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Backstepping controller of five-level three-phase inverter

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Abstract. Multilevel converters are becoming increasingly used in many industrial applications due to the many advantages that they offer. The improvements in the output signal quality, lower Total Harmonic Distortion (THD) and many other properties make multilevel converters very attractive for connecting photovoltaic generators to medium voltage grid directly or to be used in a local power supply. In this paper, we focus on the implementation of a three-phase five-level diode clamped inverter and design of a performing nonlinear controller using the Backstepping approach. The control objective is to generate, at the system output, sinusoidal three-phase voltages with amplitude and frequency fixed by the reference signal independently of load variations. The performance study of the multilevel inverter and the designed controller are made by simulations in Matlab/Simulink environment.

1 Introduction

In the last years, static power converters have become widely used in numerous applications. They can be found in domestic applications, renewable energy source, railways, urban and ship transport, and in many industrial systems, which require higher power with increased performance.

Moreover, due to technological advances made in the field of power electronics and digital electronics, static converters gradually see their function improve and their field of application widened. Semiconductor switches (MOS or IGBT) increasingly faster have been developed, only their voltage rating remains limited compared to SCRs or GTOs. For a medium voltage grid, it is difficult to connect only one power semiconductor switch directly. As a result, a multilevel power converter structure has been introduced as an alternative in high power and medium voltage situations, due to their many advantages such as low power dissipation on power switches, low distortion of the output voltage, low harmonic contents and low electromagnetic interference outputs. The selected switching technique to control the inverter will also have an effective role on harmonic elimination while generating the ideal output voltage. These, so-called multilevel structures, can generate several voltage levels at the output of the converter. Unfortunately, multilevel converters do have some disadvantages. The number of semiconductor required for achieving these topologies increases with the number of desired levels and the complexity of their structure is thereby increased and reduced reliability [1-3].

In this paper, we are interested in implementing three-phase five-level voltage inverter topology controlled by a nonlinear regulator using performing nonlinear control technique. The Backstepping regulator must ensure that its output voltage has a good pursuit of the reference and good robustness to large variations in the load. Thus, the inverter must be able to generate pure sinusoidal voltage with amplitude and frequency fixed by reference. So this multilevel inverter can be used for produce purely sinusoidal voltages from photovoltaic generators. These can be used in a local power supply or be connected to the distribution network.

In the second part in this paper, the state of art of the most typical three-phase multilevel power converter technology is reviewed. A brief description is made of the three-level inverter with an emphasis on modulation and control techniques used for these converters. In third section, an equivalent mathematical model of the three-phase five-level inverter is developed and presented using the theory of averaging values widely used in the literature. In fourth section, we develop an advanced nonlinear controller using the Backstepping approach. Finally, the performance of this controller and the three-phase five-level inverter are tested, simulated and presented in the last section with comments and conclusions.

2 Common multilevel inverter topologies and PWM modulation strategies

Three major multilevel inverter structures, which have been mostly applied in industrial applications, have been emphasized as the diode clamped, the flying capacitor, and the cascaded H-bridge converters with separate DC sources [3-8]. We briefly present the topologies of these three types of multilevel converters.

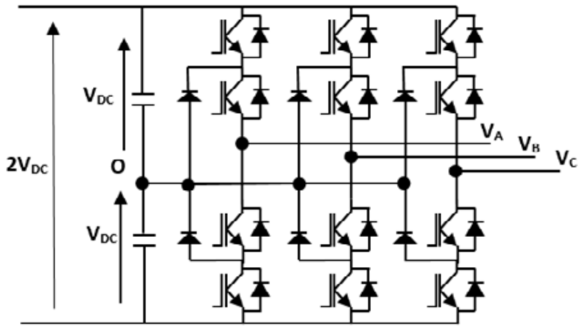

Fig. 1. Three-phase three-level diode clamped inverter.

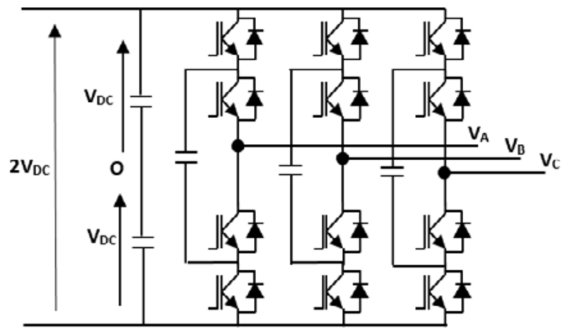

Fig. 2. Three-phase three-level flying capacitors inverter.

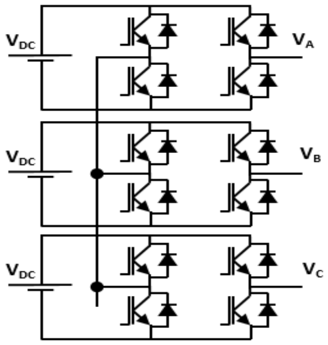

Fig. 3. Three-phase three-level cascaded H-bridge inverter.

PWM modulation strategies

The multilevel PWM (Pulse With Modulation) method most discussed in the literature have been multilevel carrier-based PWM; it is extension of traditional two-level PWM strategies to several levels: this strategy consists in compare several triangular signals to a sinusoidal reference [9]. In a five-level converter, four triangle carriers are arranged in contiguous bands across the full linear modulation range of the multilevel converter. All the carriers have the same frequency and amplitude and the reference waveform is placed in the middle of the carrier bands [9-10]. As an example, a five-level PWM schema is shown in Figure 4 [10].

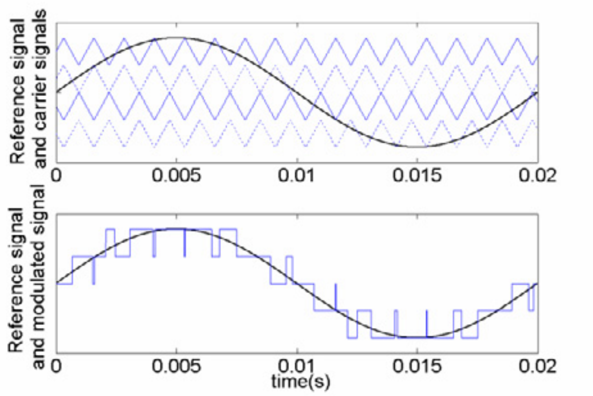

Fig. 4. Five-level PWM schema using four triangular carriers disposed to carry out PWM control signals and converter output voltage [10].

Other multilevel PWM methods have been used to a much lesser extent by researchers. Finally, it must be noticed that many more strategies have been proposed in order to improve some characteristics of the converter operation [9, 14].

3 Multilevel inverter modelling

In this work, we propose to implement the three-phase five-level diode clamped inverter associated with an LC filter and controlled by performing Backstepping regulator. For this, we try to model this inverter with sinusoidal PWM control strategy in order to design the laws of the controller. The schema of this converter is shown in Figure 5. The performance of this multilevel inverter and the designed regulator are tested during a large reference change or a large load variation.

The three-phase five-level NPC inverter debiting on a load, shown in Figure 5, is composed of three arms of eight bi-directional switches (IGBT or MOSFET with antiparallel diode) and nine arms of two diodes.

V_{AO}	*Switches States*							
	S_{A1}	S_{A2}	S_{A3}	S_{A4}	S'_{A1}	S'_{A2}	S'_{A3}	S'_{A4}
2V_{DC}	1	1	1	1	0	0	0	0
V_{DC}	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0
-V_{DC}	0	0	0	1	1	1	1	0
-2V_{DC}	0	0	0	0	1	1	1	1

Table. 1: The switches state for the five-level of voltage output

Table 1 shows the correspondence between the states of the switches and the five-level output voltage V_{AO}.

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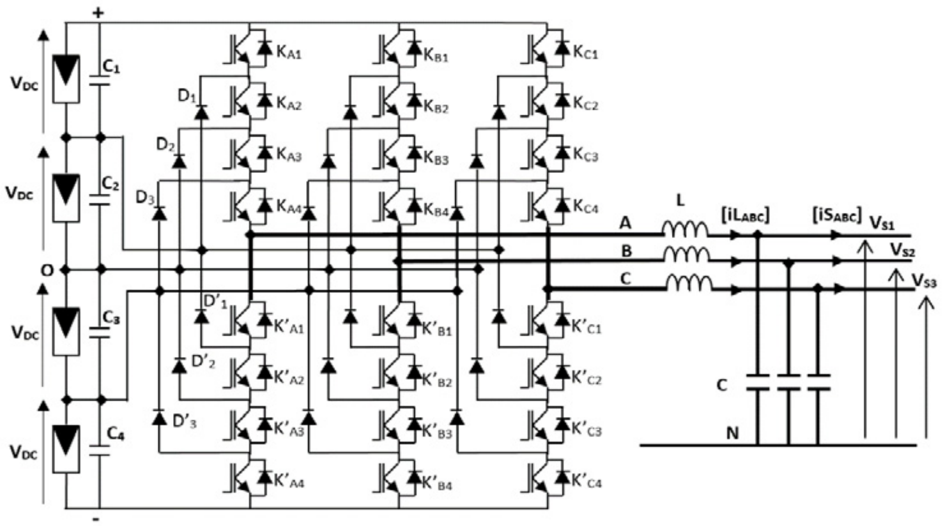

Fig. 5. The three-phase five-level diode clamped inverter.

Posing

$$\mu_x = S_{Ax} - \frac{1}{2} = \begin{cases} \frac{1}{2} \ when \quad S_{Ax} = 1 \\ -\frac{1}{2} \ when \ S_{Ax} = 0 \end{cases}$$

then we can write:

$$V_{AO} = (\mu_1 + \mu_2 + \mu_3 + \mu_4)\,.V_{DC} \tag{5}$$

what drives us to design four PWM generators or one generator with four PWM outputs, comparing a single reference to four triangular carriers distributed between -1 and 1. So we can summarize the equation (5) by noting:

$$\mu_A = \frac{(\mu_1+\mu_2+\mu_3+\mu_4)}{2} \tag{6}$$

$$V_{AO} = \mu_A\,.2V_{DC} \tag{7}$$

with $\mu_A \in \{-1, -\frac{1}{2}, 0, \frac{1}{2}, 1\}$

V_{AO} is not a continuous variable and can take five discrete values $\{-2V_{DC}, -V_{DC}, 0, V_{DC}, 2V_{DC}\}$ unsuitable for the design of a continuous control law. To overcome this difficulty it is usually made use of average model (widely used for modeling static converters) [11-12]; it supposes that the switching period is very small compared to the system dynamics. In our case, this is largely justified. Thus, we obtain:

$$\bar{V}_{AO} = u_A\,.2V_{DC} \tag{8}$$

The control variable $\boldsymbol{u_A} \in [-1, 1]$ takes values between -1 and 1 and represents the mean value of the control signal μ_A formed by pulse width modulated rectangular.

The neutral point voltage of the load with respect to the point O is given by the following relationship:

$$V_{NO} = \frac{(V_{AO}+V_{BO}+V_{CO})}{3} \tag{9}$$

$$V_{AN} = V_{AO} - V_{NO} \tag{10}$$

The three phase voltages with respect to the neutral point of the load are given in matrix form:

$$\Rightarrow \begin{pmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{pmatrix} = \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \begin{pmatrix} u_A \\ u_B \\ u_C \end{pmatrix} \frac{2V_{DC}}{3} \tag{11}$$

At the output of the inverter, is mounted a filter (L, C) of the three phases, the electrical quantities equations across the filter elements is established:

$$L\,\frac{d}{dt}\begin{pmatrix} i_{L1} \\ i_{L2} \\ i_{L3} \end{pmatrix} = \begin{pmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{pmatrix} - \begin{pmatrix} V_{S1} \\ V_{S2} \\ V_{S3} \end{pmatrix} - R\begin{pmatrix} i_{L1} \\ i_{L2} \\ i_{L3} \end{pmatrix} \tag{12}$$

$$C\,\frac{d}{dt}\begin{pmatrix} V_{S1} \\ V_{S2} \\ V_{S3} \end{pmatrix} = \begin{pmatrix} i_{L1} - i_{S1} \\ i_{L2} - i_{S2} \\ i_{L3} - i_{S3} \end{pmatrix} \tag{13}$$

All three-phase electrical quantities will be rewritten in the coordinate system (d, q) using the transformation Park-Clark to reduce the complexity of the equations. Knowing that the system is balanced, homopolar component is then zero. Then, we can write for any electrical quantity

$$\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) \\ \cos(\theta - 4\pi/3) & -\sin(\theta - 4\pi/3) \end{bmatrix} \begin{bmatrix} X_d \\ X_q \end{bmatrix}$$

$$\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} = P(\theta)\begin{bmatrix} X_d \\ X_q \end{bmatrix} \quad and \quad \begin{bmatrix} X_d \\ X_q \end{bmatrix} = P^{-1}(\theta)\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix}$$

The equations (12) and (13) become

$$\begin{aligned} C\,\dot{x}_{1d} &= x_{2d} + C\,\omega\,x_{1q} - i_{sd} \\ C\,\dot{x}_{1q} &= x_{2q} - C\,\omega\,x_{2d} - i_{sq} \\ L\,\dot{x}_{2d} &= 2V_{DC}\,u_d + L\,\omega\,x_{2q} - V_{Sd} - R\,x_{2d} \\ L\,\dot{x}_{2q} &= 2V_{DC}\,u_q - L\,\omega\,x_{2d} - V_{Sq} - R\,x_{2q} \end{aligned} \tag{14}$$

where the state variables $(x_{1d}, x_{1q})^T and\ (x_{2d}, x_{2q})^T$, respectively, represent average values over a sampling period of the output voltages $(V_{Sd}, V_{Sq})^T$ across the capacitors C and currents $(i_{Ld}, i_{Lq})^T$ flowing in the inductances L.

4 Backstepping Controller Design

4.1 Presentation of Backstepping approach

In control theory, backstepping is a technique developed for designing stabilizing controls for nonlinear dynamical systems. These systems are built from subsystems that radiate out from an irreducible subsystem that can be stabilized using some other method. Because of this recursive structure, the designer can start the design process at the known-stable system and "back out" new controllers that progressively stabilize each outer subsystem. The process terminates after a many step procedures, when the final external control is reached. Hence, this process is known as Backstepping [13].

4.2 Controller design objectives

After implementation and modelling of the converter, our goal now is to design a Backstepping controller allowing the five-level converter to provide a purely sinusoidal voltage with fixed amplitude and frequency regardless of the load. The three-phase output voltages must follow a three-phase reference signals

$$\begin{pmatrix} V_{S1}^*(t)=V\sqrt{2}\,sin(\omega t) \\ V_{S2}^*(t)=V\sqrt{2}\,\sin\left(\omega t-\frac{2\pi}{3}\right) \\ V_{S2}^*(t)=V\sqrt{2}\,sin\left(\omega t-\frac{4\pi}{3}\right) \end{pmatrix} \Rightarrow \begin{pmatrix} x_{1d}^* = 0 \\ x_{1q}^* = -V\sqrt{3} \end{pmatrix}$$

where V=230V and f =50Hz (ω = 2πf) represent, respectively, the RMS value and the frequency of the sine wave reference signal.

4.3 Control laws design

The controller synthesis will be performed in two steps.

Step 1:

Consider the tracking error z_1 defined by:

$$z_{1d} = C\,(x_{1d} - x_{1d}^*) \quad (15a)$$
$$z_{1q} = C\,(x_{1q} - x_{1q}^*) \quad (15b)$$

and its dynamics are given by:

$$\dot{z}_{1d} = C\,(\dot{x}_{1d} - \dot{x}_{1d}^*) \quad (16a)$$
$$\dot{z}_{1d} = x_{2d} + C\,\omega\,x_{1q} - i_{Sd} - C\dot{x}_{1d}^* \quad (16b)$$
$$\dot{z}_{1q} = C\left(\dot{x}_{1q} - \dot{x}_{1q}^*\right) \quad (16c)$$
$$\dot{z}_{1q} = x_{2q} - C\,\omega\,x_{1d} - i_{Sq} - C\dot{x}_{1q}^* \quad (16d)$$

We use the following Lyapunov candidate function:

$$V_1 = \frac{1}{2}z_{1d}^2 + \frac{1}{2}z_{1q}^2 \quad (17)$$

Its derivative with respect to time is given by:

$$\dot{V}_1 = \dot{z}_{1d}z_{1d} + \dot{z}_{1q}z_{1q} \quad (18)$$

Posing: $\dot{z}_{1d} = -k_1\,z_{1d}$ *and* $\dot{z}_{1q} = -k_1\,z_{1q}$ (19)

it leads to a Lyapunov candidate function whose dynamics is negative definite. Thus, we obtain

$$\dot{V}_1 = -k_1\,z_{1d}^2 - k_1\,z_{1q}^2 \quad (20)$$

Therefore, global asymptotic stability is achieved and z_1 tends exponentially to zero. In the system (16b) and (16d), x_{2d} *and* x_{2d} are considered as virtual control inputs. So z_{1d} *and* z_{1q} can be regulated to zero if:

$$x_{2d} = x_{2d}^* \text{ and } x_{2q} = x_{2q}^*$$

According to the equations (16) and (19), we deduce:

$$x_{2d}^* = -k_1\,z_{1d} + i_{Sd} - C\,\omega\,x_{1q} + C\dot{x}_{1d}^* \quad (21a)$$
$$x_{2q}^* = -k_1\,z_{1q} + i_{Sq} + C\,\omega\,x_{1d} + C\dot{x}_{1q}^* \quad (21b)$$

where x_{2d}^* *and* x_{2q}^* are called stabilizing functions. New variables errors between virtual drives and its desired values are defined

$$z_{2d} = x_{2d} - x_{2d}^* \quad (22a)$$
$$z_{2q} = x_{2q} - x_{2q}^* \quad (22b)$$

We can deduce from equations (16), (21) and (22) that:

$$\dot{z}_{1d} = -k_1\,z_{1d} + z_{2d} \quad (23a)$$
$$\dot{z}_{1q} = -k_1\,z_{1q} + z_{2q} \quad (23b)$$

Step 2:

The dynamic of z_2 is calculated as follows:

$$\dot{z}_{2d} = \dot{x}_{2d} - \dot{x}_{2d}^* \quad (24a)$$
$$\dot{z}_{2q} = \dot{x}_{2q} - \dot{x}_{2q}^* \quad (24b)$$
$$\dot{z}_{2d} = \frac{1}{L}(2V_{DC}\,u_d + L\,\omega x_{2q} - V_{Sd} - R\,x_{2d}) - \dot{x}_{2d}^* \quad (25a)$$
$$\dot{z}_{2q} = \frac{1}{L}(2V_{DC}\,u_q - L\,\omega\,x_{2d} - V_{Sq} - R\,x_{2q}) - \dot{x}_{2d}^* \quad (25b)$$

We note the appearance of the real control system. The problem of stabilization of the system described by (23) and (25) can be apprehended by the following Lyapunov function:

$$V_2 = \frac{1}{2}z_{1d}^2 + \frac{1}{2}z_{2d}^2 + \frac{1}{2}z_{1q}^2 + \frac{1}{2}z_{2q}^2 \quad (26a)$$
$$\dot{V}_2 = \dot{z}_{1d}z_{1d} + \dot{z}_{2d}z_{2d} + \dot{z}_{1q}z_{1q} + \dot{z}_{2q}z_{2q} \quad (26b)$$
$$\dot{V}_2 = -k_1 z_{1d}^2 + z_{2d}(z_{1d} + \dot{z}_{2d}) - k_1 z_{1q}^2 + z_{2q}(z_{1q} + \dot{z}_{2q}) \quad (26c)$$

By imposing the following equations:

$$\begin{cases} (z_{1d} + \dot{z}_{2d}) = -k_2 z_{2d} \\ (z_{1q} + \dot{z}_{2q}) = -k_2 z_{2q} \end{cases} \quad (27)$$

one obtains

$$\dot{V}_2 = -k_1 z_{1d}^2 - k_2 z_{2d}^2 - k_1 z_{1d}^2 - k_2 z_{2d}^2 \quad < 0 \quad (28)$$

Thus, the equations (25) and (27) allow us to deduce the control signals of the controller Backstepping:

$$u_d = -\frac{L}{2V_{DC}}\left(z_{1d} + k_2 z_{2d} - \frac{x_{1d} + R x_{2d}}{L} + \omega x_{2q} - \dot{x}_{2d}^{*}\right) \quad (29)$$

$$u_q = -\frac{L}{2V_{DC}}\left(z_{1q} + k_2 z_{2q} - \frac{x_{1q} + R x_{2q}}{L} - \omega x_{2d} - \dot{x}_{2q}^{*}\right) \quad (30)$$

The control law chosen so that $\dot{V}_2 < 0$ allows the system (z_1, z_2) to be globally asymptotically stable.

5 Simulation results

In this section, using MATLAB/SIMULINK, we achieve a three-phase five-level voltage inverter with an LC output filter and controlled by the performing Backstepping regulator. To evaluate the performance of the proposed controller, we test them at a high reference change and at a strong perturbation of the output current: for testing pursuit, the output voltage must follow a sinusoidal reference who undergoes suddenly a sharp increase: RMS value changes from 115V to 230V. The second test relates the response of controller following a disturbance caused by a sharp increase in the output current of 23A to 46A RMS.
Table. 2 listed below summaries the considered simulation parameters for the control system.

	Parameters	*Numerical values*
Voltage DC bus	V_{DC}	*500V*
Output filter	*L*	*2mH*
	C	*50µF*
Switching frequency	f_{PWM}	*10KHZ*
Reference signal	*ω*	*100π*
	V	*230V*
Load	*R*	*10Ω*
Backstepping controller parameters	K_1	*13000*
	K_2	*13000*

Table. 2: Simulation parameters

5.1 Evaluating performances in pursuit

In this section, we present the simulation results of tracking of three-phase sinusoidal references. The waveform of the inverter output voltage with five levels is given in Figure 6. Figures 7 to 9 show the output voltages, currents in inductances L and control signals generated by the Backstepping regulator during a high change of references.
In these figures, we can see that the output voltages follows the references perfectly and converges quickly to it even when it undergoes a strong modification. The response time of Backstepping controller is low; its excellent performance in pursuit, are then confirmed.

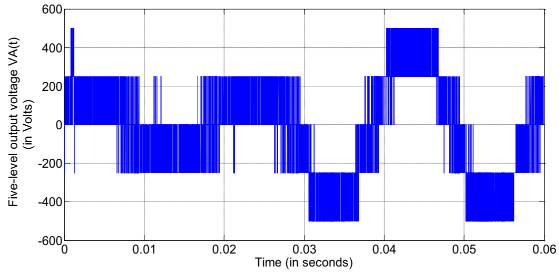

Fig. 6. Waveform of the output voltage $V_A(t)$ of the five-level inverter.

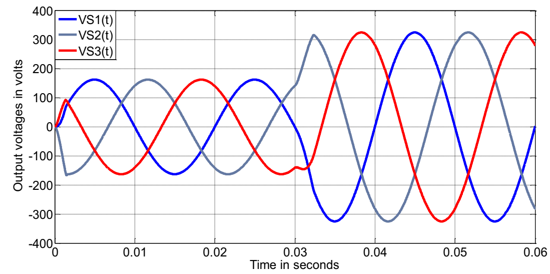

Fig. 7. Shape of the three-phase output voltage in pursuit with the Backstepping controller.

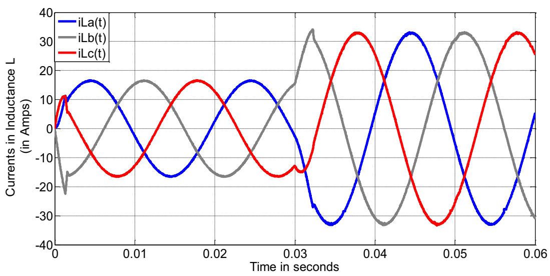

Fig. 8. Shape of the three currents flowing in inductances L.

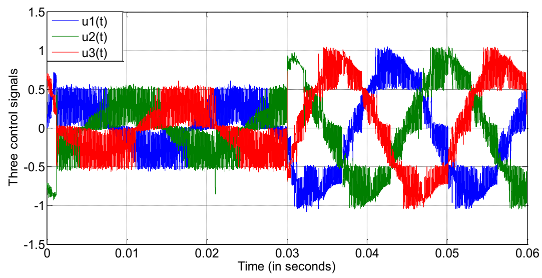

Fig. 9. Waveform of the three control laws generates by the controller in pursuit

5.2 Performance evaluation during regulation and compensation of a large load variation

Figures 10 to 13 show also the output voltages, currents in inductances L and the control signal during a high change of the load current. The Backstepping controller responds very well during the perturbation, the output voltage decreases and converges quickly to the reference after a sudden and sharp increase in output current.

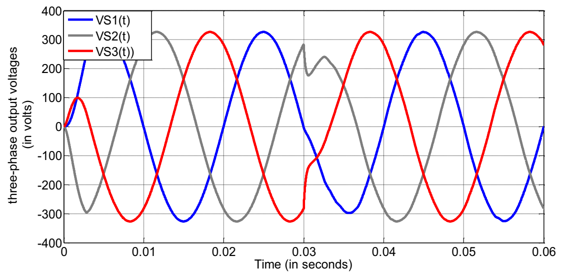

Fig. 10. Shapes of the three-phase output voltage during a large perturbation with the Backstepping controller

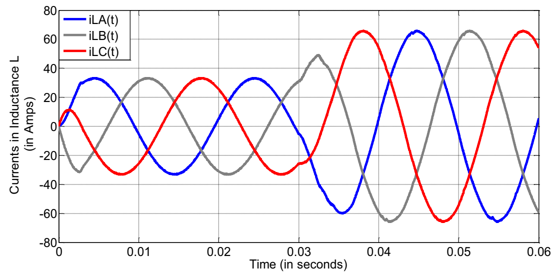

Fig. 11. Shape of the three currents flowing in inductances L during a large perturbation

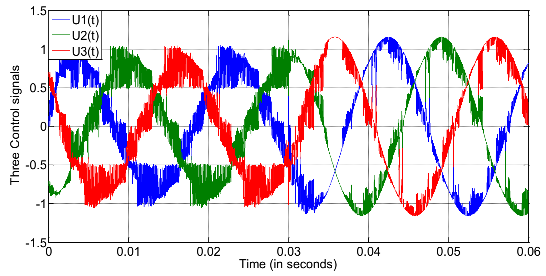

Fig. 12. Shapes of the three control signals generates by the Backstepping controller during a large perturbation

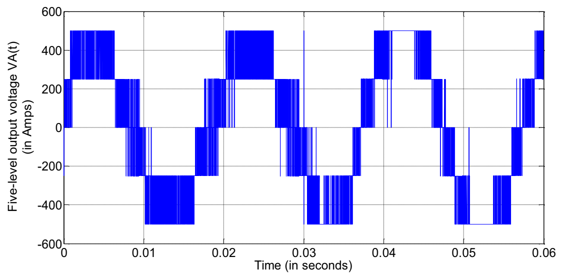

Fig. 13. Waveform of the output voltage $V_A(t)$ of the five-level inverter during perturbation.

6 Conclusion

This work is focused on the study of five-level three-phase inverter controlled by Backstepping regulator. Our objective was twofold: i) implement the three-phase five-level structure of a diode clamped inverter with multilevel carrier-based PWM. ii) design a Backstepping regulator using performing nonlinear control technique: stability tools with Lyapunov function.

The simulation results show that the Backstepping controller allows output voltages to have a good tracking of the reference and good robustness to large variations in the load. Simulation results also illustrate the performance and effectiveness of the five-level inverter for generates a high-quality output voltage waveform. The harmonic components of output voltage and current are low. Other benefits of using multilevel diode clamped inverter may be mentioned: voltage stress across each device is lower therefor capacitors and semiconductor switches could have lower voltage ratings which sometimes are much cheaper and have greater availability.

References

[1] J. Rodriguez, J. S. Lai and F. Z. Peng, Multilevel Inverters: Survey of Topologies, Controls, and Applications. IEEE Transactions on Industry Applications. **49**, 2002, 724-738.

[2] J. S. Lai and F. Z. Peng, Multilevel Converters-A new Breed of Power Converters. IEEE Transactions on Industry Applications. **32**, 1996, 509-517.

[3] A. Nabae, I. Takahashi, H. Akagy, A neutral-point clamped PWM inverter. IEEE Transactions on Industrial Applications. 1A,**17,** 1981**,** 518–523.

[4] L. Tolbert, F.-Z. Peng, and T. Habetler, Multilevel converters for large electric drives. IEEE Trans. Ind. Applicat. **35**, 1999, 36–44.

[5] L. Tolbert, F.-Z. Peng, and T. Habetler, Multilevel inverters for electric vehicle applications. Proceedings of IEEE workshop on power electronics in tran, Michigan, USA (1998).

[6] F. Z. Peng, J. W. McKeever, D. J. Adams, Cascade multilevel inverters for utility applications. Proceedings of 23rd international conference on industrial elect. Control and inst, New Orleans USA (1997).

[7] M. D. Manjrekar, T. A. Lipo, A hybrid multilevel inverter topology for drive applications. Proceedings of IEEE applied power elec conference (1998).

[8] G. Joos, X. Huang, B. T. Ooi, Direct-coupled multilevel cascaded series VAR compensators. Proceedings of IEEE industrial applications society 32nd meeting; (1997).

[9] L. M. Tolbert, T. G. Habetler, Novel Multilevel Inverter Carrier-Based PWM Method. IEEE Transactions on Industry Applications. **35**, 1999, 1098-1106.

[10] J. L. Galvan, Multilevel Converters: Topologies, Modelling, Space Vector Modulation Techniques and Optimizations. thesis from University of Seville (2006).

[11] P.T. Krein, J. Bentsman, R.M. Bass and B. Lesieutre, On the use of averaging for analysis of power electronic system. IEEE Transactions on Power Electronics. **5**, 1990, 182-190.

[12] B. Lehman, R M. Bass, Switching Frequency dependent Averaged Models for PWM DCDC Converters. IEEE Transactions on Power Electronics. **11**, 1996, 89-98.

[13] M. Krstic, I.Kanellakopoulos, and P.V. Kokotovic, Nonlinear and adaptive control design. John Willy & Sons, NY, (1995).