An Implementation Mechanisms of SVM Control Strategies Applied to Five Levels Cascaded Multi-Level Inverters

Mohammed Yaichi*, Mohammed-Karim Fellah**
* Photovoltaic Pumping Team, Research Unit in Renewable Energies in the Saharan Medium URER/MS-Adrar, CDER
** Intelligent Control and Electrical Power Systems Laboratory, Djillali Liabes University of Sidi-Bel-Abbes

Article Info

Article history:

Received Dec 26, 2013
Revised Mar 20, 2014
Accepted Apr 1, 2014

Keyword:

Cascaded Multilevel Inverter
SVM(Space vector modulation)
Trajectory
Harmonics

ABSTRACT

In the area of the energy control with high voltage and power, the multilevel inverters constitute a relatively recent research orientation. The current applications of this technology are in the domains of the high voltage (over hundred kV), variable speed drives, transport and distribution of a good quality of electrical energy (HVDC, FACTS system, ...). To improve the output voltage for such inverters, many different modulation strategies have been developed. Among these strategies, the SVM (Space Vector Modulation). The technique provide the nearest switching vectors sequence to the reference vector without involving trigonometric functions and provide the additional advantages of superior harmonic quality. In this paper, we analyze different mechanisms of the output voltage synthesis and the problem of even order harmonic production. With the proposed a new trajectory SVM, which can eliminate all the even order harmonics for five levels inverter. Show clearly how to deduce the trajectories from the sequences allowing to have better performances among several possible trajectories. It is dedicated to the application of two particular trajectories.

Corresponding Author:

Mohammed Yaichi,
Photovoltaic Pumping Team, Photovoltaic Conversion Division,
Research Unit in Renewable Energies in the Saharan Medium URER/MS-Adrar, Algeria
Email: yaichi_mohammed@yahoo.fr

1. INTRODUCTION

The main interest of the multilevel inverters is the remarkable improvement of the spectral quality of its output signals. Multilevel inverters can reach the increasing demand for power quality and power ratings along with lower harmonic distortion and lesser electromagnetic interference (EMI). This spectrum is, by far, relatively better than the classical two levels inverter [1]-[5].

To improve much more quality of electrical energy, we apply the space vector modulation (SVM) strategy which stands out because it offers significant flexibility to optimize switching waveforms, and because it is well suited for implementation on a digital computer [1], [2], [6]-[9]. The technique provide the nearest switching vectors sequence to the reference vector and calculates the on-state durations of the respective switching state vectors without involving trigonometric functions and provide the additional advantages of superior harmonic quality. It will be studied on a five levels cascaded three-phase inverter. This converter consists of a series-connection of two 4-quadrant converter by phase [2].

The implementation of SVM produces, for some cases, even order harmonics. We will propose a new trajectory SVM for the cascaded inverter, allowing to eliminate the even order harmonics from the output voltage and resulting in a solution where the number of commutation and hence the switching losses may be reduced in the inverter.

2. PRINCIPLE OF SVM APPLIED FOR FIVE LEVELS INVERTERS

Figure 1 shows the simplified circuit of a five levels cascaded inverter. The output voltage of the inverter of a phase, characterize its state. It is defined by the formula (1) [2].

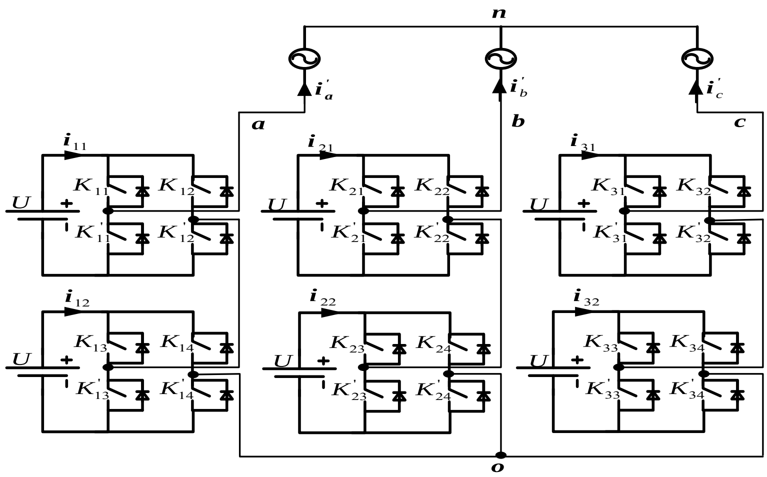


Figure 1. Simplified circuit diagram of 3-phase 5-levels cascaded inverter

$$V_{so} = \begin{cases} +2U \text{ noted}(4) \text{ if } (K_{d1}, K'_{d2}) \text{ and } (K_{d3}, K'_{d4}) \text{ closed} \\ +U \text{ noted } (3) \text{ if } (K_{d1}, K'_{d2}) \text{ and } (K_{d3}, K_{d4}) \text{ closed} \\ 0 \quad \text{noted } (2) \text{ if} (K_{d1}, K'_{d2}) \text{ and } (K'_{d3}, K_{d4}) \text{ closed} \\ -U \text{ noted}(1) \text{ if } (K_{d1}, K_{d2}) \text{ and } (K'_{d3}, K_{d4}) \text{ closed} \\ -2U \text{ noted}(0) \text{ if } (K'_{d1}, K_{d2}) \text{ and } (K'_{d3}, K_{d4}) \text{ closed} \end{cases} \qquad (1)$$

with s = a, b or c;

d = 1, 2, 3: represent the number of the phase (leg).

Theoretical tools allowing evaluating and identifying the representation of the vectors and commutations (hexagonal structure) is corresponding to the vectors of output of the 2 levels and Multilevel inverters have been studied in detail by [2], [6], [10].

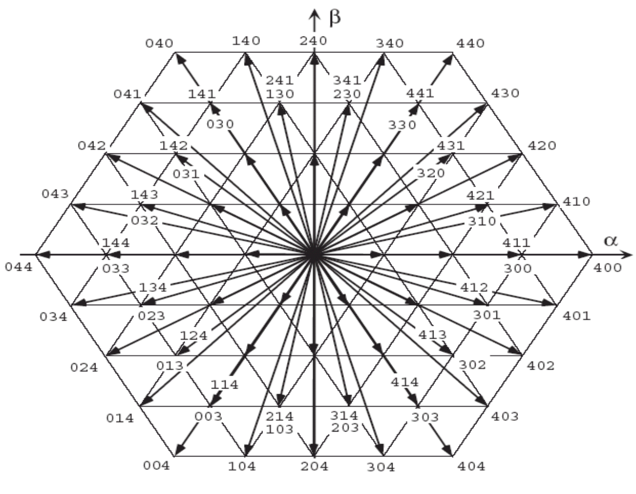


Figure 2. Space vector states for 5-levels inverter

Figure 2 shows all the switching vectors (61 vectors) of a five levels inverter labelled with the position of the equivalent switching states (125 states) [2], [10]-[12]. These vectors of voltage divide the $\alpha - \beta$ plane into 96 triangular portions.

It is the task of the modulator (SVM) to determine which position the switches should assume (switching state) in the (α, β) plane, the duration needed (duty cycle) and the triangular area in which it is, in order to synthesize the reference voltage vector V_{ref} [2], [6]. The generalized algorithm being used to determine, for the hexagonal structure, the exact position of the vector of reference (detection of nearest three vectors and duty cycles computation) was developed and studied in detail in [2], [5], [8] and [13].

3. PRINCIPLE AND MECHANISM OF TRAJECTORY AND SELECTION OF THE VECTORS OF STATE OF THE FIVE LEVELS INVERTERS

3.1. Description

Figure 3 illustrates a subset of a five level space vector plot, and Table 1 summarises all possible sequences for this subset that achieve the required minimum of three switching transitions per phase leg in a switching period, i.e. if we locate the exact triangle where V_{ref} is located, limited by some sort three switching stats (s_1, s_2, s_3) in one switching intervals T_e, then the sequence is given like continuation: s_1 s_2 s_3 s_1 s_3 s_2 s_1 [2], [10]-[12].

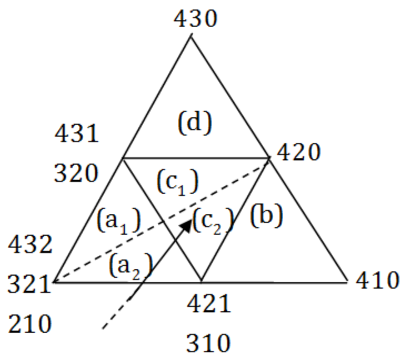


Figure 3. Subset of 5 levels space vector diagram

Table 1. Possible sequences in five levels space vector subset (See Figure 3). Reverse are not shown

Triangle		Sequences
$(a_1)+(a_2)$	$a(i)$	{432 to 431 to 421 to 321}
	$a(ii)$	{321 to 421 to 431 to 432}
	$a(iii)$	{321 to 320 to 310 to 210}
	$a(iv)$	{210 to 310 to 320 to 321}
(a_1)	$a(v)$	{431 to 421 to 321 to 320}
	$a(vi)$	{320 to 321 to 421 to 431}
(a_2)	$a(vii)$	{421 to 321 to 320 to 310}
	$a(viii)$	{310 to 320 to 321 to 421}
(b)	$b(i)$	{421 to 420 to 410 to 310}
	$b(ii)$	{310 to 410 to 420 to 421}
(c_1)	$c(i)$	{431 to 421 to 420 to 320}
	$c(ii)$	{320 to 420 to 421 to 431}
(c_2)	$c(iii)$	{421 to 420 to 320 to 310}
	$c(iv)$	{310 to 320 to 420 to 421}
(d)	$d(i)$	{431 to 430 to 420 to 320}
	$d(ii)$	{320 to 420 to 430 to 431}

3.2. Synthesis of the reference vector

The best way to synthesize the voltage reference vector is by using the nearest three vectors (V_1, V_2 and V_3) and their duty cycles (d_1, d_2 and d_3) [2]:

$$V_{ref} = d_1 \cdot V_1 + d_2 \cdot V_2 + d_3 \cdot V_3 \quad (2)$$

With the additional constraint:

$$d_1 + d_2 + d_3 = T_e \quad (3)$$

For example, for triangles (b) and (d), there are two possible sequences. For triangles (a) and (c) the correct sequence can be identified from the possible alternatives by ensuring that no extra switching transitions occur when moving between triangles. For example, sequence c(iii) (or c(iv)) should be used when moving from triangle (b) to (c) since it begins with the same state as the sequence in (b), or sequence c(i) (or c(ii)) should be used when moving from triangle (c) to (d) since it begins with the same state as the sequence in (d). Applying this principle to triangle (a) means that sequences a(i) to a(iv) cannot be used because they will introduce extra switching transitions when moving into triangle (c).

Table 2 shows two seven-segment switching sequences for V_{ref} falling into region (a_2).

Table 2. Example of two switching sequences

Segments	Sequence 1	Sequence 2
1st	V_1[310]	V_1[421]
2nd	V_2[320]	V_3[321]
3rd	V_3[321]	V_2[320]
4th	V_1[421]	V_1[310]
5th	V_3[321]	V_2[320]
6th	V_2[320]	V_3[321]
7th	V_1[310]	V_1[421]

It is interesting to note that for sequence 1, the switching sequence of the three vectors, V_1, V_2 and V_3, in the first three segment rotates in a counter clockwise (CCW) direction in the space vector diagram shown in Figure 4, whereas for sequence 2, the switching sequence for these vectors rotating in a clockwise (CW) direction. Thees notations "+" and "-" indicate the direction of the switching sequence rotation.

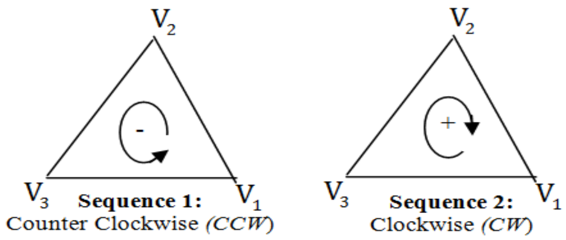


Figure 4. The switching sequence rotation directions in region (a_2)

While basing itself on the sequence 1, the switching sequence for all the triangular regions is shown in Figure 5.

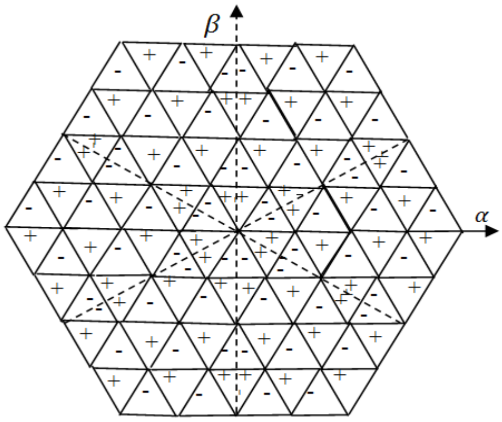


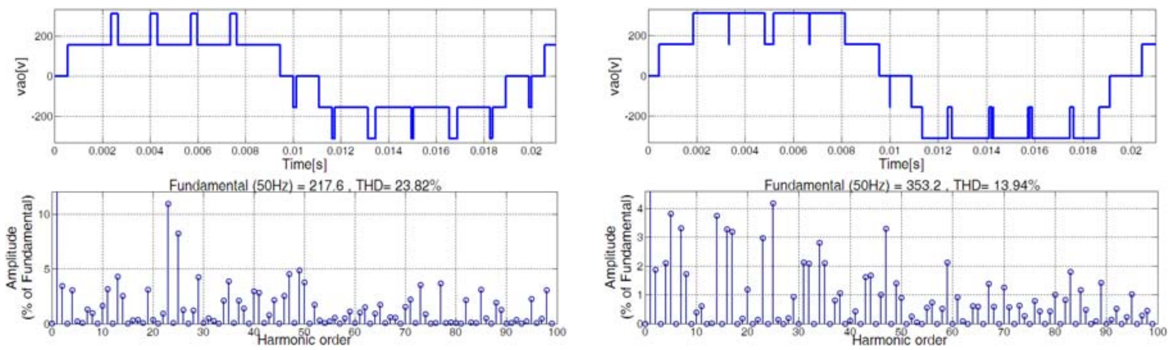
Figure 5. The switching sequence rotation directions for SVM based on sequence 1

By carrying out the first simulation for:

- ✓ Input voltage $U = 311Volt$;

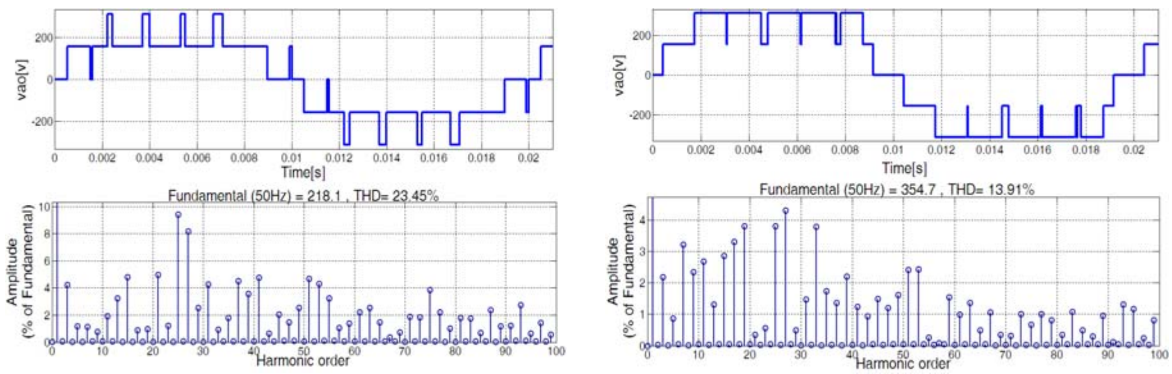
The modulation index $r = 0.7$ and $r = 1.15$ for sampling frequency $f_e = 600Hz(m = 12)$ and $f_e = 650Hz(m = 13)$.
with $m = {f_e}/{f_r}$; f_r: fundamental frequency=50Hz.

We obtain the results given in Figure 6. In the spectrum of output signal, the amplitude of fundamental is equal to 100%.



$f_e = 600Hz(m = 12)$ and $r = 0.7$ $f_e = 600Hz(m = 12)$ and $r = 1.15$

(a)



$f_e = 650Hz(m = 13)$ and $r = 0.7$ $f_e = 650Hz(m = 13)$ and $r = 1.15$

(b)

Figure 6. Waveforms produced by the SVM sequence

By analyzing the spectrum of the SVM signal on five levels, it is noted that it is made up, in addition to the fundamental one which is at the frequency f_r and whose peak value is equal to rU, components of harmonics gathered in families. However, the above discussed trajectory SVM produces even order harmonics for even values of m because of the no-symmetry of the output voltage.

To explain that, now consider the region (Figure 7) which is symmetrical by report to the origin with the area represented on Figure 3. When V_{ref} lies in regions (a_2) and (a_3) (which are 180° apart in space), the switching sequence and corresponding waveform of v_{ao} are shown in Figure 8.

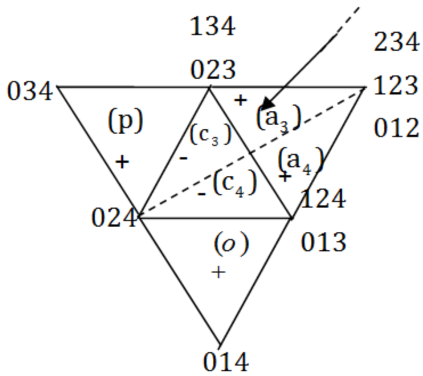


Figure 7. V_{ref} in region (a_3)

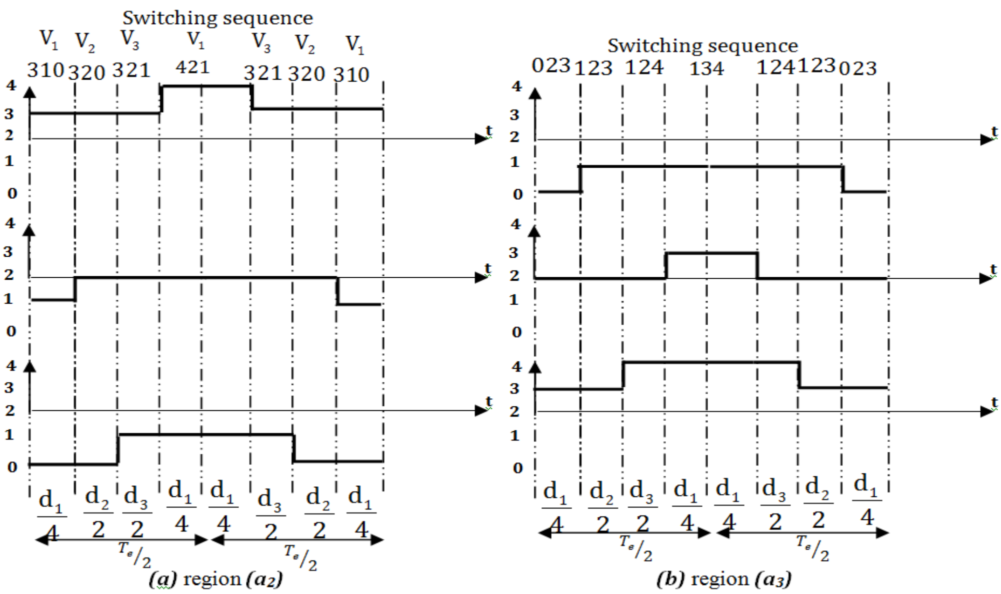


Figure 8. Switching sequence for V_{ref} in region (a_2) and (a_3)

To eliminate even order harmonics, the waveforms have to be of half-wave symmetry.

Obviously, the waveforms shown in Figure 8 do not meet this condition, which indicates that it contains even order harmonics. This phenomenon can be more clearly demonstrated in Figure 6(a), where the inverter phase voltage v_{ao} for one cycle of the fundamental frequency is shown. None of the waveforms is half-wave symmetrical.

4. EVEN ORDER HARMONIC ELIMINATION (SECOND TRAJECTORY)

As discussed earlier, waveform with half-wave symmetry does not contain any even order harmonics. To achieve this, the switching sequence should be arranged such that the inverter phase voltage generated by V_{ref} in any two regions symmetrical to the origin of the space vector diagram should have mirror image.

Consider two regions (a_2) and (a_3), which are symmetrical to the origin of the space diagram. To make the waveform of v_{ao} for V_{ref} in region (a_2) a mirror image of that for V_{ref} in region (a_3), the switching sequence of the three vectors, V_1, V_2 and V_3, should be changed from its original CCW to CW. The resultant waveform of v_{ao} is shown in Figure 9, which becomes a mirroreste image of that shown in Figure 8(b).

It is worth noting that although the waveforms of v_{ao} in Figure 9 and Figure 8(a) seems quite different.

Figure 10 shows a new switching sequence arrangement, where the switching sequences, in some areas, are modified for even order harmonic elimination.

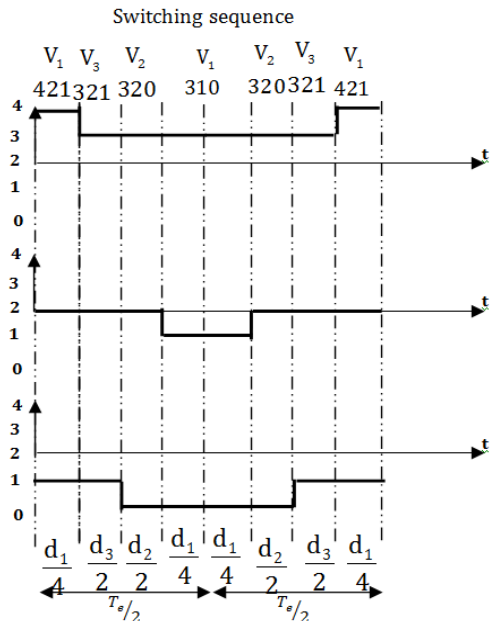


Figure 9. New switching sequence for V_{ref} in region (a_2)

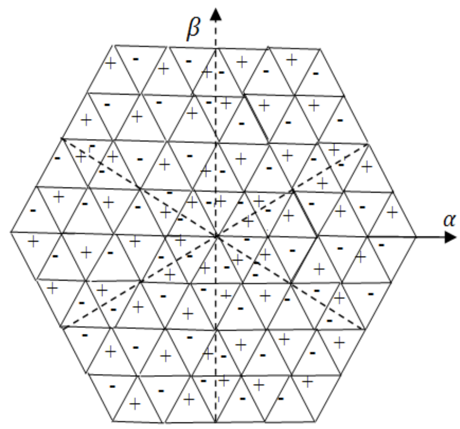


Figure 10. New switching sequence (second trajectory)

5. SIMULATION AND INTERPRETATION OF THE RESULTS

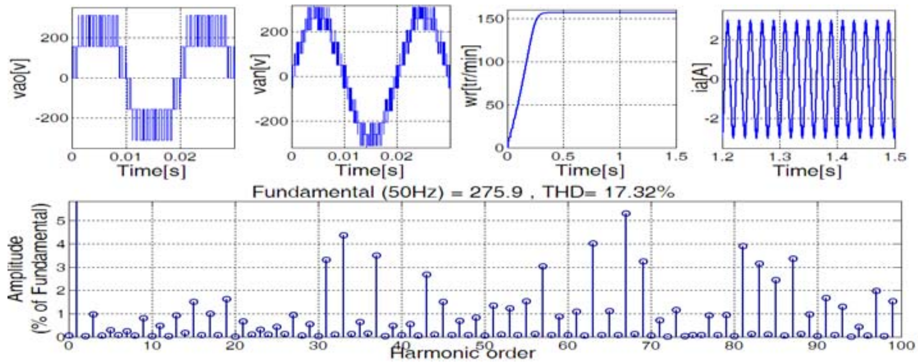
We made a simulation test for a five levels inverter supplying an asynchronous motor, for (r=0.9, m=25), then for (r=0.9, m=26). In the Figures 11 and 12, we have represented the output voltages v_{ao}, v_{an} and its spectral analysis, the current i_a and the speed.

The switch trigger signal K_{11} is plotted in Figure 13.

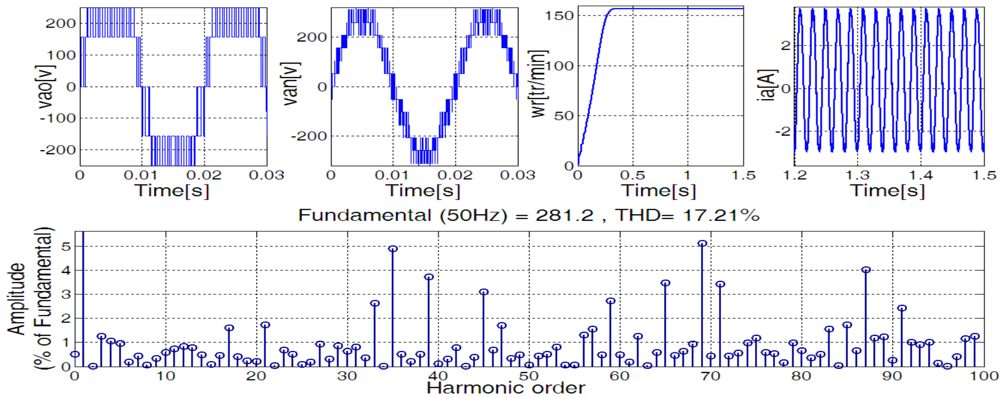
For the trajectory 1 (Figure 11), we note that there is no symmetry of simple voltage v_{ao} in half-wave for even values of m, thus, in addition to the odd harmonics, the voltage contains both even order harmonics. In addition, the harmonic spectre shows that all the even order harmonics are eliminated for odd m, and gather in family centered around the multiple frequencies of $m \cdot fr$.

For the trajectory 2 (Figure 12), we note that there is no symmetry of simple voltage v_{ao} in half-wave for odd values of m, thus, in addition to the odd harmonics, the voltage contains both even order harmonics. In addition, the harmonic spectre shows that all the even order harmonics are eliminated for even m, and gather in family centered around the multiple frequencies of $m \cdot fr$.

This is understandable since the switching pattern generation mechanism, including the selection of the stationary vectors and dwell time calculations, is the same for both trajectories. The only difference is that some of the switching sequences are rearranged for the new trajectory.

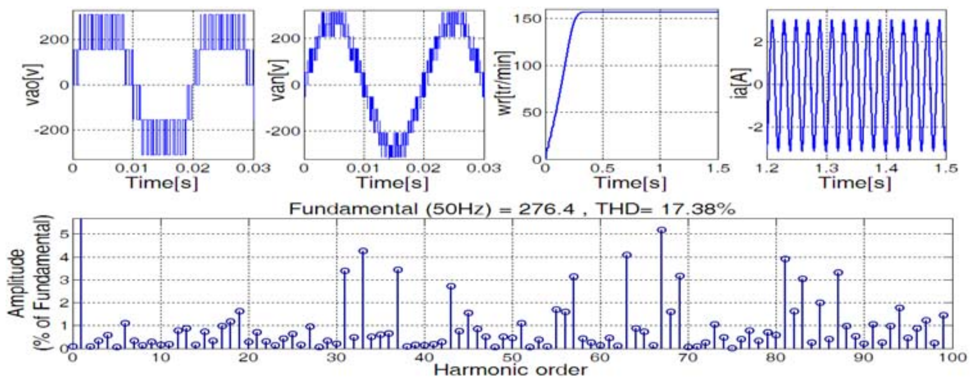


$f_e = 1250Hz(m = 25)\,, r = 0.9,\ THD_{current} = 2.51\%$

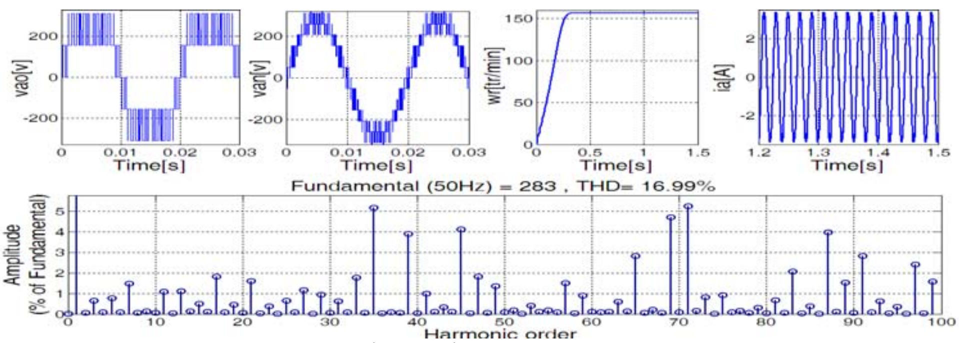


$f_e = 1300Hz(m = 26)\,, r = 0.9, THD_{current} = 2.99\%$

Figure 11. Simulation results on 5 levels inverter ordered by the SVM (trajectory 1)



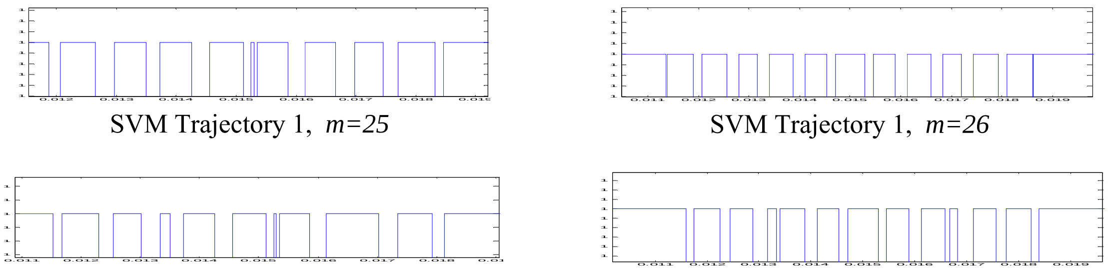
$f_e = 1250Hz(m = 25)\,, r = 0.9, THD_{current} = 2.72\%$



$f_e = 1300Hz(m = 26)\,, r = 0.9, THD_{current} = 2.29\%$

Figure 12. Simulation results on 5 levels inverter ordered by the SVM (trajectory 2)

It should be pointed out that the device switching frequency of the SVM trajectory 2 is slightly higher than that of the trajectory 1 for a given sampling frequency data corresponding to m odd. However, the device switching frequency of the SVM trajectory 1 is slightly higher than that of the trajectory 2 for a given sampling frequency data corresponding to even m (Figure 13).



SVM Trajectory 1, $m=25$ SVM Trajectory 1, $m=26$

SVM Trajectory 2, $m=25$ SVM Trajectory 2, $m=26$

Figure 13. Signals waveforms of the switch attack K_{11} for the inverter on five levels

6. CONCLUSION

Two space vector modulation trajectories are proposed for five levels cascaded inverters. The main feature lies in its ability to eliminate even order harmonics in the inverter output voltage of the modulation trajectory 1 for even m and of the modulation trajectory 2 for odd m.

Considering the similar form of the hexagonal structure of the SVM for the multilevel inverters, we thus can carry out an algorithm which uses either trajectory 1 or trajectory 2, according to the value of m, so as to obtain output signals which contain only odd harmonics, and this for any levels of voltage.

The advantage of the SVM technique is that all the even order harmonics can be eliminated. This is favorable in the industry applications.

REFERENCES

[1] S Chatterjee. A Multilevel Inverter Based on SVPWM Technique for Photovoltaic Application. *International Journal of Power Electronics and Drive System (IJPEDS)*. 201; 33(1): 62~73.

[2] M Yaichi. Analyse de la technique de modulation vectorielle SVM (Space Vector Modulation) appliquée aux onduleurs multiniveaux. Magister in electrical engineering. Djillali Liabes University of Sidi-Bel-Abbes, Algeria, 2006.

[3] N Celanovic. Space vector modulation and control of multilevel converters. Doctor of philosophy, Blacksburg, Virginia. 2000.

[4] J Pou, R Pindado, D Boroyevich, P Rodriguez, J Vicente. *Voltage-balancing strategies for diode-clamped multilevel converters.* Proceeding of the 35th Annual IEEE Power electronics specialists conference. 2004: 3988-3993.

[5] D Lalili. MLI Vectorielle et Commande Non Linéaire du Bus Continu des Onduleurs Multiniveaux.Application à la Conduite de la Machine Asynchrone. Doctor of Sciences in electrical engineering, Polytechnic national school, Algeria. 2009.

[6] Groupe schneider, Merlin gerin, medicon, sguare D. Telemecanique. Les techniques de commande du moteur asynchrone. *The Schneider magazine technological and professional teaching International*. 1998.

[7] MA Khan, A Iqbal, SM Ahmad, Z Husain. Analysis of Discontinuous Space Vector PWM Techniques for a Seven-Phase Voltage Source Inverter. *International Journal of Power Electronics and Drive System (IJPEDS)*. 2012; 2(2): 203~218.

[8] N Celanovic, D Boroyevich. A fast space-vector modulation algorithm for multilevel three-phase converters. *IEEE transaction on industry application*. 2001; 37(2): 637-641.

[9] N Celanovic, D Boroyevich. A comprehensive study of neutral-point voltage balancing problem in three-level neutral-point-clamped voltage source PWM inverter. *IEEE Transactions on power electronics.* 2000; 15(2): 242-249.

[10] PC Loh, DG Holmes. A new flux modulation technique for multilevel inverter. *IEEE Transactions on industry application.* 2002; 38(5): 1389-1399.

[11] BP Mcgrath, DG Holmes, TA Lipo. Optimised space vector switching sequences for multilevel inverter. *IEEE Transactions on power electronics*. 2003; 18(6): 1293-1301.

[12] DW Feng, B Wu, S Wei, D Xu. *Space vector modulation for neutral point clamped multilevel inverter with even order harmonic elimination.* Proceeding of the CCECE 2004-CCGEI 2004, Niagara Falls. 2004; 1471-1475.

[13] T Georgios, A Georgios. A multi-function grid connected PV system with three level NPC inverter and voltage oriented control. *Solar Energy*. 2011; 85(11): 2595-2610.

BIOGRAPHIES OF AUTHORS

Mohammed Yaichi was born on 1980 in Adrar, Algeria. He received the engineer degree in electrical engineering from the the University of Bechar, Bechar, Algeria, in 2003. And the magister degree from Djillali Liabes University, Sidi-Bel-Abbes, Algeria in 2006. He is currently working toward the doctorate degree in the Power Electronics, and the Photovoltaic Pumping System, Djillali Liabes University of Sidi-Bel-Abbes, Algeria. Since 2009, he is with the Photovoltaic Pumping Team, Research Unit in Renewable Energies in The Saharan Medium (URER/MS) Adrar, Algeria. His research interests include a study on performance improvement of a stand-alone photovoltaic pumping systeme, variable-speed AC motor drives, and different multilevel inverter circuit topologies thus its technique of control PWM.

Mohammed-Karim Fellah was born in Oran, Algeria, in 1963. He received the Eng. degree in Electrical Engineering from University of Sciences and Technology, Oran, Algeria, in 1986, and The Ph.D. degree from National Polytechnic Institute of Lorraine (Nancy, France) in 1991. Since 1992, he is Professor at the University of Sidi Bel-Abbes (Algeria) and Member of the Intelligent Control and Electrical Power. His current research interest includes Power Electronics, HVDC links, and Drives.