Vitor Fernão PIRES[1,2], Manuel GUERREIRO[1], João F. MARTINS[3,5], J. Fernando SILVA[2,4]

ESTSetubal- Inst. Politécnico Setúbal (1), CIEEE(2), FCT - Univ. Nova de Lisboa (3), IST-T U Lisbon (4), CTS-UNINOVA (5)

Multilevel Power Converter Based on a Three Single-Phase Voltage Source Inverters

***Abstract**. In this paper it is proposed a new three-phase multilevel power conversion structure. This structure uses a three single-phase voltage source inverters and Scott transformer. The structure composed by the three single-phase voltage source inverters has two single-phase outputs. These outputs will connect to the Scott transformer. This transformer allows deriving two-phase voltage to a three-phase source. The proposed multilevel power conversion structure allows obtaining a five-level three-phase inverter. To control the proposed power converter it is used a sliding mode controller with a vectorial modulator. Several test results of the proposed converter structure with their control system are presented. From the obtained results it is possible to confirm the voltage multilevel waveforms and the effectiveness of the proposed control system technique.*

***Streszczenie.** W artykule zaproponowano nową strukturę wielopoziomowego przekształcania energii elektrycznej. W strukturze tej użyto trzy jednofazowe falowniki napięcia oraz transformator Scotta. Struktura ta posiada dwa jednofazowe wyjścia. Wyjścia te są połączone z transformatorem Scotta. Transformator ten umożliwia zamianę napięć dwufazowych na napięcia trójfazowe. Proponowana struktura multipoziomowego przekształcania energii elektrycznej umożliwia otrzymanie trójfazowego, pięciopoziomowego falownika napięcia. W układzie sterowania wykorzystano sterowanie ślizgowe (sliding mode) z modulatorem wektorowym. Zaprezentowano kilka wyników badań proponowanej struktury z użyciem tego typu układu sterowania. Z otrzymanych wyników możliwe jest potwierdzenie uzyskania napięć wielopoziomowych oraz efektywności proponowanego układu sterowania. (**Przekształtnik wielopoziomowy bazujący na trzech jednofazowych falownikach napięcia**).*

Keywords: Multilevel converter, Scott transformer, sliding mode controller.
Słowa kluczowe: Przekształtnik wielopoziomowy, transformator Scotta, sterownik ślizgowy.

Introduction

The standard three-phase inverter has been used in many distinct applications, however its use is quite limited, particularly regarding its output voltage levels, since it only allows three phase-to-phase output voltage levels. In order to obtain more output voltage levels one can use multilevel inverters, which has been used in several industrial applications over the last decades. From the industry point of view these converters present several attractive features, like reduced current and voltage harmonics on the ac side, high voltage capability and low dv/dt's. These power converters have been extensively studied, not only regarding topology but also their modulation strategy and performance. Several multilevel topologies have been proposed, where the most relevant are: the neutral point clamped [1]-[4], the flying capacitor [5]-[8] and the cascaded H-bridge inverter [9]-[11]. A hybrid multilevel topology has also been proposed [12], being this topology is similar than the cascaded H-bridge inverter but uses only one DC source.

In addition to the above attractive features of the multilevel inverters, in medium and high-power applications features like safety and robustness are also important. For this purpose isolated systems in low frequency are used, being multilevel converters associated with line-frequency power transformers proposed. Three single-phase or one three-phase transformer are usually the option, however another type of transformers has also been used. Power converters with special line-frequency transformers such as Scott or LeBlanc have also been proposed [13]-[15]. These special transformers allow deriving two-phase currents from a three-phase power source or vice-versa.

Given the above considerations a new three-phase power conversion structure is proposed, based on a multilevel power inverter and on a Scott transformer. The considered multilevel power converter has a five-level cascade structure. The output of the multilevel power inverter provides two 90 degrees shifted phase voltages while the Scott transformer provides the desired three-phase system.

Several control methodologies have been proposed for multilevel power converters, such as the sinusoidal PWM extended to multiple carrier arrangements [16]-[18] or the sliding mode control [19]-[20]. Sliding mode control, being one of the most fast and robust techniques, will be used for controlling the proposed power converter. In this way, a vectorial sliding mode controller adapted to this power converter will be proposed. Simulation results are presented in order to illustrate the converter performance.

This paper is organized in five sections. After this introduction the proposed multilevel inverter based on Scott transformer is presented in Section II. In section III it is presented the developed theoretical expressions for the study of this multilevel converter. The control system for the proposed system is described in Section IV. Some simulation results obtained from the proposed converter are presented in Section V. Finally, in section VI, the conclusions of the work are synthesized.

Proposed multilevel power converter

Fig. 1 shows the new power conversion structure for a three-phase multilevel inverter.

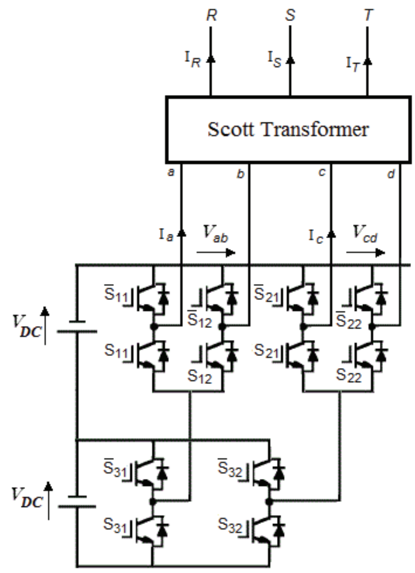

Fig.1. Proposed conversion structure

This topology uses two dc sources and three single-phase voltage source converters in order to maximize the output voltage. A 2-to-3 phase transformer is used at the output of the voltage source converters. Due to the connection of the three single-phase inverters, at the output of the power converter structure a five level voltage is obtained (2V,V,0,-V,-2V). One of the drawbacks of this topology is that two of the single-phase inverters withstand a voltage of 2V.

The transformer uses a three-phase core with a winding system as presented in Fig. 2 (a). This transformer is known as Scott transformer.

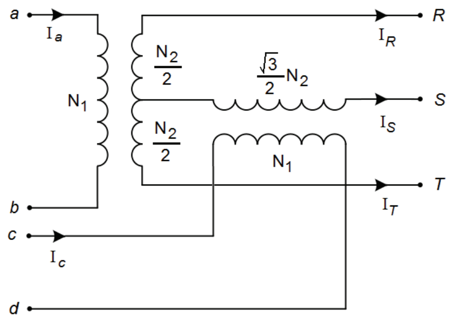

Fig.2. Scott transformer Connections

The primary windings of the Scott transformer are fed by two different voltages $V_{ab}(t)$ and $V_{cd}(t)$. These voltages are generated by the power converter with a phase angle 90º between them. The secondary windings are the three-phase system $V_R(t)$, $V_S(t)$ and $V_T(t)$. The phasorial diagram is presented in Fig. 3.

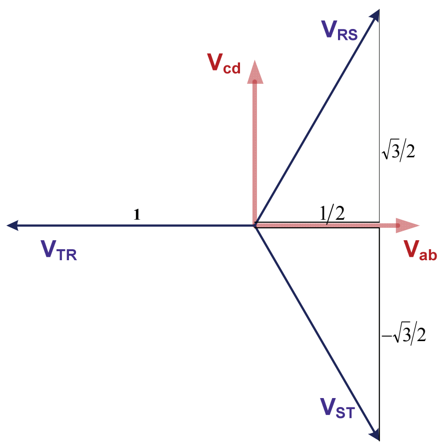

Fig.3. Voltage vectors of the Scott transformers

System model

In order to obtain suitable theoretical expressions for the study of the proposed multilevel converter with their control system, ideal power switches will be assumed. In this way, the states of the switches of the k^{th}, $k \in \{1,2,3,4,5,6\}$, power converter leg can be represented by the time dependent variable γ_{ij}, $i \in \{1,2,3\}$, $j \in \{1,2\}$, defined by (1).

(1) $$\gamma_{ij} = \begin{cases} 1 & if \;\; S_{ij} \;\; is \; ON \;\wedge\; \bar{S}_{ij} \; is \; OFF \\ 0 & if \;\; S_{ij} \;\; is \; OFF \;\wedge\; \bar{S}_{ij} \; is \; ON \end{cases}$$

The output multilevel voltages V_{ab} and V_{cd} are dependent of the switches states. So, according condition (1) these output voltages are obtained by (2).

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

From equations (1) and (2), it is possible to verify that this converter presents 25 combinations (labelled 0 to 24) V_{ab}, V_{cd} or vectors (Fig. 3). Table 1 shows the output voltage vectors according to the state of the switches.

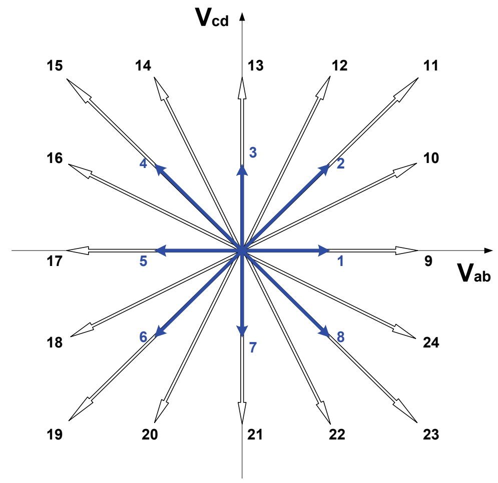

Fig.3. Output voltage vectors of the power converter

Table 1. Voltage vectors according the switching states

S_{31}	S_{32}	S_{21}	S_{22}	S_{11}	S_{12}	V_{ab}	V_{cd}	Nº
0	0	0	0	0	0	0	0	**0**
0	0	0	0	0	1	-V	0	**5**
0	0	0	0	1	0	+V	0	**1**
0	0	0	0	1	1	0	0	**0**
0	0	0	1	0	0	0	-V	**7**
0	0	0	1	0	1	-V	-V	**6**
0	0	0	1	1	0	+V	-V	**8**
0	0	0	1	1	1	0	-V	**7**
0	0	1	0	0	0	0	+V	**3**
0	0	1	0	0	1	-V	+V	**4**
0	0	1	0	1	0	+V	+V	**2**
0	0	1	0	1	1	0	+V	**3**
0	0	1	1	0	0	0	0	**0**
0	0	1	1	0	1	-V	0	**5**
0	0	1	1	1	0	+V	0	**1**
0	0	1	1	1	1	0	0	**0**
0	1	0	0	0	0	0	0	**0**
0	1	0	0	0	1	-V	0	**5**
0	1	0	0	1	0	+V	0	**1**
0	1	0	0	1	1	0	0	**0**
0	1	0	1	0	0	0	-2V	**21**
0	1	0	1	0	1	-V	-2V	**20**
0	1	0	1	1	0	+V	-2V	**22**
0	1	0	1	1	1	0	-2V	**21**
0	1	1	0	0	0	0	+2V	**13**
0	1	1	0	0	1	-V	+2V	**14**
0	1	1	0	1	0	+V	+2V	**12**
0	1	1	0	1	1	0	+2V	**13**
0	1	1	1	0	0	0	0	**0**
0	1	1	1	0	1	-V	0	**5**
0	1	1	1	1	0	+V	0	**1**
0	1	1	1	1	1	0	0	**0**
1	0	0	0	0	0	0	0	**0**
1	0	0	0	0	1	-2V	0	**17**
1	0	0	0	1	0	+V	0	**1**
1	0	0	0	1	1	0	0	**0**
1	0	0	1	0	0	0	-V	**7**
1	0	0	1	0	1	-2V	-V	**18**
1	0	0	1	1	0	+2V	-V	**24**
1	0	0	1	1	1	0	-V	**7**
1	0	1	0	0	0	0	+V	**3**
1	0	1	0	0	1	-2V	+V	**16**
1	0	1	0	1	0	+2V	+V	**10**

1	0	1	0	1	1	0	+V	**3**
1	0	1	1	0	0	0	0	**0**
1	0	1	1	0	1	-2V	0	**17**
1	0	1	1	1	0	+2V	0	**9**
1	0	1	1	1	1	0	0	**0**
1	1	0	0	0	0	0	0	**0**
1	1	0	0	0	1	-2V	0	**17**
1	1	0	0	1	0	+2V	0	**9**
1	1	0	0	1	1	0	0	**0**
1	1	0	1	0	0	0	-2V	**21**
1	1	0	1	0	1	-2V	-2V	**19**
1	1	0	1	1	0	+2V	-2V	**23**
1	1	0	1	1	1	0	-2V	**21**
1	1	1	0	0	0	0	+2V	**13**
1	1	1	0	0	1	-2V	+2V	**15**
1	1	1	0	1	0	+2V	+2V	**11**
1	1	1	0	1	1	0	+2V	**13**
1	1	1	1	0	0	0	0	**0**
1	1	1	1	0	1	-2V	0	**17**
1	1	1	1	1	0	+2V	0	**9**
1	1	1	1	1	1	0	0	**0**

Considering that the magnetization current of the Scott transformer can be neglected, then from the MMF equations the following expression can be obtained:

(3) $$\begin{cases} N_1 I_c + \frac{\sqrt{3}}{2} N_2 I_S = 0 \\ N_1 I_a + \frac{1}{2} N_2 I_R - \frac{1}{2} N_2 I_T = 0 \end{cases}$$

From Kirchhoff current law and considering (3), the equation that gives the relationship between the secondary and the primary side currents is given by (4).

(4) $$\begin{bmatrix} I_R \\ I_S \\ I_T \end{bmatrix} = \frac{N_1}{N_2} \begin{bmatrix} -1 & \frac{1}{\sqrt{3}} \\ 0 & -\frac{2}{\sqrt{3}} \\ 1 & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} I_a \\ I_c \end{bmatrix}$$

Similarly the three-phase output voltages are given by the following equation:

(5) $$\begin{bmatrix} V_{RS} \\ V_{ST} \\ V_{TR} \end{bmatrix} = \frac{N_2}{N_1} \begin{bmatrix} \frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -1 & 0 \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{cd} \end{bmatrix}$$

Control of the proposed system

To control the multilevel inverter a vector sliding mode controller will be used. The sliding mode controller will be obtained from the controllable canonical form of the system model. The controller should impose that, in each switching period T, the output voltages V_{ab} and V_{cd} average values must be equal to their reference average values (6).

(6) $$\begin{cases} \frac{1}{T}\int_0^T V_{ab\_ref}\, dt - \frac{1}{T}\int_0^T V_{ab}\, dt = e_{V_{ab}} = 0 \\ \frac{1}{T}\int_0^T V_{cd\_ref}\, dt - \frac{1}{T}\int_0^T V_{cd}\, dt = e_{V_{cd}} = 0 \end{cases}$$

From the previous assumption, a sliding surface $S(e_{ab,cd},t)$ can be obtained. Equation (7) shows the sliding surface that allows to enforce the control goal $V_{ab,cd}=V_{ab,cd\_ref}$, where $k_{ab,cd}$ is used to impose the switching frequency.

(7) $$S(e_{ab,cd},t) = \frac{k_{ab,cd}}{T}\int_0^T \left(U_{ab,cd\ ref} - U_{ab,cd}\right) dt = 0$$

The control strategy must guarantee that the system trajectory moves towards and stays on the sliding surface from any initial condition. This can be obtained by the stability condition (8).

(8) $$S(e_{ab}, e_{cd})\,\dot{S}(e_{ab}, e_{cd}) < 0$$

To ensure the sliding surface (7), the switching law must be select according to the conditions expressed in (9).

(9) $$\begin{cases} \mathbf{S}(\mathbf{e}_{ab,cd},t) > 0 \Rightarrow \dot{\mathbf{S}}(\mathbf{e}_{ab,cd},t) < 0 \Rightarrow \mathbf{U}_{ab,cd} > \mathbf{U}_{ab,cd\,ref} \\ \mathbf{S}(\mathbf{e}_{ab,cd},t) < 0 \Rightarrow \dot{\mathbf{S}}(\mathbf{e}_{ab,cd},t) > 0 \Rightarrow \mathbf{U}_{ab,cd} < \mathbf{U}_{ab,cd\,ref} \end{cases}$$

In order to ensure this, the switching strategy must select the proper values of $V_{ab,cd}$ from the available outputs. From the analysis of the proposed topology it is possible to verify that, there are 25 different output voltage combinations. Table 2 show the relationship between the output voltages levels of the inverter and the output voltage vectors. To select one of the 25 vectors it will be used Table 1 and 2. In this way, at the output of the sliding mode controller (7) a vectorial modulator will be used (Fig 4).

Table 2. Relationship between the output voltage levels and voltage vectors

V_{ab} / V_{cd}	-2V	-V	0	+V	+2V
+2V	15	14	13	12	11
+V	16	4	3	2	10
0	17	5	0	1	9
-V	18	6	7	8	24
-2V	19	20	21	22	23

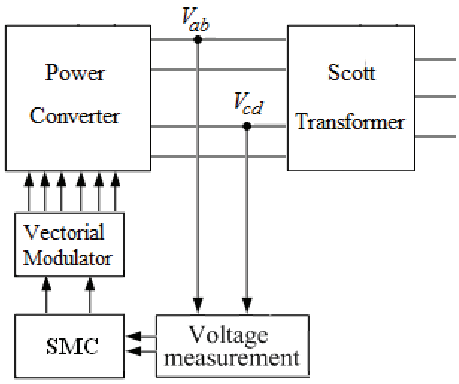

Fig.4. Control structure of the proposed power converter

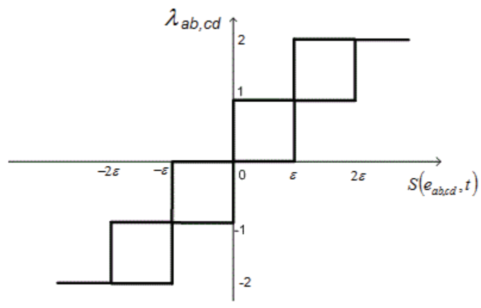

Fig.5. Five level hysteretic comparator

To implement the vectorial modulator, two five-level hysteretic comparators (with hysteresis ε in order to limit the maximum switching frequency) are used. Fig. 5 shows the five-level hysteretic comparator that has been used. The output of these comparators are the integer variables λ_{ab} and λ_{cd} (λ_{ab}, $\lambda_{cd}\in${2;1;0;-1;-2}) corresponding to the five selectable levels. These integer variables are related with the desired desired V_{ab} and V_{cd} voltages. According variables λ_{ab}, λ_{cd} and table 1 the switches that must be on are selected.

Simulation results

The behaviour of the proposed power converter and their control system has been carried out by several simulations. These results have been obtained using the program Matlab-Simulink/Power System Blockset. For the simulated system it was used the parameters presented in table 3.

Table 3. System Parameters

Description	Value
DC Source voltage	200 V
Output Frequency	50 Hz
Output inductor	5 mH
Output resistor	10 Ω

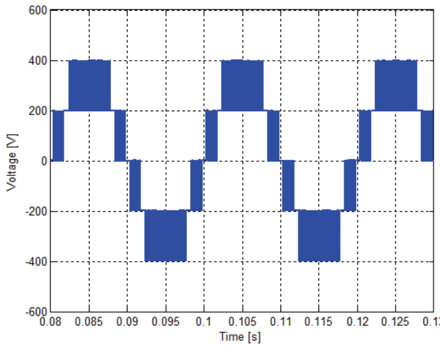

Fig.6. Output voltage v_{ab} of the power converter

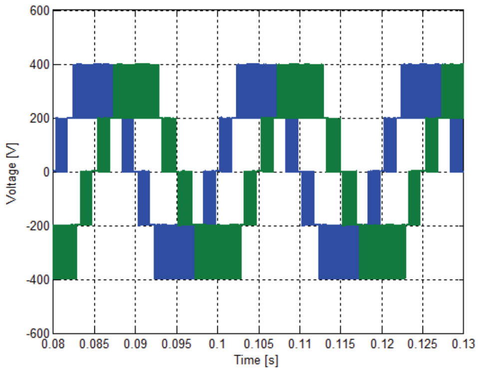

Fig.7. Output voltages v_{ab} and v_{cd} of the power converter

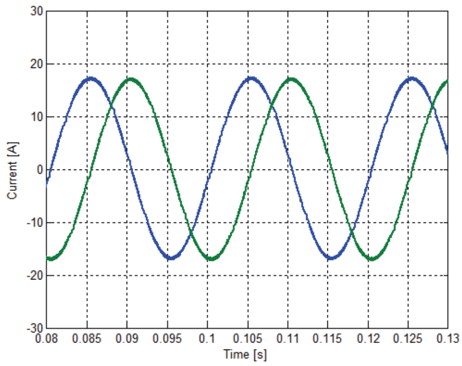

Fig.8. Converter output currents I_{ab} and I_{cd}

Fig. 6 show one of the output voltage of the power converter (v_{ab}). As can be seen there are five levels with a 2Vdc maximum output voltage. Fig. 7 shows the output voltages v_{ab} and v_{cd}. From this last figure it possible to verify that the power converter output voltages are 90º phase-shifted from each other. At the transformer output a RL load was connected. Fig. 8 shows the converter output currents I_{ab} and I_{cd}. As expected these currents are nearly sinusoidal and 90º phase-shifted from each other with equal amplitudes. The sinusoidal waveform is due to the RL load and Scott transformer.

Fig. 9 shows the three-phase load currents I_R, I_S and I_T. From this result it is possible to verify that the output currents are balanced and nearly sinusoidal. The obtained results also show the effectiveness of the proposed control system.

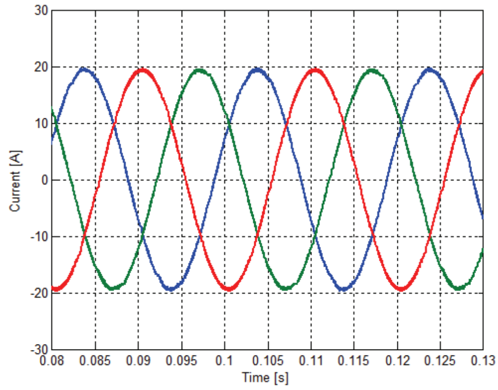

Fig.9. Three-phase load currents

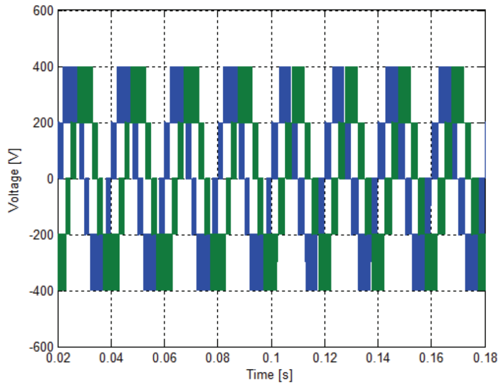

Fig.10. Output voltage v_{ab} of the power converter for a change in the voltage reference

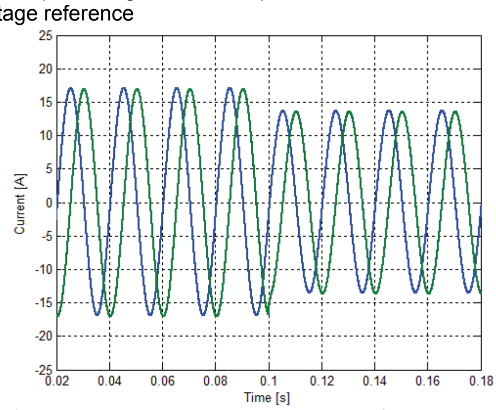

Fig.11. Converter output currents I_{ab} and I_{cd} for a change in the voltage reference

To investigate the transient response of the system controller new tests have been made. Figs. 10-12 show the behaviour of the output voltages and currents of the power converter and the three-phase load currents for a sudden change in the voltage reference. The voltage reference changes to 80% of its nominal value at 0.1 s.

Fig. 13 shows the behaviour of the three-phase load currents for a sudden change in the load. At 0.1 s the load changes from 9,2 Ω and 4,2 mH to 100 Ω and 5 mH. From these results it is possible to verify that the controller it is not affected by the change of the system parameters.

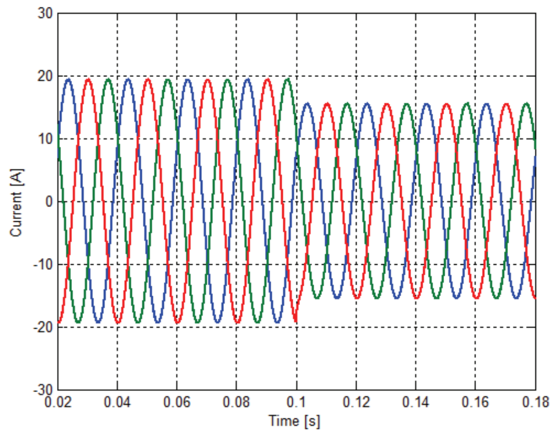

Fig.12. Three-phase load currents for a change in the voltage reference

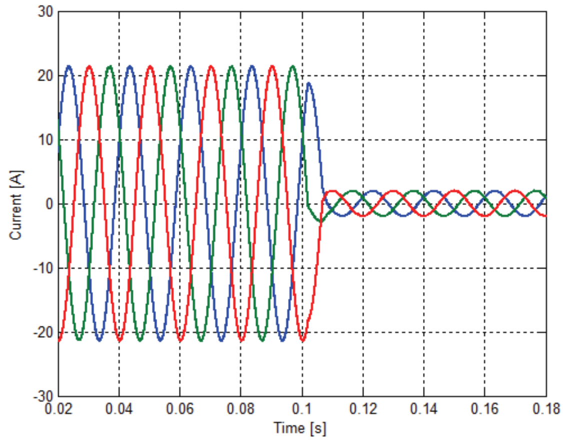

Fig.13. Three-phase load currents for a load change

Conclusions

In this work it was presented a new configuration for a three-phase dc/ac multilevel power converter. This structure it is based on a three single-phase voltage source inverter. This structure allows converting two dc voltages into two ac voltages. In order to obtain a three-phase system, at the output of the power converter structure a Scott transformer is connected. This transformer is normally used to convert a three-phase system into a two phase system. However, in this structure it used in an inverse way. Then, it is possible to obtain a multilevel three-phase system. To control the proposed power converter structure it was used sliding mode controller with a vectorial modulator. This fast and robust converter allows obtaining the desired five level output voltages. This topology is characterized by 25 different output voltage vectors. In this way, it was used two five-level hysteretic comparators in order to implement the vectorial modulator. The proposed multilevel structure has been validated using computer simulations.

REFERENCES

[1] Nabae A., Takahashi I., Akagi H., A New Neutral-Point Clamped PWM Inverter, *IEEE Trans. Ind. Appl.*, IA-17 (1981), No. 5, 518-523

[2] Yuan X., Barbi I., Fundamentals of a New Diode Clamping Multilevel Inverter, *IEEE Trans. Power Electron.*, 15 (2000), No. 4, 711-718

[3] Barros J.D., Silva J.F., Optimal Predictive Control of Three-Phase NPC Multilevel Converter for Power Quality Applications, *IEEE Trans. Ind. Electron.*, 55 (2008), No. 10, 3670-3681

[4] Rodriguez J., Lai J.S., Peng F.Z., Multilevel inverters: a survey of topologies, controls, and applications, *IEEE Trans. Ind. Electron.*, 49 (2002), No. 4, 724-738

[5] Meynard T.A., Foch H., Multi-level choppers for high voltage applications, *Eur. Power Electron. J.*, 2 (1992), No. 1, 45-50

[6] Yuan X.M., Stemmler H., Barbi I., Self-balancing of the clamping-capacitor-voltages in the multilevel capacitor clamping inverter under sub-harmonic PWM modulation, *IEEE Trans. Power Electron.*, 16 (2001), No. 2, 256-263

[7] Feng C., Liang J., Agelidis V.G., Modified phase-shifted PWM control for flying capacitor multilevel converters, *IEEE Trans. Power Electron.*, 22 (2007), No. 1, 178-185

[8] Wilkinson R.H., Mouton H., Meynard T., Natural balance of multicell converters: the two-cell case, *IEEE Trans. Power Electron.*, 21 (2006), No. 6, 1649-1657

[9] Hammond P.W., A New Approach to Enhance Power Quality for Medium Voltage AC Drives, *IEEE Trans. Ind. Appl.*, 33 (1997), No. 1, 202-208

[10] Loh P.C., Holmes D.G., Lipo T.A., Implementation and control of distributed PWM cascaded multilevel inverters with minimal harmonic distortion and common-mode voltage, *IEEE Trans. Power Electron.*, 20 (2005), No. 1, 90-99

[11] Antunes V.M.E., Pires V.F., Silva J.F., Narrow Pulse Elimination PWM for Multilevel Digital Audio Power Amplifiers Using Two Cascaded H-Bridges as a Nine-Level Converter, *IEEE Trans. Power Electron.*, 22 (2007), No. 2, 425-434

[12] Chiasson J.N., Ozpineci B., Tolbert L.M., A Five-Level Three-Phase Hybrid Cascade Multilevel Inverter Using a Single DC Source for a PM Synchronous Motor Drive, *Appl. Power Electron. Conf.*, (2007), 1504-1507

[13] Ruffer A., Andrianirina Ch.-B., A symmetrical 3 phase 2-switch PFC-power supply for variable output voltage, *Europ. Conf. on Power Electron. and Appli.*, (1995)

[14] Badin A.A., Barbi I., Unity Power Factor Isolated Three-Phase Rectifier With Split DC-Bus Based on the Scott Transformer, *IEEE Trans. Power Electron.*, 23 (2008), No. 3, 1278-1287

[15] Pires V.F., Guerreiro M., Martins J.F., Silva J.F., Three-Phase PWM Rectifier Employing Two Single-Phase Buck-Boost PFC Modules and a Scott Transformer, *Przeglad Elektrotechniczny*, 85 (2009), nr 10, 213-216

[16] Carrara G., Gardella S., Marchesoni M., Salutari R., Sciutto G., A new multilevel PWM method: A theoretical analysis, *IEEE Trans. Power Electron.*, 7 (1992), No. 3, 497-505

[17] McGrath B.P., Holmes D.G., Multicarrier PWM strategies for multilevel inverters, *IEEE Trans. Ind. Electron.*, 49 (2002), No. 4, 858-867

[18] Kouro S., Lezana P., Angulo M., Rodriguez J., Multicarrier PWM with DC-link ripple feedforward compensation for multilevel inverters, *IEEE Trans. Power Electron.*, 23 (2008), No. 1, 52-59

[19] Gao W., Hung J., Variable structure control: A Survey, *IEEE Trans. Ind. Electron.*, 40 (1993), No. 1, 2-22

[20] Silva J.F., Sliding Mode Control Design of Drive and Regulation Electronics for Power Converters, *Journal on Circuits, Syst. and Comput.*, 5 (1995), No. 3, 355-371

***Authors**: Prof. Dr Vitor Fernão Pires, ESTSetubal- Instituto Politécnico Setúbal, Campus do IPS, 2910-761 Setúbal, Portugal, E-mail: vitor.pires@estsetubal.ips.pt; Prof. Dr Manuel Guerreiro, ESTSetubal- Instituto Politécnico Setúbal, Campus do IPS, 2910-761 Setúbal, Portugal, E-mail: manuel.gaspar@estsetubal.ips.pt; Prof. Dr João Martins, CTS/UNINOVA and Faculdade Ciências e Tecnologia, Univ. Nova de Lisboa, 2829-516 Caparica, Portugal, E-mail: jf.martins@fct.unl.pt; Prof. Dr José Fernando Silva, Instituto Superior Técnico, Av. Rovisco Pais, 1, 1049-001 Lisboa, Portugal, E-mail: fernandos@alfa.ist.utl.pt.*