A Grid Connected Photovoltaic System with a Multilevel Inverter and a Le-Blanc Transformer

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Abstract- In this paper a novel power conversion structure for grid-connected photovoltaic applications is presented. This structure is based on a multilevel inverter and on a LeBlanc transformer. The proposed multilevel power converter uses two single-phase voltage source inverters and a four wire voltage source inverter. The Le-Blanc transformer is connected at the output of the multilevel inverter. The configuration of the PV system is based on the multi-string technology. The structural design of this new power converter allows a seven level shaped output voltage wave at the output of the multilevel inverter. To control this power converter a sliding mode controller with a vectorial modulator is used. This control system allows obtaining a fast a robust response for the multilevel inverter. Several experimental results are presented, confirming the expected performance of the proposed power conversion structure.

Keywords- Photovoltaic power conversion; grid connection; multilevel converter; LeBlanc transformer; cascade structure; sliding mode controller.

1. Introduction

In the last years, new energy sources have proposed and developed due to the dependency and constant increase of costs of fossil fuels. On other hand, fossil fuels have a huge negative impact on the environment. In this context, the new energy sources are essentially renewable energies. It is estimated that the electrical energy generation from renewable sources will increase from 19%, in 2010, to 32%, in 2030, leading to a consequent reduction of CO2 emission [1]. Among these renewable energy sources, solar photovoltaic energy is one of the fastest growing.

In photovoltaic systems, solar energy is converted into electrical energy by photovoltaic (PV) arrays. PV arrays are very popular since they are clean, inexhaustible and require little maintenance. Photovoltaic systems require interfacing power converters between the PV arrays and the grid. These power converters are used for two major tasks. First, to ensure that the PV arrays are operated at the maximum power point (MPPT) [2-7]. Second, to inject a sinusoidal current into the grid. Normally there are two power converters [8,9]. The first one is a DC/DC power converter that is used to operate the PV arrays at the maximum power point. The other one is a DC/AC power converter to interconnect the photovoltaic system to the grid. The classical single or three-phase two level voltage source inverter is normally used for this power converter type [10-12]. However, other topologies have been proposed. Multilevel converter topologies are a very interesting choice for realizing this objective.

Multilevel power converters present several advantages over a conventional two level converter such as: reducing switching frequency, output voltage with very low distortion and reduced dv/dt stress [13-16]. In this way, several multilevel topologies have been applied to photovoltaic systems [18-23].

There are several PV system configurations. These configurations are the centralized technology, string technology, multi-string technology and AC-module technology. The number and type of power converters that is used to interconnect the PV system to the grid is dependent of the technology that is used. The multi-string technology has several different groups of PV arrays. Each group is connected in series with a DC/DC converter. This allows using this technology with some multilevel topologies, such as, the cascaded multicell inverters. This topology is based on the series connection of single-phase inverters with separated DC sources. In this way, each group of PV arrays will be used as a single DC source. This allows avoiding high voltage amplification. In order to obtain a galvanic connection between the grid and the PV generator many PV systems use a power transformer, avoiding that a leakage current may flow through the capacitance between PV generator and ground. Some systems use a transformer embedded in a high-frequency DC/DC converter. Others use a line frequency transformer at the output of the inverter.

Related to these developments, this paper presents a new power converter structure for PV systems. The proposed structure uses two single-phase voltage source inverters, a four wire voltage source inverter and a LeBlanc transformer. This structure is specially developed to use with the multi-string technology. A control system for the multilevel power converter is also proposed. This control system is based on a sliding mode controller with a vectorial modulator. Several experimental results are presented in order to confirm the characteristics of the proposed system.

2. Proposed Power Converter Struture

The base configuration of the proposed grid connected photovoltaic system is presented in Fig. 1. This system consists of several PV modules, DC/CD power converters, a multilevel DC/AC power converter and a power transformer. For the PV modules arrangements a multi-string technology is used. Each string of the PV array is connected to a DC/DC converter with a MPPT algorithm. The output of these converters is the DC power supply of the multilevel DC/AC power converter. The proposed multilevel inverter uses a four-wire voltage source inverter and two single-phase voltage source inverters.

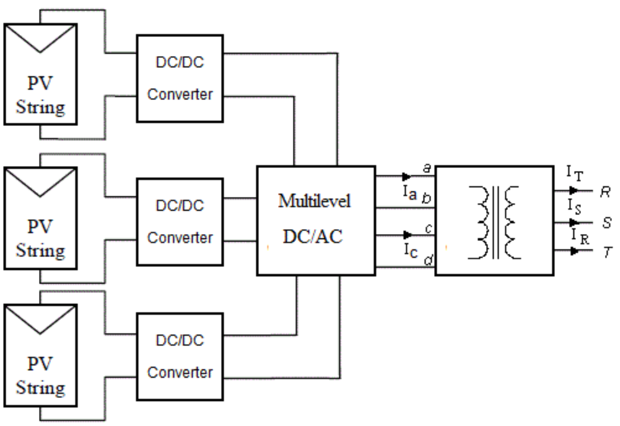

Fig. 1. Configuration of the proposed grid connected photovoltaic system.

Fig. 2 presents the configuration of this power converter. In order to obtain different DC voltages, at the output of the DC/DC power converters, the PV strings are not equally distributed. To fulfil this purpose, the four-wire voltage source inverter must have an input DC voltage which is the double of the input DC voltage of both single-phase voltage source inverters. Considering a VDC input voltage for the two single-phase voltage source inverters, the four-wire voltage source inverter must have an input DC voltage of 2VDC. In this way, the multilevel inverter is able to generate a seven level shaped output voltage wave. Using equal DC voltages for all inverters only a five level shaped output voltage wave could be obtained. With this different DC voltage arrangement one can obtain the following multilevel inverter output voltage combinations: $-3V_{DC}$, $-2V_{DC}$, $-V_{DC}$, 0; $+V_{DC}$, $+2V_{DC}$, $+3V_{DC}$. The output of the AC/DC power converter is connected to a Le-Blanc transformer, and the secondary windings of this transformer are connected to the grid.

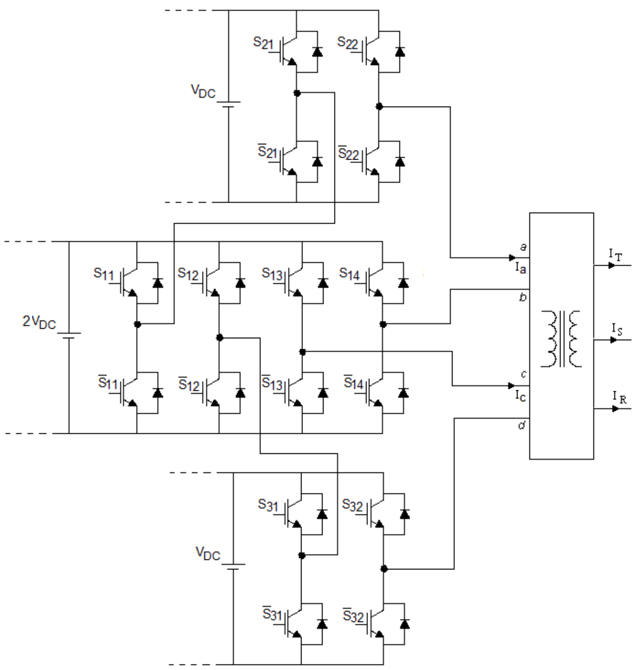

Fig. 2. Multilevel DC/AC converter.

The proposed multilevel inverter generates two output voltages that must be shifted by 90 degrees. The Le-Blanc transformer is used to obtain a three-phase balanced voltage system at the output of the power converter system. The Le-Blanc connection transformer is an asymmetrical winding transformer, which is usually used to transform a three-phase voltage system into a two-phase supply, by means of a special winding connection [24,25]. The winding connection of Le-Blanc transformer is shown in Fig. 3. There are five windings on the primary side, separated into two distinct phases, and three windings of the secondary side, which are delta connected.

To ensure a three-phase balanced system on the grid side, the turn ratio of the windings (Fig.3) must be given by (1).

$$\frac{\frac{1}{\sqrt{3}}N_1}{N2}\;;\;\frac{\frac{1}{3}N_1}{N2}\;;\;\frac{\frac{2}{3}N_1}{N2}\;;\;\frac{\frac{1}{\sqrt{3}}N_1}{N2}\;;\;\frac{\frac{1}{3}N_1}{N2} \qquad (1)$$

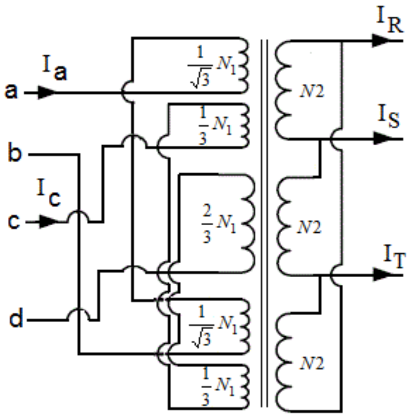

Fig. 3. Le-Blanc connection scheme.

The voltage and line currents relationship of the Le-Blanc connection can be written as (2) and (3), respectively. V_{ab} and V_{cd} denote the two voltages, on the five windings side. V_R, V_S and V_T denote the line voltages on the three windings side.

$$\begin{cases} V_{ab} = -\dfrac{2}{\sqrt{3}}\dfrac{N_2}{N_1}V_R + \dfrac{1}{\sqrt{3}}\dfrac{N_2}{N_1}V_S + -\dfrac{2}{\sqrt{3}}\dfrac{N_2}{N_1}V_T \\ V_{cd} = \dfrac{N_2}{N_1}V_S - \dfrac{N_2}{N_1}V_T \end{cases} \tag{2}$$

$$\begin{cases} I_R = \dfrac{2}{\sqrt{3}}\dfrac{N_2}{N_1}I_a \\ I_S = -\dfrac{1}{\sqrt{3}}\dfrac{N_2}{N_1}I_a + \dfrac{N_2}{N_1}I_c \\ I_T = -\dfrac{1}{\sqrt{3}}\dfrac{N_2}{N_1}I_a - \dfrac{N_2}{N_1}I_c \end{cases} \tag{3}$$

The proposed multilevel power converter allows to obtain a seven level output voltage ($-3V_{DC}$, $-2V_{DC}$, $-V_{DC}$, 0; $+V_{DC}$, $+2V_{DC}$, $+3V_{DC}$). The output voltage is dependent of the states of the switches of the k^{th}, $k\in\{1,2,3,4,5,6,7,8\}$ converter leg. Considering the time dependent variable γij, $i\in\{1,2\}$, $j\in\{1,2,3\}$, defined in (4) the multilevel output voltages can be obtained by (5).

$$\gamma_{ij} = \begin{cases} 1 \text{ if } S_{ij} \text{ is ON} \wedge \bar{S}_{ij} \text{ is OFF} \\ 0 \text{ if } S_{ij} \text{ is OFF} \wedge \bar{S}_{ij} \text{ is ON} \end{cases} \tag{4}$$

$$\begin{cases} V_{ab} = (\gamma_{22}-\gamma_{21})\,V_{DC} + (\gamma_{11}-\gamma_{14})\,2V_{DC} \\ V_{cd} = (\gamma_{13}-\gamma_{12})\,2V_{DC} + (\gamma_{31}-\gamma_{32})\,V_{DC} \end{cases} \tag{5}$$

3. Control System

In order to maximize the photovoltaic system, continuously tracking the maximum power point is ensured by the DC/DC converters and correspondent control system. This is also ensured by the use of the perturb and observe (P&O) technique [26].

Synchronous with grid is achieved by using a phase locked loop (PLL). It is used the Modified synchronous reference frame method [27]. The transformation angle is obtained with the voltages of the AC network. The speed of the reference frame varies instantaneously depending of the waveform of the three-phase voltage system. Let q be the transformation angle (variable in time). This angle is computed using the AC voltages using (6) and (7). In this method, no synchronizing circuit is needed.

$$\cos\theta = \frac{e_\alpha}{\sqrt{e_\alpha^2 + e_\beta^2}} \tag{6}$$

$$\sin\theta = \frac{e_\beta}{\sqrt{e_\alpha^2 + e_\beta^2}} \tag{7}$$

Switching power converters are nonlinear and time variant systems. Sliding mode approach offers a very good way to implement a control strategy which exploits the inherent variable structure of this type of power converters [28, 29]. Due to these inherent characteristics, this type of control [30, 31] was chosen to control the proposed multilevel inverter.

Using the controllable canonical form of the system model the sliding mode controller can be obtained. On other hand, this controller should impose in each switching period *T*, that the output voltages V_{ab} and V_{cd} average values must be equal to their reference average values (8).

$$\begin{cases} \dfrac{1}{T}\displaystyle\int_0^T V_{abref}\,dt - \dfrac{1}{T}\int_0^T V_{ab}\,dt = e_{Vab} = 0 \\ \dfrac{1}{T}\displaystyle\int_0^T V_{cd\,ref}\,dt - \dfrac{1}{T}\int_0^T V_{cd}\,dt = e_{Vcd} = 0 \end{cases} \tag{8}$$

From (6) it is possible to obtain the sliding surfaces given by (9), where kab and kcd are the gains used to impose the switching frequency:

$$\begin{cases} S(e_{ab},t) = \dfrac{k_{ab}}{T}\displaystyle\int_0^T (V_{ab\,ref} - V_{ab})\,dt = 0 \\ S(e_{cd},t) = \dfrac{k_{cd}}{T}\displaystyle\int_0^T (V_{cd\,ref} - V_{cd})\,dt = 0 \end{cases} \tag{9}$$

Due to the characteristics of the switching power converters it is not possible to always ensure that the system trajectory always moves on the considered sliding surfaces (9). Thus, it must be ensured that the trajectory of the system should move directly towards the sliding surface. Stability condition (8) assures this assumption. According to (9) and (10) the switching law must obtained from condition (11).

$$S(e_{ab})\,\dot{S}(e_{ab}) < 0 \quad and \quad S(e_{cd})\,\dot{S}(e_{cd}) < 0 \tag{10}$$

$$\begin{cases} \mathbf{S}(\mathbf{e}_{ab},t) > 0 \Rightarrow \dot{S}(\mathbf{e}_{ab},t) < 0 \Rightarrow V_{ab} > V_{abref} \\ \mathbf{S}(\mathbf{e}_{cd},t) > 0 \Rightarrow \dot{S}(\mathbf{e}_{cd},t) < 0 \Rightarrow V_{cd} > V_{cd\,ref} \\ \mathbf{S}(\mathbf{e}_{ab},t) < 0 \Rightarrow \dot{S}(\mathbf{e}_{ab},t) > 0 \Rightarrow V_{ab} < V_{abref} \\ \mathbf{S}(\mathbf{e}_{cd},t) < 0 \Rightarrow \dot{S}(\mathbf{e}_{cd},t) > 0 \Rightarrow V_{cd} < V_{cd\,ref} \end{cases} \tag{11}$$

From (9) it is possible to verify that the switching law is V_{ab} and V_{cd} dependent. On other hand, these voltages depend on the switches states, as can be seen from (4) and (5). Tables 1 and Table 2 show the obtained multilevel output voltages for each possible switching state. As mentioned before, with the proposed multilevel inverter it is possible to obtain a seven level shaped output voltage wave, just before the Le-Blanc transformer. So, considering the two inverter outputs there are 49 possible combinations.

Table 1. Multilevel output voltage V_{ab} according the switching states

S_{11}	S_{14}	S_{21}	S_{22}	V_{ab}
0	0	0	0	0
0	0	0	1	+V
0	0	1	0	-V
0	0	1	1	0
0	1	0	0	-2V
0	1	0	1	-V
0	1	1	0	-3V
0	1	1	1	-2V
1	0	0	0	+2V
1	0	0	1	+3V
1	0	1	0	+V
1	0	1	1	+2V
1	1	0	0	0
1	1	0	1	+V
1	1	1	0	-V
1	1	1	1	0

Table 2. Multilevel output voltage V_{cd} according the switching states

S_{12}	S_{13}	S_{31}	S_{32}	V_{cd}
0	0	0	0	0
0	0	0	1	+V
0	0	1	0	-V
0	0	1	1	0
0	1	0	0	-2V
0	1	0	1	-V
0	1	1	0	-3V
0	1	1	1	-2V
1	0	0	0	+2V
1	0	0	1	+3V
1	0	1	0	+V
1	0	1	1	+2V
1	1	0	0	0
1	1	0	1	+V
1	1	1	0	-V
1	1	1	1	0

Fig. 4 shows the 49 space vectors that that can be obtained with this inverter. Since the control and switching laws depend on the output voltages, each combination must be chosen in order to ensure (9) and (11).

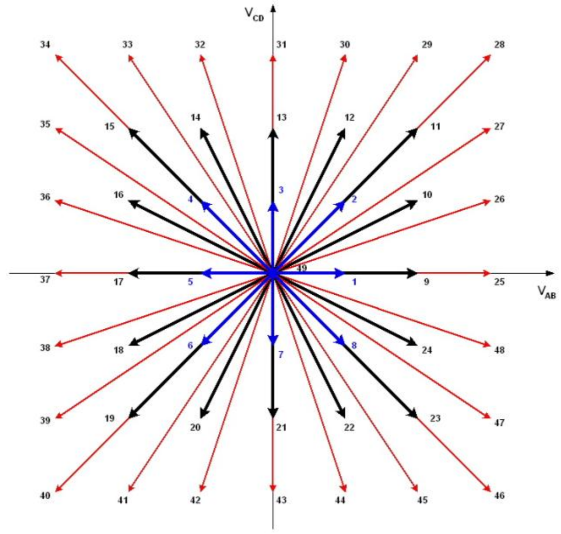

Fig. 4. Output voltage vectors of the proposed multilevel inverter.

4. Simulation Results

The proposed power converter structure and control system have been implemented in Matlab/Simulink and its Sim Power System Toolbox. The multilevel operation of the power converter can be seen in Figs. 5-7. Fig. 5 presents the output voltage of the four-wire inverter that connects to terminal b and the single-phase inverter that connects to terminal a. Fig. 6 shows the output voltage of the single-phase inverter that connects to terminal a and the four-wire inverter. The output voltage of the multilevel power converter V_{ab} is the association of those converters. Fig. 7 shows V_{ab} voltage, that is the sum of the inverter voltages that are presented in Figs. 5 and 6. From this last figure it is also possible to confirm the multilevel operation of the proposed power converter. Fig. 7 also allows confirming the seven level shape of the output voltage waveform of full power converter.

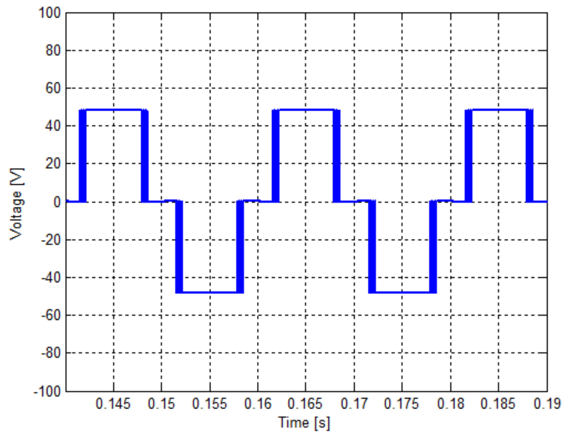

Fig. 5. Simulation result of the output voltage of the four-wire inverter that connects to terminal b and single-phase inverter connecting terminal a.

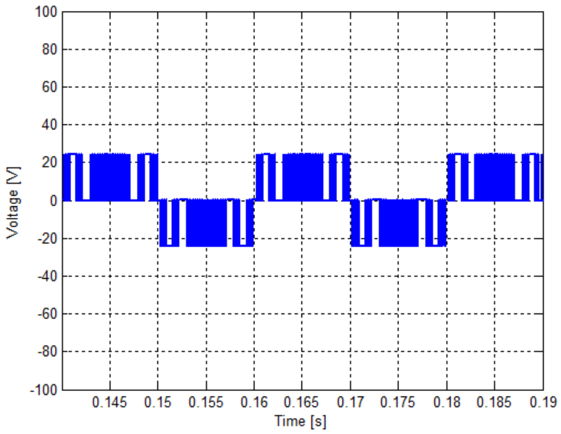

Fig. 6. Simulation result of the output voltage of the single-phase inverter that connects to terminal a and four-wire inverter connecting terminal b.

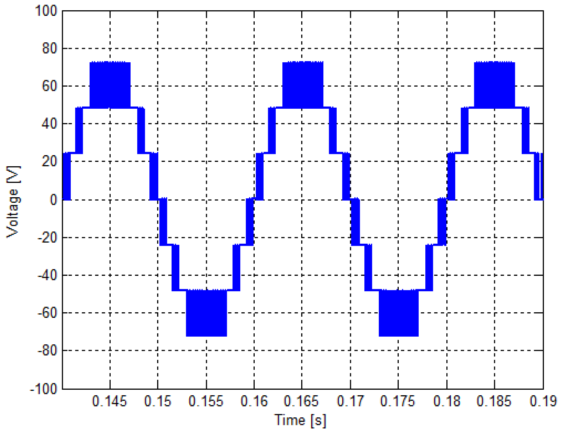

Fig. 7. Simulation result of the output voltage Vab of the multilevel inverter.

This power converter allows obtaining two output voltages shifted by 90 degrees. The simulation result presented in Fig. 8 shows the power converter output voltages. From this figure it is possible to confirm the expected output voltages.

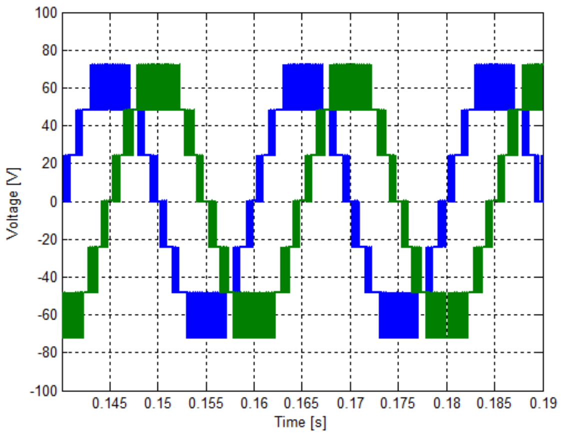

Fig. 8. Simulation result of the output voltages Vab and Vcd of the multilevel inverter.

Fig. 9 shows the simulation result of the output currents of the multilevel power converter. From this figure it is also to confirm that these currents are 90º shifted. Le-Blanc transformer allows obtaining a three-phase system from a bi-phase system. Fig. 10 shows the simulation result of the Le-Blanc output currents. From this result it is possible to confirm the Le-Blanc transformer characteristics. Three-phase output currents are obtained. It is also possible to verify that these currents are balanced.

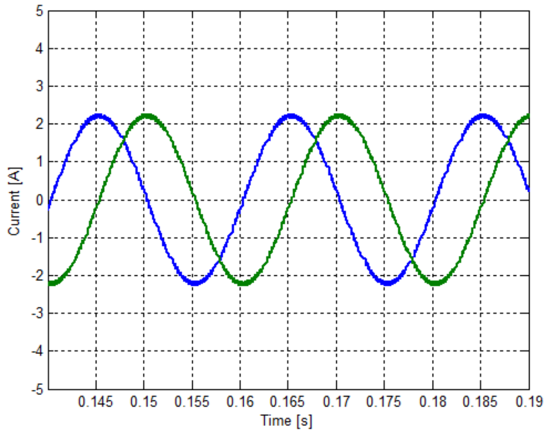

Fig. 9. Simulation result of the output currents Ia and Ic of the multilevel inverter.

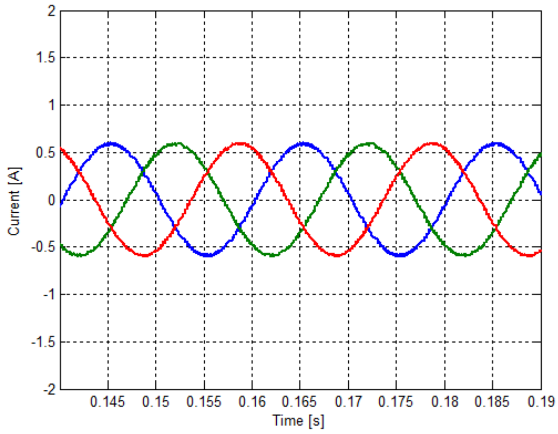

Fig. 10. Simulation result of the output currents IR, IS and IT of the Le-Blanc transformer.

5. Experimental Results

In order to verify the effectiveness of the proposed topology and respective control system, an experimental prototype was implemented. In this way, several experiments were conducted. The output voltage V_{ab} of the multilevel inverter is the result of the output voltages of the four-wire inverter that connects to terminal b and the single-phase inverter that connects to terminal a. Fig. 13 shows the experimental result of the multilevel inverter output voltage V_{ab}. This voltage is the sum of the output voltages of the four-wire inverter that connects to terminal b (Fig. 11) and the single-phase inverter that connects to terminal a (Fig. 12). From Fig. 13 it is also possible to confirm the multilevel operation of the proposed power converter. As designed, this inverter generates a seven level shaped output voltage wave.

The output of the multilevel power inverter is connected to the Le-Blanc transformer. In order to obtain an AC three phase balanced voltage system, on the transformer grid side, the power inverter must generate a 90º shifted two phase balanced voltage system. Fig. 14 presents both power inverters' output voltages. It is possible to verify that the 90º output voltages' shifting condition is assured. Fig. 15 presents the output currents of the multilevel inverter. They are balanced, nearly sinusoidal and also 90º shifted. The Le-Blanc transformer's output currents, injected into the grid, are presented in Fig. 16.

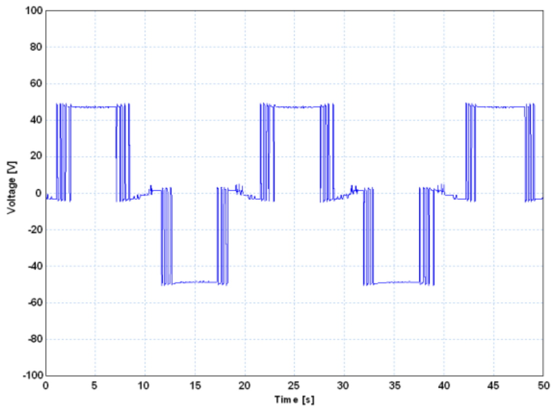

Fig. 11. Experimental result of the output voltage of the four-wire inverter that connects to terminal b and single-phase inverter connecting terminal a.

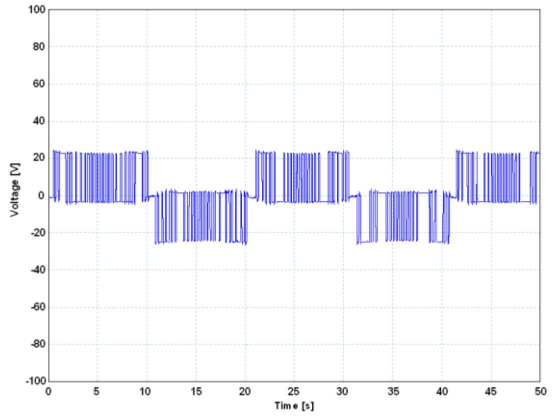

Fig. 12. Experimental result of the output voltage of the single-phase inverter that connects to terminal a and four-wire inverter connecting terminal b.

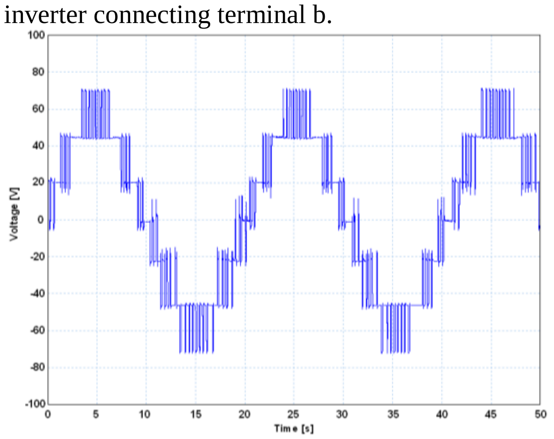

Fig. 13. Experimental result of the output voltage V_{ab} of the multilevel inverter.

As can be seen, an AC three-phase balanced current system is obtained. Figs. 15 and 16 clearly show the advantage of using a Le-Blanc transformer converting a two-phase supply into a three-phase grid connected power source.

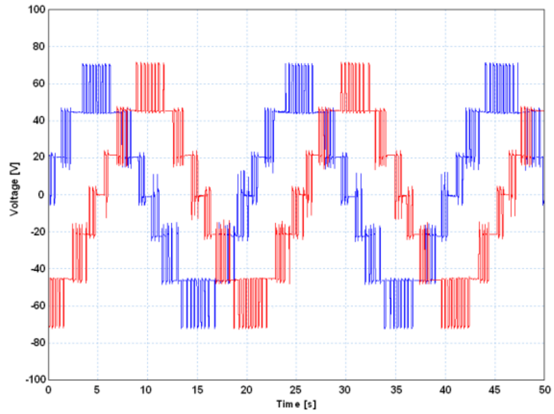

Fig. 14. Experimental result of the output voltages V_{ab} and V_{cd} of the multilevel inverter.

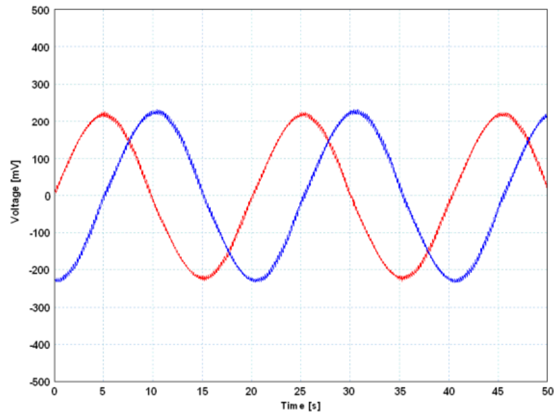

Fig. 15. Experimental result of the output currents I_a and I_c of the multilevel inverter (100mV - 1A).

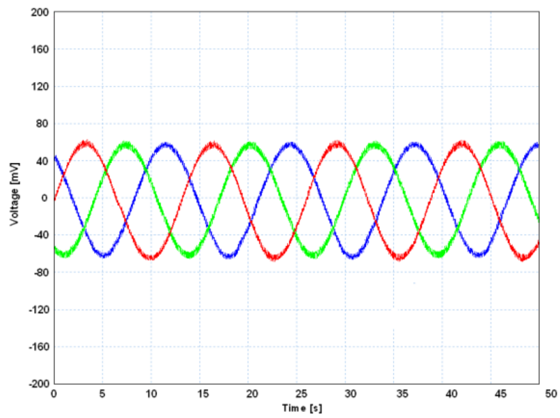

Fig. 16. Experimental result of the output currents I_R, I_S and I_T of the Le-Blanc transformer (100mV - 1A).

6. Conclusion

A new power conversion structure for a grid-connected photovoltaic system has been presented. This conversion structure was developed for a multi-string technology configured PV system. At the output of each PV array string is connected a DC/DC power converter with a MPPT algorithm. To obtain an AC signal a DC/AC multilevel with two single-phase voltage source inverters and a four wire voltage source inverter is used. Considering distinct input DC voltages for the two single-phase inverters and for the four wire inverter, allows to extend the number of achievable voltage levels at the multilevel inverter output. To achieve this characteristic, the DC/DC power converter connected to the single-phase voltage source inverter must generate a V voltage, while the DC/DC power converter connected to the four wire inverter must generate a 2V voltage. In this way, a seven level shaped output voltage signal is obtained. The multilevel inverter generates two 90º shifted output voltages. To obtain a grid connected three phase balanced system Le-Blanc transformer was used.

To control the proposed multilevel power converter a sliding mode controller was used. At the output of this controller it was used a vectorial modulator. To verify the effectiveness of the proposed system, several experimental results have been presented. From the obtained results it is possible to confirm the proposed multilevel power converter outputs a seven level voltage, and that the Le-Blanc transformer allows a three-phase balanced system from a two-phase system.

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