AN IMPROVED SPACE VECTOR MODULATOR MODEL FOR HIGH PERFORMANCE AC DRIVES

Abdallah Saadoun Ali Yousfi Yacine Amirat
e-mail: saadoun_a@yahoo.fr e-mail: a_yousfi@yahoo.fr e-mail : y_amirat@yahoo.fr
Annaba University, Faculty of Engineering, Department of Machines & Electrical Drives, 23000, Annaba, Algeria

Key words: sv pwm modelling, vsi inverter, pmsm, foc

ABSTRACT

The present work is concerned with the development of a Matlab/Simulink model of a SV PWM VSI which can be switched from a switched mode inverter to a nearly perfect sine wave space vector controlled generator in the course of the simulation process. The proposed model is characterised by its ability to ride through external disturbances owing to the stiffness of the inverter formulation. The theoretical principles underlying the space vector modulation technique are presented but have been confined to the few relations needed for the model implementation. The reliability of the proposed models has been checked against the experimental results available in the literature provided by the major electronic manufacturers [1, 2, 3, 4]. To check further its performance, the new model has been used to build up a field oriented control drive around the permanent magnet synchronous motor, described in the Simulink demonstration [5].

.

I. INTRODUCTION

Speed control of ac motor, which requires concomitant variation of the frequency and stator voltage to keep the air gap flux to its rated value, was mainly implemented by PWM controlled inverters. In the last two decades, a more flexible power dc to ac power conditioning technique, space vector PWM [5,6], has became increasingly popular in high performance ac servo drives applications. Unlike conventional PWM control strategies, where the determination of the switching pattern of the inverter power switches is in essence an analog signal processing problem, SV PMW, in contrast, deals with the three phase inverter as a unique space vector using the Clark's Transformation. More importantly, because of the placement of the target voltage space vector, representing the desired inverter output voltage, is an anticipative process, this technique is easily implemented using dedicated microcontrollers and DSP processors [1, 2, 3]. Because of the availability of dedicated timers for sv pwm pulse pattern generation, within most of present DSPs, and software routines for implementing reference frame transformations, field oriented control of ac drives can be directly formulated in terms of space vector theory [7]. Performance assessment of sv pwm control strategies through theoretical investigation and modelling is another present field of interest [8,4]. Although several models have been reported in different publications, they are either formulated in terms of S_function, state variable model or given as SUMILINK black boxes. Model implementation using S_function requires not only thorough understanding of Simulink but also programming skills when it comes to use various specific macros needed by this task; state variable modelling [8], besides the inevitable mathematic formulation of the model, does neither gives the physical understanding of the model nor provides the flexibility for parameter variation for performance analysis. In either case, the intrinsic graphical programming facility of Simulink is not used. This paper proposes a new space vector pwm Simulink modulator which emulates DSP implementation of a space vector modulator.

II. SPACE VECTOR CONTROL STRATEGY

In a 180° square wave VSI inverter, the three phase output voltages are synthesised according to a predetermined switching pattern of the semiconductor switches. Within one sixth of a period the output voltage is constant because the conduction times of any semiconductor switch is held constant over 180° electrical degrees. By shifting the gating signals from each other by 60°, the resulting output phase voltage is a six steps approximation of a sinusoidal wave. These discrete operating states of the inverter can be described by a space vector

$$\bar{v}_k = \begin{cases} \frac{2}{3} V_d e^{j(k-1)\frac{\pi}{3}} & for\ k = 1 \div 6 \\ 0 & for\ k = 7,8 \end{cases} \quad (1)$$

which represents the stator phase voltages and two additional null vectors mapped into the origin of the stationary reference frame $\alpha\beta$. In contrast, the space vector PWM control strategy consists of elaborating a switching pattern of the power semiconductor switches, within a sector, by varying the conduction time of the semiconductor switches in order to impose a discrete sinusoidal variation of the output phase voltage between two consecutive states of the six step inverter. By switching at high frequency the power switches according to a predetermined pattern the tip of the reference space vector, which represents the desired approximation of the output voltage, is forced to follow a smooth circular path. This objective is met by building the target reference space vector from the time weighted combination of two adjacent sampled vectors. In terms of volt-second, the averaging process within a sampling period is

$$\frac{1}{T}\int_0^T \vec{V}^* dt = \frac{1}{T}\int_0^{t_1} \vec{V}_1 dt + \frac{1}{T}\int_0^{t_2} \vec{V}_2 dt \qquad (2)$$

Hence

$$\overrightarrow{V^*} = \frac{t_1}{T}\vec{V}_1 + \frac{t_2}{T}\vec{V}_2 \qquad (3)$$

where t_1 and t_2, for instance, are the time to be spent in the active states 100 and 110.

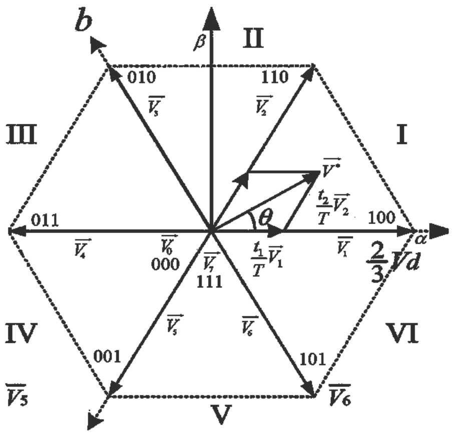

Figure 1: Inverter operating states

According to figure 1, which shows the reference vector $\overrightarrow{V^*}$ for a particular angular position θ, into the stationary stator reference frame $\alpha\beta$

$$t_1 V_m e^{i0} + t_1 V_m e^{i\frac{\pi}{3}} = T V^* e^{i\theta} \qquad (4)$$

The active state durations are finally found from the previous relation as

$$\frac{t_1}{T} = m\frac{sin(60^\circ - \theta)}{sin 60^\circ} \quad \frac{t_2}{T} = m\frac{sin\theta}{sin 60^\circ} \qquad (5)$$

where $m = \frac{V^*}{V_m}$ is the modulation index. Although infinite vector samples can be obtained within a sector, their components are always linearly dependent on the base vectors delimiting a given sector. For that reason, only two adjacent switching states say (100 and 110) are required to synthesise the current reference vector. To reduce the switching frequency of the inverter, the next position of the space vector is obtained by changing the conducting state of only one single power switch. A transition is made by including a null state between every two target vectors. The duration of the null vector is the remaining time from the switching period

$$t_0 = t_7 = \frac{t_Z}{2} = \frac{T - (t_1 + t_2)}{2} \qquad (6)$$

Therefore a switching sequence includes always a starting null vector, the required switching pattern, finally ending by a null vector; the reverse sequence is then applied for the next sampling period. If the time application of the null vector is divided equally [2] a symmetrical space vector modulation is obtained. The maximum output phase voltage is obtained when the reference space vector lies in the middle of the first sextant. In that case

$$\overrightarrow{V_{max}^*} = \frac{1}{2}\vec{V}_1 + \frac{1}{2}\vec{V}_2 = \frac{t_1}{T}\vec{V}_1 + \frac{t_2}{T}\vec{V}_2 \qquad (7)$$

therefore $t_0 = 0$, no time is then available for a null vector insertion to enable smooth transition between two consecutive target vectors. Over-modulation, is reached for

$$V^* > V^*_{max} = V_m \cos\frac{\pi}{6} = \frac{\sqrt{3}}{3}V \qquad (8)$$

i.e. for $m > 0.866$, is used in some applications to boost of the inverter output voltage. Although two different over-modulation modes are available, only mode I, suitable for Simulink implementation, has been used, the active switching durations of which are calculated according to

$$\frac{t_1}{T} = \frac{\sqrt{3}\cos\theta - \sin\theta}{\sqrt{3}\cos\theta + \sin\theta},\ t_2 = T - t_1, t_0 = 0 \qquad (9)$$

III. SIMULINK MODEL OF THE SV PWM VSI

By comparison to the space vector modulator proposed by MathWorks [4], which is made up from seven blocks, the present model includes only four blocks, namely:

ACTIVE STATE COMPUTATION BLOCK

In ac drives, the control effort signal of the inner current loop represents the reference voltage, whereas in an open loop configuration this signal

$$v^* = v_\alpha + j\,v_\beta\,,\; v^* = V^* e^{i\theta} \qquad (10)$$

is derived from the Clark's transformation of the desired three phase output voltage. The simulation of the on time duration is carried out, according to relations 5 and 6, by sampling, at fixed frequency the reference space vector. Since the time duration values remain the same within an interval of 60°, a modulus block is used to divide, a time period of v^*, into six intervals. Figure 2 shows some features of this block. Depending on the sign of t_Z, the linear or over modulation mode is selected; through a selector bloc, the resulting output is fed to the next block, the task of which is to compute the duty time cycle of each inverter leg.

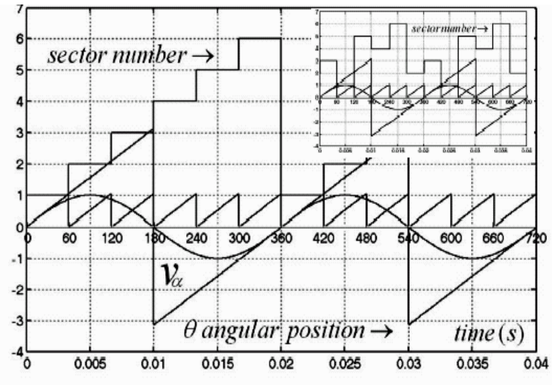

Figure 2 : Sector number deternimation

DUTY CYCLE COMPUTATION BLOCK

Its purpose is to assign the on duty time duty cycles Ta_{on}, Tb_{on} and Tc_{on} to the right inverter leg; such a task requires the knowledge of the sector number in which the reference vector is currently lying. Two techniques have been used to simulate the sector number as a sub block. The first, used with DSP [2], is not suitable for Simulink programming as it can be seen from the figure shown in the top right corner of figure 2. The second relies on the sampled magnitude and position of the reference vector, carried out in the previous block, to retrieve the sector number stored in a two dimensional look up table. For instance, in the first sector the on duty time cycles Ta_{on}, Tb_{on} and Tc_{on} are related to the inverter the active state duration through the matrix formulation

$$\begin{bmatrix} Ta_{on} \\ Tb_{on} \\ Tb_{on} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ \dfrac{t_z}{2} \end{bmatrix} \qquad (11)$$

The element of the matrix can be found from the required gating signal [2], applied to the upper power switches of the six steps inverter. To each sector corresponds a well defined matrix [2]. In the simulation, the on time duty cycle are normalised with respect to the sampling period of the reference space vector.

POWER OUTPUT STAGE BLOCK

The final block consists of the control and the six steps inverter blocks. By comparing the on time duty signals generated by the previous block with a high frequency triangular carrier wave, the gating pulses of the inverter power switches are produced using a relay block, and then fed to the inverter block. The power inverter has been implemented in terms of the switching function g_i associated with each power switch. The switching function g_i of a given power switching can assume either 1 or 0 according to its conducting state. Since, two power switches of the same leg can not be on simultaneously, the switching function of the phase $'a'$, for instance, is defined as

$$g_a + g_{\bar{a}} = 1 \qquad (12)$$

The output phase voltages, in terms of the switching functions, are

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_d}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} g_a \\ g_b \\ g_c \end{bmatrix} \qquad (13)$$

IV. SIMULATION RESULTS

The validity of the proposed model has been checked using the experimental data available in reference [1]. The comparison has been restricted to the over modulation mode I, which gives a full measure of the reliability of the new model. Comparison of figure 3 with the simulated results shows that the model emulates faithfully the DSP space vector implementation with the ADMC401 [1].

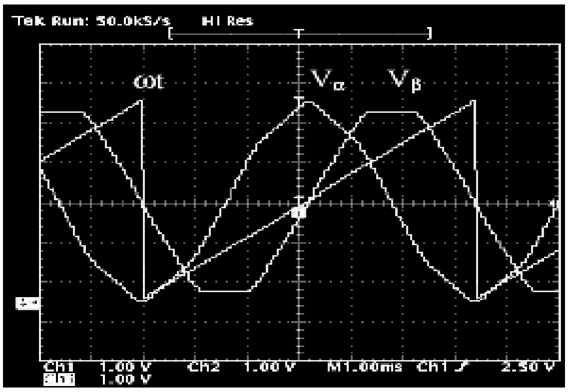

Figure 3: Reference Vector in full modulation Courtesy of Analog Devices Corp.)

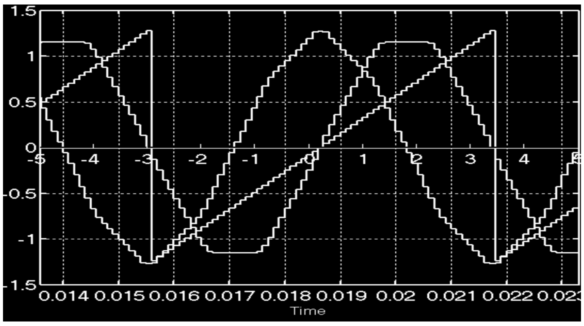

Figure 4: Simulated reference space vector in over modulation

The simulation results are presented in a way to highlight only the specificities of the present model. Open loop operation of the inverter has been restricted to figure 5 showing the output voltage when the model is commutated from the switched to the sine mode

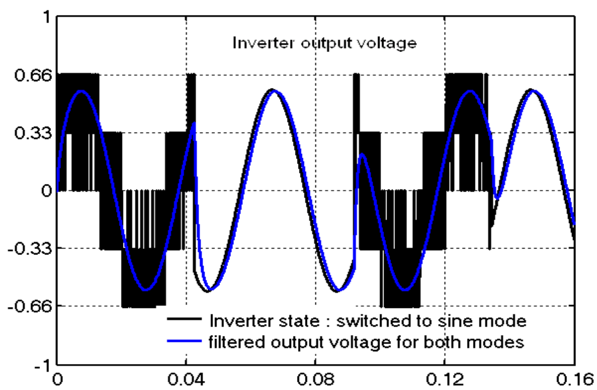

Figure 5: Commutation of the inverter from the switched to sine mode

In open loop operation the reference space vector is isolated from the inverter output; hence, the drawbacks of the inverter; which result from the high switching frequency of the power switches [9], are not highlighted. To analyse its actual performance, the model has been included in a field oriented pmsm drive. Figure 7 depicts the inverter response to a stepped speed reference, each step being of 500 rpm, with the motor subjected to a repeating load sequence the magnitude of which is two fold and half the capability of the actual machine [4].

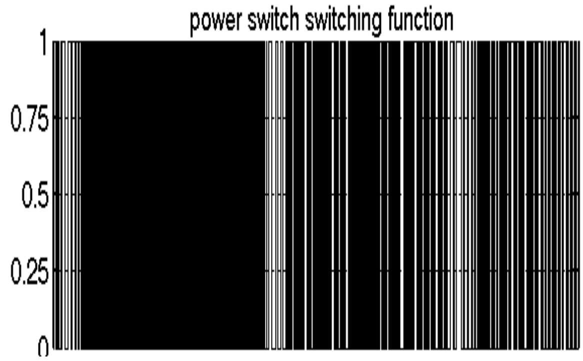

Figure 6: Relay block output

For the sake of comparison, figure 7 and the lower graphs of figure 8 and 9 show the evolution of the on time duty cycle ratio of the switched and the sine inverter modes.

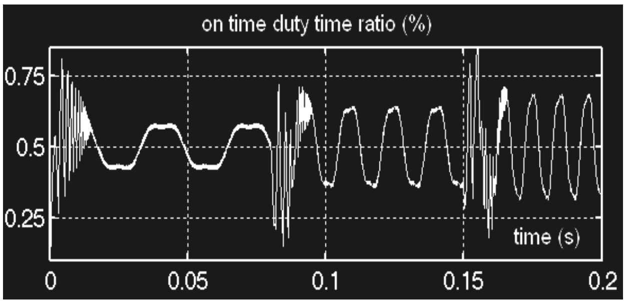

Figure 7: Switched mode inverter response to the speed profile of figure 8

It can be seen from figure 7 that the pole voltage of the switched mode inverter deteriorates as the speed loop controller tries to match the speed reference profile at higher speed. In contrast, the response of the sine mode inverter shown in figure 8, obtained for the same simulation conditions, reveals not only a low harmonic content of the output inverter voltage but also the tendency of the control loops to adjust the air gap flux. Similar deterioration of the output voltage is reported in [8] although the space vector modulated inverter, feeding a passive load, has been implemented through space state formulation. This is predictable since the high frequency chopped output voltage is feed back through the current sensing block which performs the Clark's transformation needed for the generation of the space vector. As a result, the on time duty ratio computation is affected and the switching pattern becomes erratic, as shown, leading to further distortion of the output voltage.

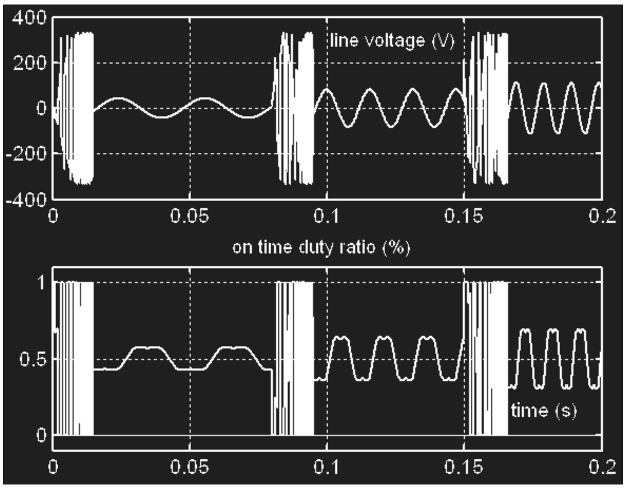

Figure 8: Inverter response to a speed profile

Figure 9 illustrates the inverter response to a variable torque demand under the control of the current loop only; the speed loop being disconnected. The voltage spikes correspond to step changes in the load torque, however the current loop reacts rapidly to the torque change by adjusting the inverter output voltage.

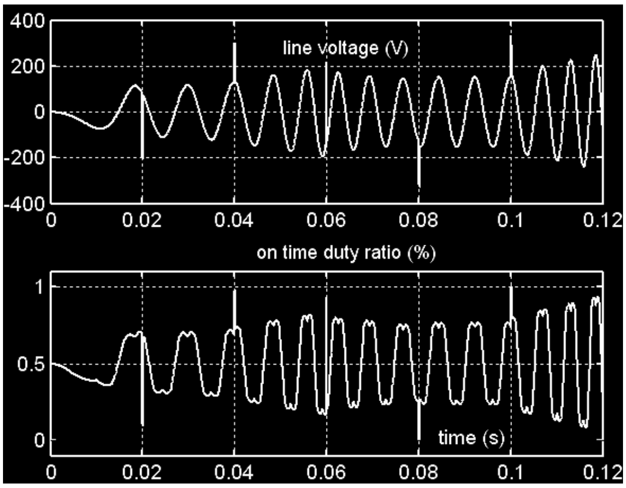

Figure 9: Inverter response to a torque profile

V. CONCLUSION

A new and flexible space vector pwm modulated inverter model, which fulfils the stringent requirements of present high performance AC drives, as far as their modelling is concerned, has been presented. Its reliability and performance have been thoroughly checked not only against existing models but also has been confronted with the experimental results provided by leading electronic companies.

VI. ACKNOWLEDGEMENTS

We want to thank the Mixed Signal DSP Group of Analog Devices Corporation for the information they made available to us and for their permission to use their experimental results. Thanks to Infineon Technologies Support Service for the information they have kindly provided us and to Prof Pinheiro, J.R for his helpful and insightful work on space vector pwm inverter modelling [8].

REFERENCES

[1] Analog Devices Corp, "Implementing Space Vector Modulation with the ADMC401,"AN401-17, Jan. 2000

[2] Texas Instruments, "Space-Vector PWM With TMS320C24x/F24x Using Hardware and Software Determined Switching Patterns", SPRA524, 1999

[3] NEC,"An Introduction to Space Vector Modulation using NEC's 8-bit Motor Control Microcontrollers ",AP 78K0, NEC Corporation,2000

[4] Infineon technologies, "Field oriented Control of a PMSM using a single dc link shunt,"AP16084, May 2004

[5] The MathWorks, "SimPowerSystems, User's Guide" Oct.2004

[6] Vander Broeck H. W. , Skudelny H. C. and Stanke G. V. , "Analysis and Realization of a Pulse Width Modulator based on Voltage Space Vector" IEEE Trans. on Ind. Applicat., V. 24, pp 142-150, Jan. 1988

[7] Vas P., "Electrical Machines and Drives: A Space Vector Approach", Oxford Science Publication, Clarendon Press, 1999

[8] Pinheiro J.R., Botteron F., Hey H.L. and Pinheiro H., "An Improved Discrete Model for Three Phase Voltage Fed Space Vector Modulated Converter,"COBEP'03, Fortelza, Vol.1, pp. 244–251, 2003

[9] Leonhard W. , "Control of Electrical Drives"2nd Edition, Springer 1997