Implementation of Space Vector Modulation Using DSP

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Abstract— **The progress of microelectronics allows the implementation of complex control algorithms while using embedded platforms such as FPGA cards and DSP cards. In this paper, we proposed to implement on a DSP digital control algorithms onboard a three-phase inverter voltage applications for variable speed electrical machines. This command is based on the use of the principle of Space Vector modulation technique PWM. The control platform is based on the DSP TMS320F240 from Texas Instruments Code Composer and Software. As further work, we developed the real time implementation of a Space Vector pulse Width Modulation (SVPWM) technique.**

Keywords—Digital Signal Processor (DSP); Space Vector Pulse Width modulation (SVPWM); Total harmonic distortion (THD)

I. INTRODUCTION

Pulse width modulation (PWM) has been extensively studied in recent decades. The modulation control pulse width is to chop the switching of the switches thereby generating pulses of different widths. In other words, we would control signals chopped and formed by pulses whose width can be varied according to the desired output voltage. Was used when the PWM to improve the signals delivered by the inverter providing AC voltage sine we would like to use to supply fixed or variable frequency loads. The PWM control is therefore to adopt a modulation frequency much higher than the frequency of the output and to form each half of an output voltage of a series pulses with a varying widths.

The principle of the PWM control inverter is applied to an open and then close the switches in order to modulate the pulse width of the switching so that the output voltage satisfies one or more criteria.

Many different methods have been developed for PWM achieve the following objectives:

Wide range of linear modulation, less switching losses, less total harmonic distortion (THD) in the spectrum of switching waveform and the implementation easier and less computation time, [1].

With the development of microprocessors, space vector modulation has become one of the most important methods for three-phase PWM converters, [2]. It uses the concept of space vector to calculate the duty cycle of the switches. It is simply implementing digital PWM modulators. Amplitude to the easy implementation digital modulation and wide range of linear output line to line voltages are the notable features of space vector modulation.

The full report of two PWM methods provides a platform not only transform from one to another, but also to develop different performance PWM modulators, [1].

In this context, we propose to implement a Space Vector Modulation technique SVPWM on a DSP to control the frequency and voltage of the converter. Structure nearest inverter topology is the two levels. We are particularly interested in this part of the general structure of the inverter that has flexibility and develop the use of a control system on board of the converter provides a platform control more robust.

Space Vector Modulation (SVPWM) technique is probably best suited to the PWM control of induction motors. For this reason, we will adopt later in this paper. In Section I we will explain the control vector PWM by introducing the three-phase inverter and its structure. In Section II, we will implement using the C language software pro DMC develop the algorithm of vector modulation (SPWM), the DSP TMS320F240 based on a digital signal processor DSP dedicated for the control of a three-phase voltage converter. Then in Section III, we will validate the developed programs (C language and assembler) on a test bench consists of a three-phase inverter voltage three-phase asynchronous machine and a set of cards dedicated to acquisition and signal conditioning. And some experimental results have been introduced to validate the work developed.

II. PRINCIPE OF SVPWM

The Space Vectors are used to control the motor frequency and its amplitude of voltage and current applied. Consequently, the PWM inverter has the highest efficiency and highest performance compared to the set frequency. The voltage which supplies an inverter to a motor is controlled by the PWM signals applied to the gates of the power transistors, as shown in Fig. 1. SVPWM is a very efficient method to generate the six pulsed signals for the inverter stage of the motor drive. SVPWM evaluates the switching system as whole results in better utilization of the DC bus and generates much less harmonic distortion the sine triangle method, [3].

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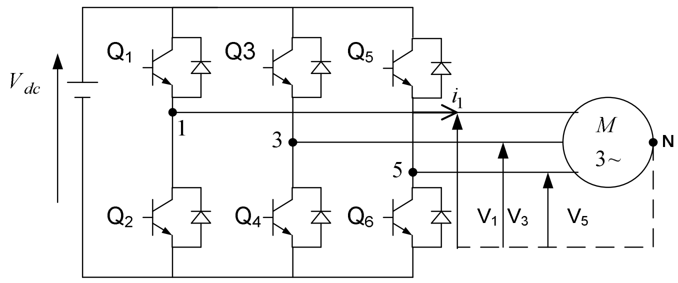

Fig. 1. Schematic diagram of the inverter

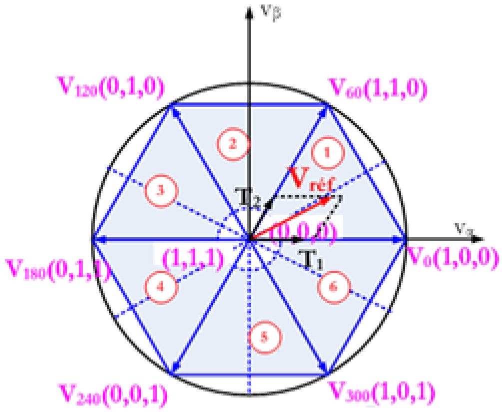

Fig. 2. Voltage vectors and Six sectors in the (α, β) reference frame

Figure. 2 presents the unit circle formed by six voltage sectors representing the evolution of the voltage vector in the (α, β) reference frame. The study of the regulation and control of the electrical machines supplied via a power electronics device for the speed and torque control needs a programming algorithms for the modulation technique. The objective of the modulation technique is to determine the moments of communication and the control commands logical of the switching in order to obtain a sequence of communications of the latter. The choice of a modulation technique can be carried to the performances desired by the user.

All the strategies have advantages and disadvantages and can be achieved by programming software or hardware, as our case we worked with the TMS320F240 DSP card with software DEVELOP PRO DMC. It should however be noted that the modulation stage shouldn't be confused with the actual control algorithm of the machine.

The Space Vector diagram is considered to be formed of six small two-level hexagons, each of them centered in one vector of the small vectors V_0, V_{60},... V_{300}, as shown in Fig. 2. The technique corrects the reference voltage vector by subtracting the center vector of the corresponding small hexagon from the original reference vector. The concept "distribution ratio" that defines the split and distribution of the duration of the zero space vectors inside the modulation interval in two-level inverters was adapted in references [4], [5].

III. Implementing Space vector PWM With the DSP TMSF230F240

The most accurate technique for obtaining an adequate voltage vector for variable speed applications of AC machines is the space vector approach, [7], [8]. The Space Vector voltage approach is a two-components-based complex variable whose magnitude and angle are varied in time according to a desirable operating point; the stator flux magnitude and the machine speed for example. For a three phase voltage inverter, the output voltage is strictly defined by the DC bus voltage (V_{dc}) supplying the inverter and the logical state of the three highest IGBT's (Q_1, Q_3, Q_5) in its configuration. There are only eight possible different logical combinations of (Q_1, Q_3, Q_5) leading to six active vector voltages and two zero voltage (V_{000} and V_{111}). It is well known that for a specified switching combination of (Q_1, Q_3, Q_5), the space vector of the inverter output voltage can be expressed as follows, [6].

$$\begin{cases} V_x = V_{\max} e^{i.\theta_{Vx}} \\ V_{\max} = \sqrt{\frac{2}{3}} V_{dc} \\ \theta_{Vx} = x(°) \\ x = 0, 60, 120, 180, 240, 300 \end{cases} \tag{1}$$

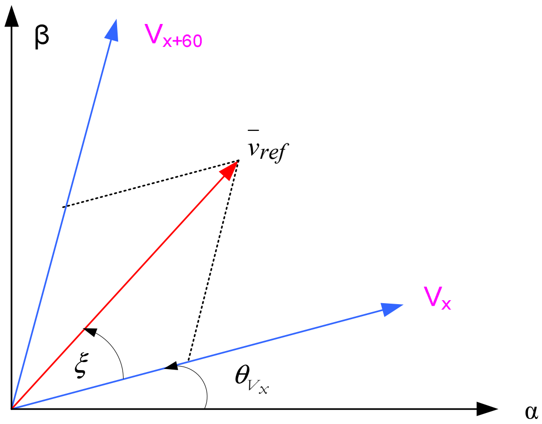

Fig. 3. Sspace Vector Voltage and its components in the (α,β) reference frame

The output voltages of the inverter can be calculated by equation (2).

$$\begin{bmatrix} V_1 \\ V_3 \\ V_5 \end{bmatrix} = \frac{V_{dc}}{3} . \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} . \begin{bmatrix} Q_1 \\ Q_3 \\ Q_5 \end{bmatrix} \tag{2}$$

A. *Configuration of hardware part of PWM*

Ended the sampling SPWM period T_{PWM} the hardware module performs the following steps:

- At the beginning of each switching period, put the code for the new states defined the register ACTR [14-13-12] bits.
- In the first comparison (CMPR1) during the counting up and during the counting between CMPR1 and T1PER at the moment ($\frac{T_1}{2}$), switch the outputs vector PWM by V_1 if ACTR [15] is 1 or V_3 if ACTR [15] is 0.

In our implementation we chose the second case, the appropriate rotation in the clock wise.

- In second comparison (CMPR2) during the counting up and during the counting between CMPR2 and T1PER at the moment ($\frac{T_1+T_2}{2}$), switch the state PWM signals to (000) or (111), in accordance with the concept of a single bit change.
- During the descent and during the counting between T1PER and CMPR2 in first compare match (CMPR2), switch PWM outputs signals to the second voltage vector previously indicated (V_{x+60}).
- During the descent (in the second compares match) during the counting between T1PER and CMPR1, switch PWM output signals to the first voltage vector previously indicated (V_x).

The principle is shown schematically in Fig. 4.

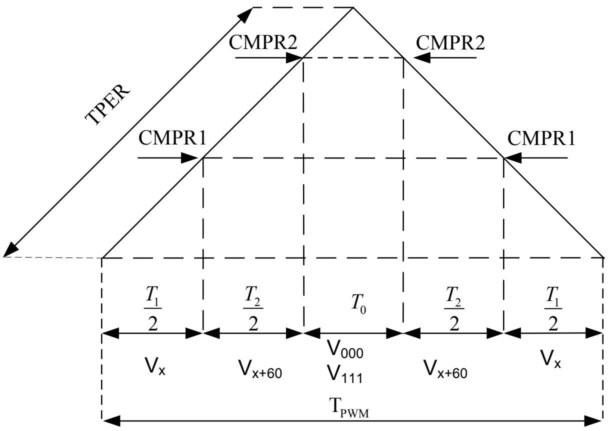

Fig. 4. Generation Scenario of SVPWM signals

The expressions of the switching time switches are given by the equation 3.

$$
\begin{cases}
\mathrm{T}_1 = \frac{2}{\sqrt{3}}.\rho.T_{PWM}.\sin(\frac{\pi}{3}\text{-}\xi) \\
\mathrm{T}_2 = \frac{2}{\sqrt{3}}.\rho.T_{PWM}\sin(\xi) \\
\xi \in \left[0 \quad 60°\right] \\
\rho \in \left[0 \quad \frac{\sqrt{3}}{2}\right]
\end{cases}
\tag{3}
$$

B. Determination of the PWM period (T1PER)

The triangular signal must have a period corresponding to half T1PER the true sampling period TPWM. T1PER value must be an integer corresponding to the ratio of $\frac{T_{PWMP}}{2}$ by the time unit of the clock consider. As an example, if 2000 is T1PER a chopping frequency of 20 kHz and a programmed clock scale 1/1; must 50ns. In such a case one can ask:
The PWM period is loaded into a register called T1PER. By convention PWM_Period = 2 * T1PER.

Expression of T1PER is given by the following relationship:

$$T1PER = \frac{\mathrm{PWM\_Period}}{2\mathrm{T}_{\mathrm{CPU}}} \tag{4}$$

If we take our case, the PWM frequency is 5 kHz, the numerical value of T1PER is:

$$T1PER = \frac{1}{2{*}5000{*}(50{*}10^{-9})} = 2000 \tag{5}$$

These mean voltages are the result of a scenario called Full Compare permanently located on the DSP. The scenario consists in comparing a triangular signal regime up/down continuous two values CMPR1 and CMPR2 defined from T1 and T2:

$$
\begin{cases}
CPMR1 = \frac{2}{\sqrt{3}}.\rho.T1PER.\sin(\frac{\pi}{3}\text{-}\xi) \\
\mathrm{CPMR2} = CPMR1 + \frac{2}{\sqrt{3}}.\rho.T1PER.\sin(\xi)
\end{cases}
\tag{6}
$$

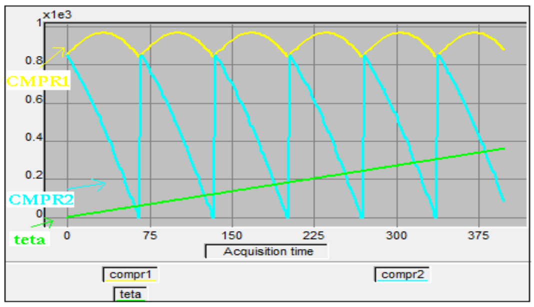

Fig. 5. Evolution of the comparators CMPR1, CMPR2 and angle position of the reference voltage in SVPWM.

Figure 5 shows the results of the comparators 1 and 2 (and CMPR1 CMPR2).

C. Switching model HARDWARE Implemented

With DSP we programmed with software MCWIN32 the DSP algorithm of 2nd sector of the voltage inverter model implemented by the hardware module SVPWM. We unscrewed the unit circle into six sectors. Was used which determines the category table according to the angle. The validation is shown in Fig. 6.

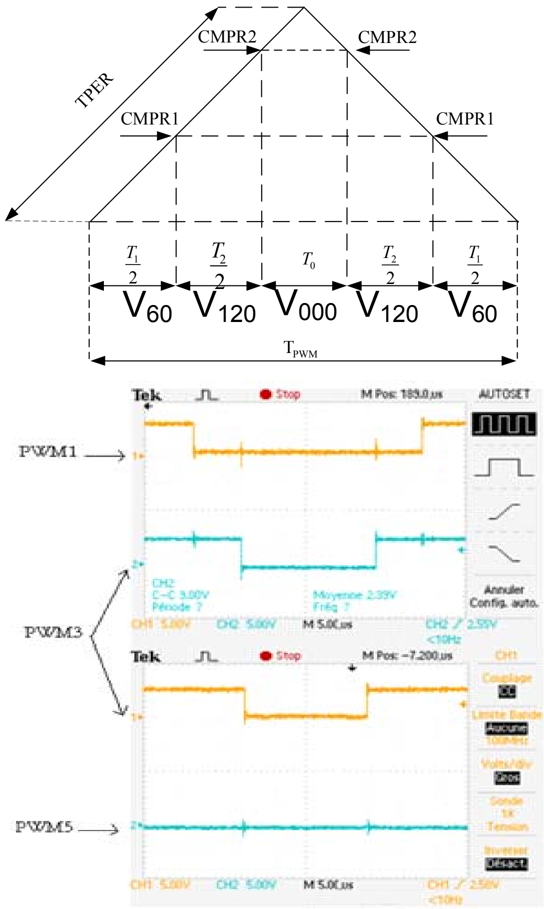

Fig. 6. The Switching Patterns on sector 2

$$\begin{cases} PWM1 \Rightarrow Q_1 \\ PWM3 \Rightarrow Q_3 \\ PWM5 \Rightarrow Q_5 \end{cases} \tag{7}$$

D. *Different strategies for PWM control*

There are several pulse width modulation techniques:

- Full wave modulation.
- Harmonic elimination method
- Space Vector modulation

These methods are different from the point of view of principle, purpose and implementation. There are those which deliver each control signal separately and which provides control of all the switches, there are those that are implemented with analog electronics and those that are implemented digitally, each tend to satisfy a specific criterion.

1) *Full wave modulation.*

The principle of this strategy is to control the arm of the inverter all the third period.

2) *Harmonic elimination method*

In some applications, is calculated beforehand on the basis of an optimization criterion, the control times. Modulation is calculated to determine the switching angles using the following criteria:

- The number of harmonics to be eliminated.
- The efficacious value of fundamental of the output voltage of the inverter.

Instead of determining the switching angles in real time, can be calculated previously the control sequences, the storing and controlling the semiconductor of the inverter from the stored sequences.

Determining angles corresponding to the sequences may be used to the same laws as used for the real-time control. The performances obtained with them are indeed far from being bad. But, since the angles are subject to a prior determination, we can adopt other laws:

- During early development of the PWM control, it was attached to discard the first harmonic of the output voltage.
- Now we take into account the nature of the ordinary filter is to minimize the weighted total harmonic distortion

By applying Fourier series analysis, the output voltage can be expressed as:

$$V(t) = \sum_{n=1,3,5}^{\infty} \frac{4}{n.\pi}[V_1\cos(n\theta_1) \pm V_2\cos(n\theta_2) \pm ... \pm V_n\cos(n\theta_C)]\sin(n\omega t) \tag{8}$$

With V_1, V_2 ... V_C the harmonic pick voltages; c is the number of switching cycles of the angles, [9].

In this expression, the positive sign implies the rising edge and the negative sign implies the edge. The solution must satisfy the condition

$$0 \le \theta_1 \le \theta_2 ... \le \theta_C \le \frac{\pi}{2} \tag{9}$$

The line to line voltage V_{13} for example, can be decomposed using the Fourier series expansion as :

$$V_{13} = \frac{\pi}{4_f} V_{dc}.(b_1\sin(\omega t)) + b_5\sin(5\omega t) + b_7\sin(7\omega t)) \tag{11}$$

So if we want to have an effective value of the fundamental equal to V ' and we want to eliminate harmonics we solve the following system:

$$\begin{cases} \frac{2\sqrt{2}}{\pi}.V_{dc} + b_1 = V' \\ b_5 = 0 \\ b_7 = 0 \\ b_{11} = 0 \end{cases} \tag{12}$$

3) *Pulse Width Modulation PWM Strategy*

The principle of this strategy is to control the switching pattern of the inverter in a decision delivered by an algorithm at the beginning of each sampling period.

IV. Experimental Results

In order to verify the feasibility and performance of the SVPWM converter, a laboratory is built and tested. The circuit parameters and components used of the converter are listed as flowing:

• The control signals generated were applied to an inverter. This inverter use a three-phase inverter type SEMIKRON 20 kVA. It essentially comprises:

• Three power modules (bridge arm: SKM50GB123D) each consisting of two switches IGBT 50A rated current.

• Six-phase rectifier diodes SKD51 PD3. This rectifier is compatible with the three-phase sources of 380 V line to line voltages.

Figure 14 shows a photo of the experimental bunch.

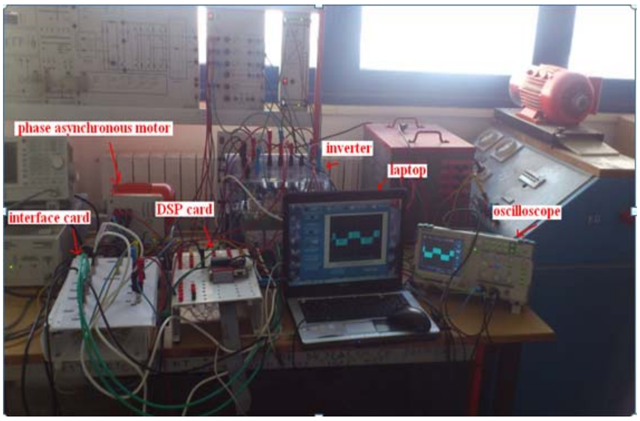

Fig. 7. Photo of the experimental bunch

A) Full wave modulation.

Figure.7 presents the experimental results of Full wave modulation.

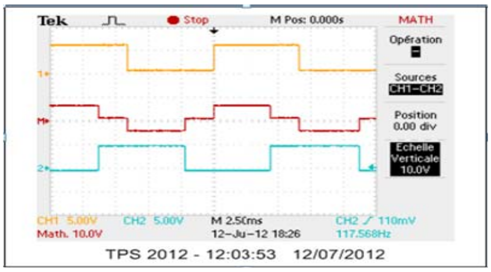

Fig. 8. The Switching Patterns of Full wave modulation.

B) Harmonic elimination method

Figure. 8 presents the experimental results of Harmonic elimination method.

If we take $\theta_1 = 9.8$ °, $\theta_2 = 15.1$ °, $\theta_3 = 85.2$ °, $\theta_4 = 86.4$ ° we obtain the following Fig.8.

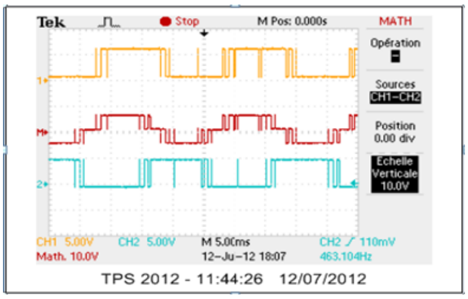

Fig. 9. The Switching Patterns of Harmonic elimination method

C) Space Vector Pulse width modulation SVPWM strategy

The control patterns of the switches (Q_1, Q_3) implemented on the DSP card F240 are given in Fig. 9.

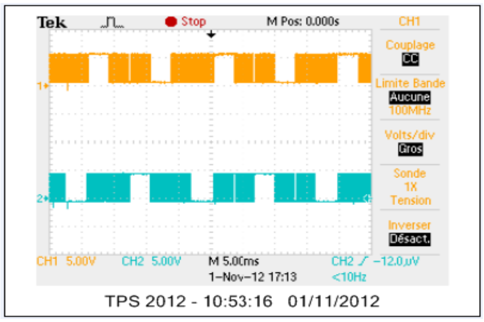

Fig. 10. Switch control patterns of Q1 & Q3 with the DSP card F240

Figure. 10 shows the control patterns of the inverter and the line voltage obtained using the SVPWM control implemented on the DSP board.

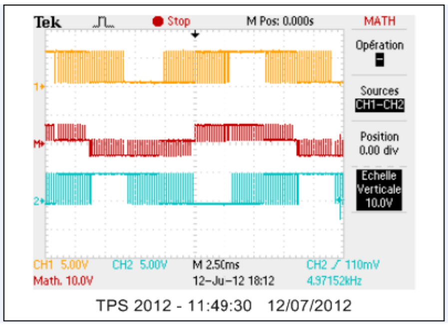

Fig. 11. *Switching Patterns*

The practical validation is very important to the implementation of the PWM vector control. The Fig. 11, represents the real magnitudes at the output of the inverter for the modulation ratio $\rho = 0.5$.

Waveforms and control signals are presented in Fig. 11.

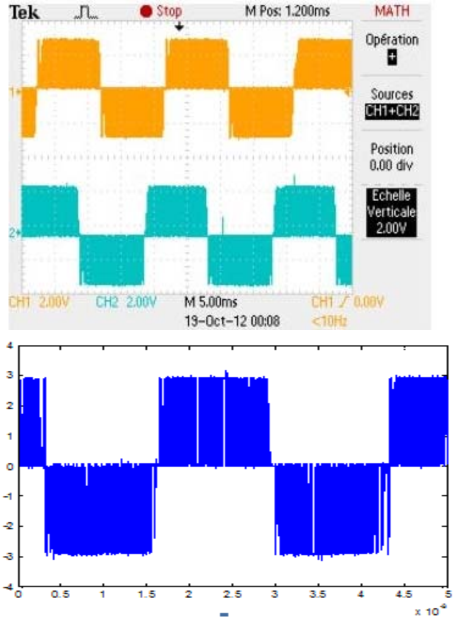

Fig. 12. *Switching Patterns* between two phases

To validate the theoretical approach presented in the previous section, we noted some output signals of the inverter and the control signals of the DSP. The practical realization has been the subject of an implementation of a routine vector control on a map DSP digital processing. The control law consists in varying the frequency of the motor supply voltages. Figure 12 show the pattern of the switching signals of the line to line voltages.

A low pass filter was used to show the fundamental line to line voltage in Fig. 13. It was the same signal as Fig. 12 that we have filtered by a low pass filter. The sinusoidal shape is clearly present.

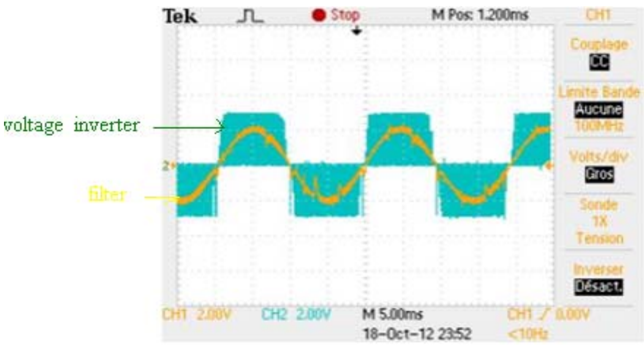

Fig. 13. Experimental recording of line to line inverter voltage and filtered signal

Figure. 14 shows the PWM outputs of model Hardware-implementation SV PWM waveform pattern after the carrier is taken with a low-pass filter. The first and third waveforms are two of the three PWM outputs. The waveform in the middle is the difference between the two PWM outputs, which has a sinusoidal shape, representing the line-to-line inverter voltage output.

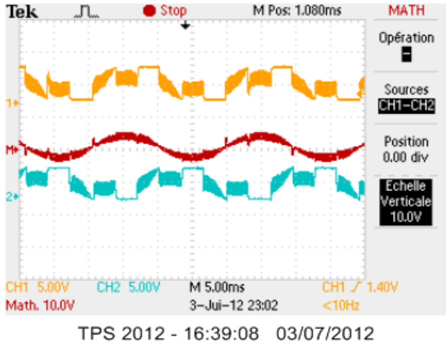

Fig. 14. SV PWM Outputs With Carrier Filtered Out

D) Validation of Space Vector Pulse width modulation SVPWM

In Sinusoidal PWM three phase reference modulating signals are compared against a common triangular carrier to generate the PWM signals for the three phases.

Figure 15 the result of experience of signal line to line voltage applied to the motor.

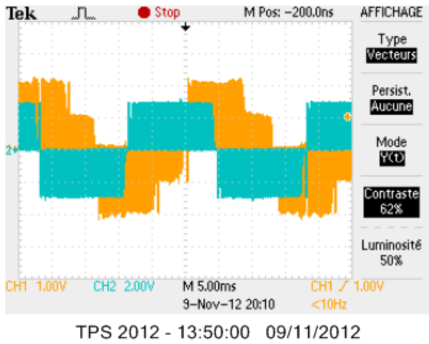

Fig. 15. Simple voltage and line to line voltage output of the inverter

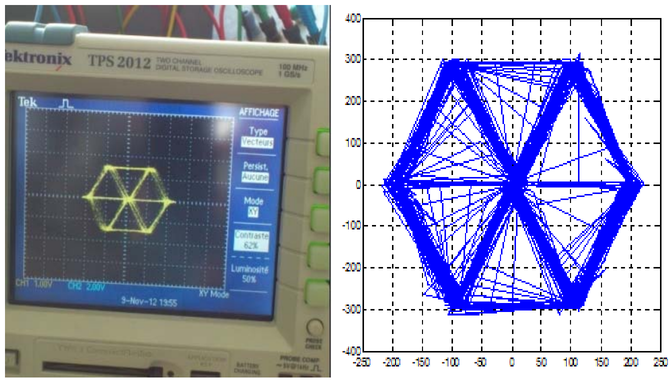

Fig. 16. The Space vector of the ouptut voltages

The simulation of the three-phase inverter SVPWM strategy gives us the final result as the vector space diagram. The latter is considered to consist of six non-zero vectors and two zero vectors are possible. Six non-zero vectors (V0 to V300) shape the axes of a hexagonal as depicted in Fig.16, and supplies power to the load. The angle between any adjacent two non-zero vectors is 60 degrees. Meanwhile, two zero vectors (V000 and V111) and are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by (V0, V60... V300).

V. CONCLUSION

The Space vector Modulation Technique has become the most popular and important PWM technique for Three Phase Voltage Source Inverters. In this paper we have implemented a PWM control in general and specially using space vector SVPWM. This work has enabled us to use the family of signal processors DSP TMS320F240 including their advanced programming based primarily on their configuration registers like Timer, Comparator... Several programming languages may DSP beings considered like language C++, assembler. On the other hand, this work wills subsequently the implementation of advanced control technique for the variable speed and torque of electrical machines. The experimental validation is done using power converter to control the induction motor speed and torque.

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