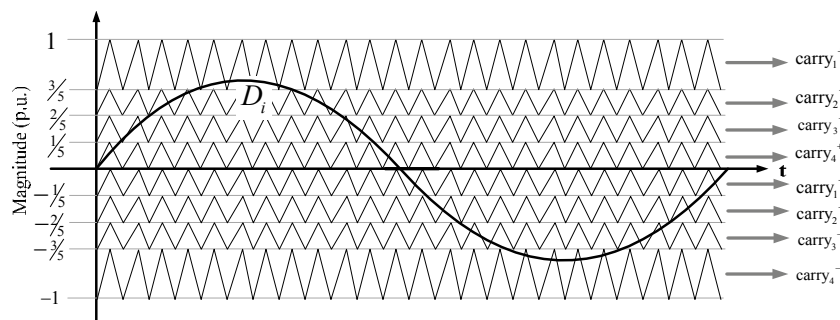


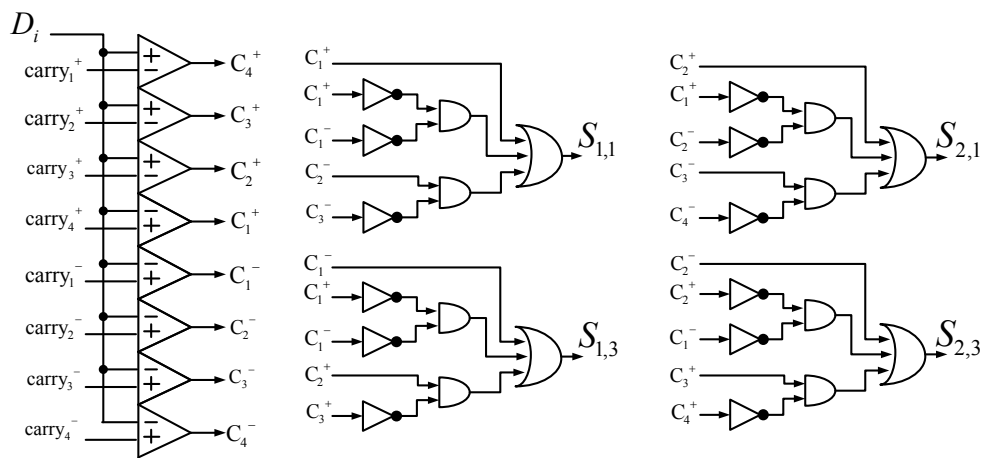
Figure 6. Nine levels SPWM scheme.

The control pulses are described by Equations (17) and (18):

$$C_i^+ = \begin{cases} 1 & \text{when } carry_i^+ < D_i \\ 0 & \text{when } carry_i^+ > D_i \end{cases} \tag{17}$$

$$C_i^- = \begin{cases} 1 & \text{when } carry_i^- > D_i \\ 0 & \text{when } carry_i^- < D_i \end{cases} \tag{18}$$

In order to obtain the necessary topological stages, described by Table 3, the combinational logic stage is necessary to obtain the required pulses for the cascaded multilevel converter. The logical diagram implemented is shown in the Figure 7.



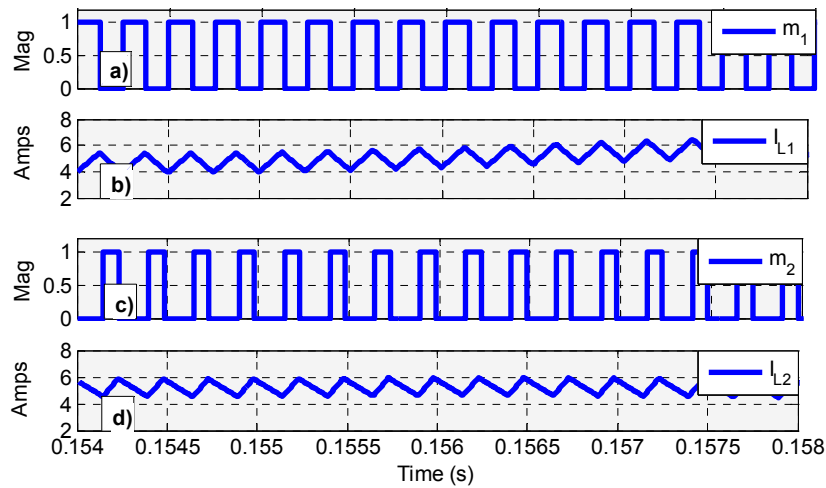
**Figure 7.** Combinational logic for IGBT pulses, on cascaded cell topology.

In order to verify the full operation of the converter stages, the Buck converters and the cascaded cells with their respective modulations, a number of simulations have been developed, which are presented in the next section.

### 3. Simulation

The proposed converter is analyzed through the Simulink—Matlab simulation platform, showing the main variables of voltage, current and control pulses involved in the conversion process of DC/DC through the Buck converters and DC/AC through hybrid cascaded cell converter.

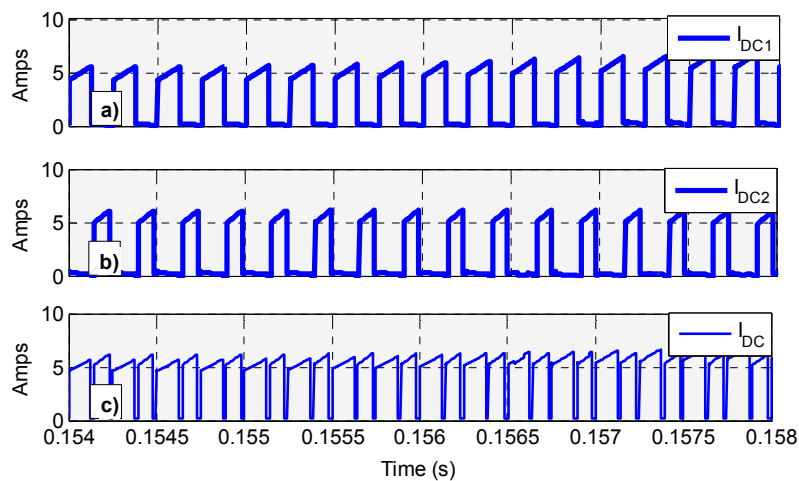
Figure 8a,c shows the switching states of converters *Buck*<sub>1</sub> and *Buck*<sub>2</sub>. The alternating duty cycles *m*<sub>1</sub> and *m*<sub>2</sub> ensures the effect of instant isolation between *V*<sub>C1</sub> and *V*<sub>C2</sub>. *I*<sub>L1</sub> and *I*<sub>L2</sub> current waveforms are shown in Figure 8b,d, respectively. The behavior of these variables has been verified on the basis of Equations (3)–(6).



**Figure 8.**  $I_{L1}$  and  $I_{L2}$  currents for buck converters.

The waveforms of currents  $I_{DC1}$  and  $I_{DC2}$ , generated by each Buck converter, are shown in Figure 10a,b, respectively. Here, are clear again the alternating switching times between each converter.

Finally the total current  $I_{DC}$  supplied by the voltage source  $V_{DC}$ , is shown in Figure 9c, which is dependent on the instantaneous sum of  $I_{DC1}$  and  $I_{DC2}$ , fulfilling Equation (9).

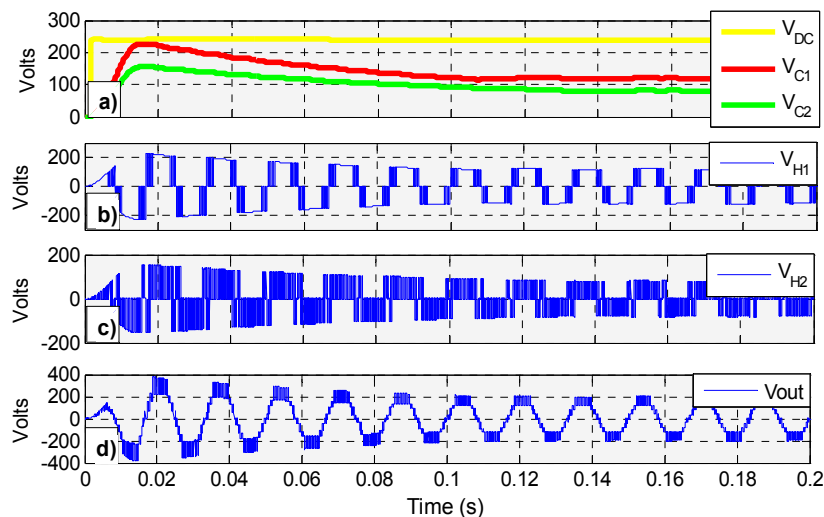


**Figure 9.** Current waveforms (a)  $I_{DC1}$ , (b)  $I_{DC2}$ , and (c)  $I_{DC}$ .

The steady-state output voltage of the Buck converters,  $V_{C1}$  and  $V_{C2}$ , are shown in Figure 10a. In this figure the relative voltage for proper operation of the hybrid cascaded cell converter is observed, as indicated by Equation (16).

The voltage waveforms generated by the H-Bridge converters,  $V_{H1}$  and  $V_{H2}$ , are shown in Figure 10b,c, respectively. From this, it can be seen the topological combinations *versus* time dependent modulation process, meeting the switching states, Table 2.

Finally, the stepped voltage waveform  $V_{out}$ , is shown by Figure 10d.  $V_{out}$  depends on the algebraic sum of the instantaneous  $V_{H1}$  and  $V_{H2}$  voltages.



**Figure 10.** Main voltage waveforms (a)  $V_{DC}$ ,  $V_{C1}$ , and  $V_{C2}$ ; (b)  $V_{H1}$ ; (c)  $V_{H2}$ ; and (d)  $V_{out}$ .

Based on the performed simulations it is possible to verify compliance of the main goal of this research: to achieve nine voltage levels DC/AC from a single power supply with only 12 power switches and without transformers.

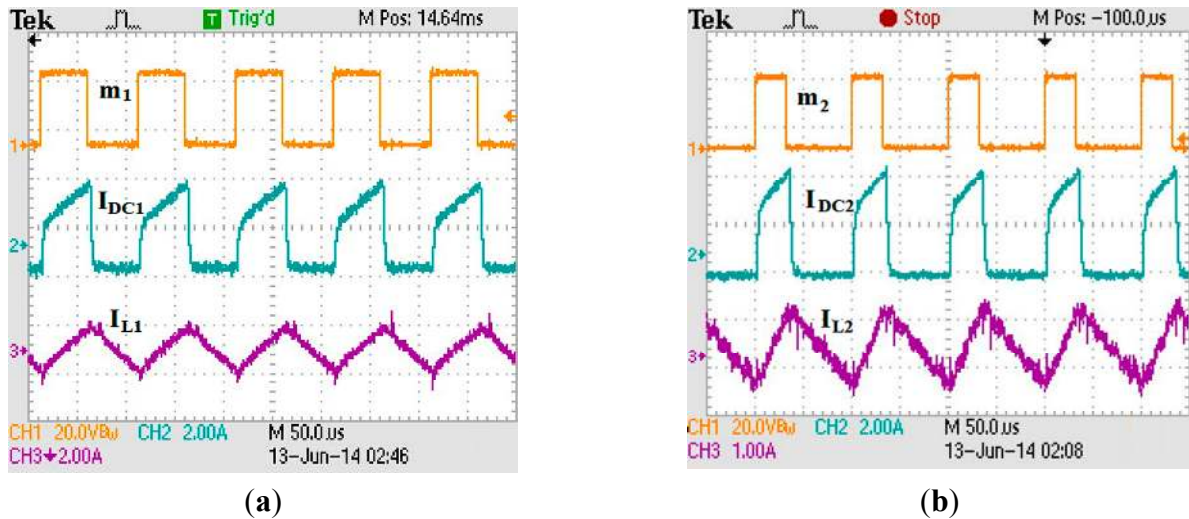
Additionally, it has been shown by means of circuit simulations that the waveforms satisfy the main equations obtained for the electrical conversion process.

#### 4. Experimental Test

In order to experimentally verify the topology presented, a laboratory prototype has been built using the parameters shown in Table 4. These parameters are the same used in the simulations. In Figure 11a,b can be corroborated experimentally the modulation process of *Buck*<sub>1</sub> and *Buck*<sub>2</sub> converters, respectively, showing the variables modulation  $m_1$  and  $m_2$ , compared to current inductance  $I_{L1}$  and  $I_{L2}$ , ending with the currents supplied by the source  $I_{DC1}$  and  $I_{DC2}$ .

**Table 4.** Parameter values for the simulation of the proposed converter.

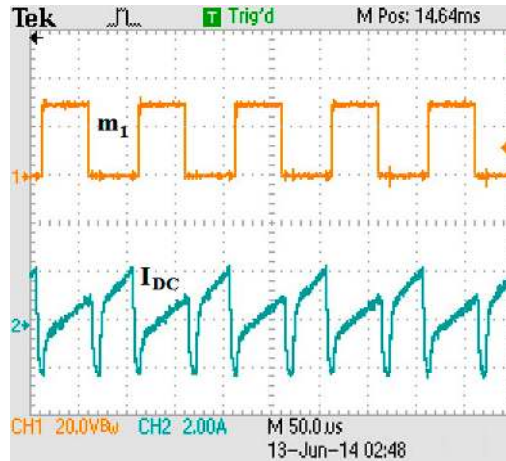
Variable, Element	Value
Bucks Switching Frequency	16 kHz
Multilevel Modulation Frequency	6 kHz
$L_1 = L_2$	6 mH
$C_1 = C_2$	2200 uF
$V_{DC}$	240 V
$D_1$	0.5
$D_2$	0.33
$D_i$	$0.95 \cdot \sin(\omega t)$



**Figure 11.** Principal waveforms of the buck converters, (a)  $m_1$ ,  $I_{L1}$  and  $I_{DC1}$  for buck<sub>1</sub> and (b)  $m_2$ ,  $I_{L2}$  and  $I_{DC2}$  for buck<sub>2</sub>.

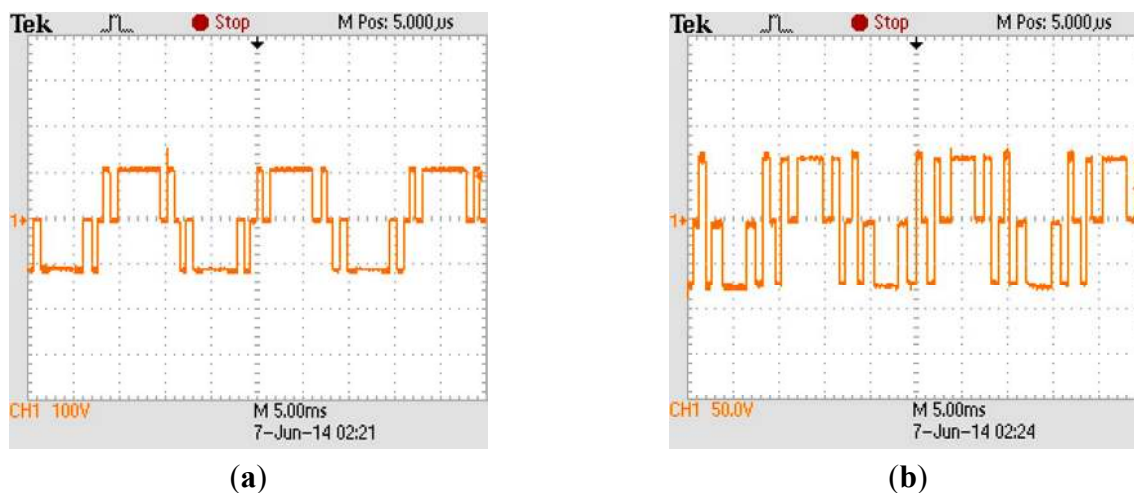
Under the same case study, Figure 12 shows current  $I_{DC}$ , which corresponds to the sum of the currents  $I_{DC1}$  and  $I_{DC2}$  with respect to the control pulse  $m_1$ .

From these waveforms is possible to corroborate the different switching states of *Buck*<sub>1</sub> and *Buck*<sub>2</sub> converters, shown in Table 2 and analyzed with Equations (7)–(9). Finally, it can be observed that the waveforms exposed in Figure 12 are similar to those shown in Figure 4.



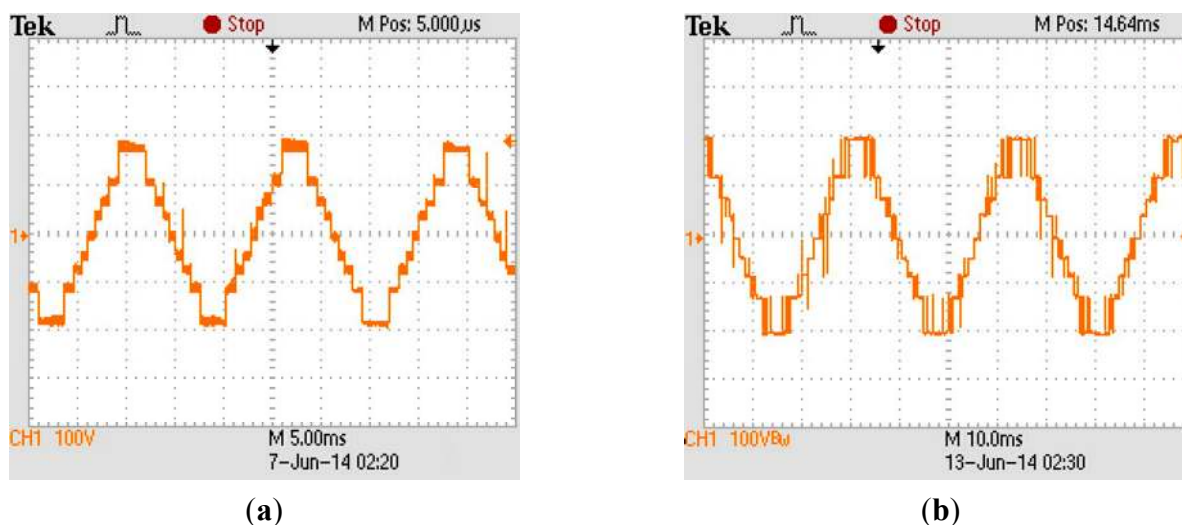
**Figure 12.**  $I_{DC}$  and  $m_1$  waveforms.

Under the principle of operation exposed previously, corresponding to the cascaded converter modulation, Figure 13a,b show the experimental voltages generated by each H bridge converter, where it can be seen that  $V_{H1} \in \{+V_{C1}, 0, -V_{C1}\}$ ; and  $V_{H2} \in \{+V_{C2}, 0, -V_{C2}\}$ , respectively.



**Figure 13.** Independent H-bridge voltages (a)  $V_{H1}$ ; (b)  $V_{H2}$ .

Based on the voltages shown by Figures 13a,b, it is possible to corroborate the voltages ratio between  $V_{C1}$  and  $V_{C2}$  as 1:1.5, as stated in Equation (16). The algebraic sum of the  $V_{H1}$  and  $V_{H2}$ , corresponding to the output voltage  $V_{out}$ , is shown by Figure 14, where Figure 14a shows an experimental validation of the staggered signal and Figure 14b shows the same output signal with SPWM modulation applied.

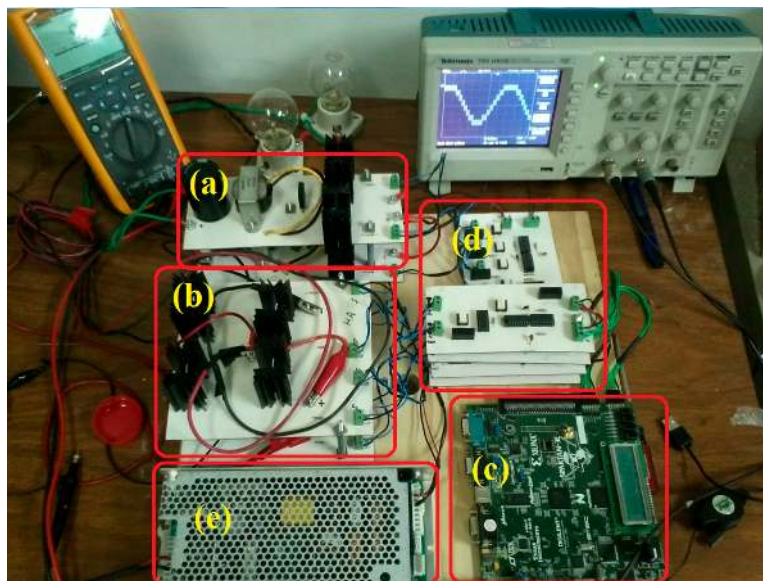


**Figure 14.**  $V_{out}$  (a) multilevel  $V_{out}$  (b) SPWM multilevel  $V_{out}$ .

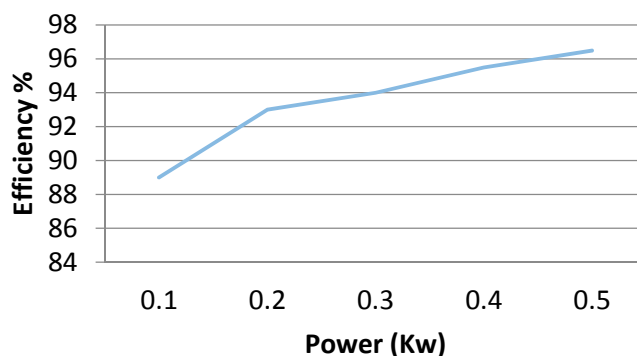
The multilevel output voltage  $V_{out}$  needs filtering to reduce THD and bring the signal closer to the ideal sinusoidal waveform. As the frequency spectrum of the 3 and 5-level converter is wider than that of the nine-level, the filtering requirements of the latter are less demanding.

Figure 15 presents the scaled-down physical prototype of the nine levels converter with FPGA-based control, the principal auxiliary subsystems and the experimental setup, respectively. Figure 16 shows the efficiency curves against power, obtained from the prototype.





**Figure 15.** Laboratory prototype of the converter and experimental testing (a) Modified DC/DC buck converters; (b) H-bridges converters; (c) FPGA based control; (d) Drivers pulses for IGBTs; and (e) DC source circuitry.



**Figure 16.** Efficiency tests.

*Discussion*

Table 5 shows a comparative analysis between basic DC/AC topologies and the proposed one. It should be remarked that the proposed topology is designed for unidirectional power flow applications only. Nevertheless, Table 5 also shows that the proposed topology has various relative advantages such as fewer power switches, diodes and capacitors compared to structures such as the clamped diode or the flying capacitor. Comparatively to the cascaded-cells topology, this novel nine-levels converter is lesser complex to build because it uses just one power source at input instead of two.

**Table 5.** Comparative analysis for nine levels DC/AC multilevel converters.

Multilevel Converter	No. IGBTs	No. Capacitors	No. Diodes	No. DC Sources
Proposed Topology	12	2	6	1
Clamped Diode	16	8	32	1
Flying Capacitor	16	32	0	1
Cascaded cells	8	0	0	2

A general advantage of the new nine-levels converter over the other configurations is its relative simple control algorithm, without the need of a transformer. These enhanced features make the nine-levels converter introduced in this paper very suitable to application in micro-grids.

The solutions and capabilities presented can be further enhanced. Additional future advances from this work focus on: (i) Minimizing the voltage and current harmonic distortion by means of a suitable modulation scheme; (ii) Obtaining a mathematical model of the dynamic behavior of the nine-level converter and its interaction with distribution grids and a microgrids; (iii) Evaluating the benefits of using various types of LC and LCL filter for the interconnection of the nine-level converter with the grid; (iv) Incorporating the converter to the Smart Grid concept; (v) Analyzing the transient behavior of the converter; and (vi) Evaluate the benefits and limitations of using various types of LC and LCL filter, located in between  $V_{in}$  and the Bucks converters, as a way for obtaining a continuous input current  $I_{DC}$ .

## 5. Conclusions

This work presents a new CD-CA nine-level topology, which combines a modified DC/DC Buck Converter and hybrid Cascade converter based on two H-bridge, in a single phase structure. The most important advantages of the proposed nine-level topology are: (i) Single DC source without need of transformer and (ii) Reduction of power switches.

This topology is a competitive option suitable for an efficient integration and controlling of renewable power sources (such as PV, fuel cells and low-voltage wind generator) into low and medium voltage power grids and microgrids. For instance, a household application is the interconnection of PV modules, while in isolated microgrids the applications may be PV and fuel cells. In other contexts, an ambitious goal is to explore the application possibilities related to the integration of large photovoltaic installations.

This work is a step forward in the direction of reducing the number of elements in a converter structure while improving overall efficiency and enhancing performance relative to other well-known converter configurations.

The authors expect that the step-up multi-level converter introduced in this paper will become a useful alternative for research and development in the area of DC/AC multilevel converters.

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## Author Contributions

All authors contributed equally to this work. J.R. Rodriguez-Rodríguez performed prototype experiments; Vicente Venegas-Rebollar wrote the manuscript; Edgar L. Moreno-Goytia gave technical support and conceptual advice; and all authors collected and analyzed the obtained data.

## Conflicts of Interest

The authors declare no conflict of interest.



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