A Simplified SVM Control Scheme for Reduced Switching Losses in Converter-Fed Drives

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Abstract

In this paper we propose a simplified space vector modulation (SVM) control scheme for reduced switching losses in converter-fed drives. This method has some practical advantages when compared to normal SVM. It is characterized by a reduction in switching losses, a lower current harmonic distortion and easier digital implementation. Our approach, which is based on space vector modulation, consists of calculating the duty ratio allocated to each inverter leg. A theoretical analysis is developed and proven based on the results of the experiments.

Sommaire

Dans cet article nous proposons un modèle simple de la commande à modulation du vecteur spatial (SVM) pour minimiser les pertes par commutations dans un convertisseur de puissance. Ce modèle présente des avantages pratiques par rapport au cas classique de la SVM. Il est caractérisé par une réduction des pertes par commutation du convertisseur de puissance, d'une moindre distorsion harmonique du courant et d'une plus simple numérisation pour fins de mise en œuvre pratique. Notre approche, basée sur la modulation de vecteur spatial, consiste à calculer le rapport de commutation alloué à chaque bras du convertisseur. Une étude théorique est développée et validée par des résultats expérimentaux.

1.0 Introduction

Space vector modulation (SVM) has been very popular in the past few years; the technique has gained ground as an effective means of generating PWM vector controlled drives [1, 2]. Space vector modulation offers many advantages, compared to the conventional pulse width modulation (PWM) method [3]. Among these, the key benefits are:

- 15% increase in the maximum line-to-line voltage obtainable, without overmodulation, when compared to conventional PWM with only 87% of the dc link voltage [4],
- Reduced switching losses converter, and
- Reduced harmonic distortion in the current.

With conventional SVM, all three inverter legs switch in any sampling period. To reduce switching power losses, a modification of SVM was developed, which assumes that two out of three inverter legs switch, while one remains without switching. The choice of the leg that does not switch depended on the orientation of the desired voltage reference. The other two inverter legs were then used to construct the desired voltage. The objective was to minimize switching losses.

The theoretical operation principles are described in the following sections. To verify its effectiveness, the proposed scheme was implemented and tested in the laboratory.

2.0 Space Vector Concept

The principle of the space vector is often used to study the behavior of ac machines. It is applied to represent the output voltage of converter-fed drives and to analyze current control methods. This concept makes it possible to represent three-phase quantities (voltages, currents, …) as space vectors [5,6].

Figure 1 shows the equivalent diagram of a typical dc link inverter-fed drive system, where S_A, S_B and S_C denote the switches of the inverter legs A, B and C respectively. For k = a, b or c, while $S_k = 1$, the corresponding upper switch is conducting. In the same way, $S_k = 0$ indicates that the lower switch is conducting. Therefore, the voltage output vector can be represented as a function of the switch states of the inverter denoted as $\vec{V}_i(S_A, S_B, S_C)$.

Consequently, there are eight states $\vec{V}_i$ (i = 0,…,7) available for this vector according to the eight switching positions of the inverter depicted in Figure 2. Of the eight possible states, $\vec{V}_1$ - $\vec{V}_6$ are vectors with magnitude V_d while $\vec{V}_0(0,0,0)$ and $\vec{V}_7(1,1,1)$ are zero vectors. For example, $\vec{V}_1$ corresponds to the switching state (1,0,0). The space vector $\vec{V}_s$ (Figure 3) is then defined as:

$$\vec{V}_s = V_d\left(S_A + S_B \cdot a + S_C \cdot a^2\right) \tag{1}$$

where: $a = e^{j \cdot \frac{2\pi}{3}}$ and $V_s(t) = V_{s\alpha} + jV_{s\beta}$ (2)

3.0 Principle Of Space Vector Modulation

According to the above analysis, the reference voltage $\vec{V}_s$ in a certain

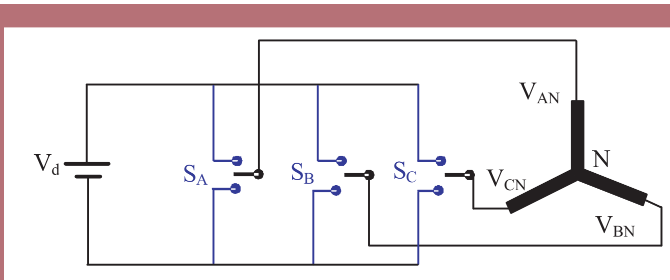
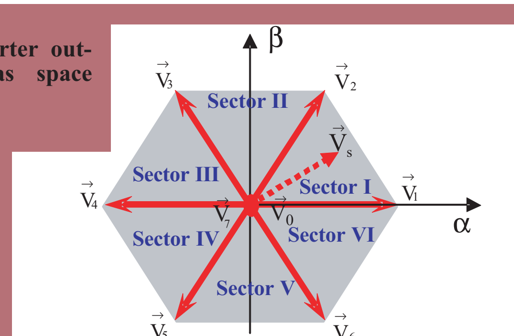


Figure 1: Typical diagram of inverter-fed drive

Figure 2: Inverter output voltage as space vectors



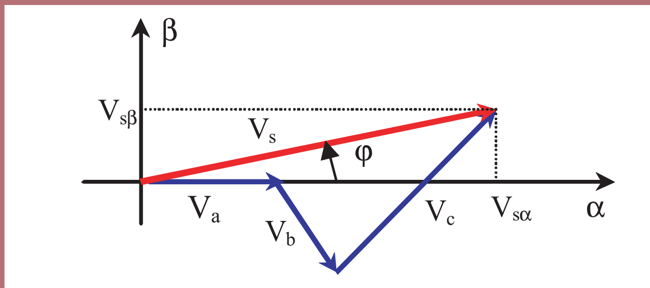


Figure 3: Output voltage as a space vector $\vec{V}_s$ (α – β : stationary coordinate)

sector consists of the two adjacent boundary vectors $\vec{V}_i$, $\vec{V}_{i+1}$ (i=1…,5) and the zero vector $\vec{V}_7$ and $\vec{V}_0$. To obtain the minimum switching frequency of each inverter leg, the switching sequence must be arranged so that the transition from one state to the next is performed by switching only one inverter leg [1]. If, for instance, the reference vector $\vec{V}_s$ is in sector I, the switching mode is as follows: $\vec{V}_0 \Rightarrow \vec{V}_1 \Rightarrow \vec{V}_2 \Rightarrow \vec{V}_7 \Rightarrow \vec{V}_7 \Rightarrow \vec{V}_2 \Rightarrow \vec{V}_1 \Rightarrow \vec{V}_0$.

Figure 4 presents a timing diagram for a sampling period T. For each leg, there are two ON-OFF and OFF-ON transitions. If f_s is the switching frequency for the PWM waveform, where f_s=2/T=2*f, then the switching frequency for three phases will be: f_s = 6 f.

4.0 Proposed Scheme

In this scheme, only one zero vector $\vec{V}_0$ or $\vec{V}_7$ is used in the switching sequence instead of two zero vectors at once. Then, in sector I, the switching mode is as follows (Figure 5): $\vec{V}_0 \Rightarrow \vec{V}_1 \Rightarrow \vec{V}_2 \Rightarrow \vec{V}_0$

In this case, phase C remains without switching and SC is always set on OFF. The switching frequency for three phases under this scheme will be: f_s = 4f. Then, switching converters are reduced by 33.3% compared to the classical SVM, and switching losses can be greatly reduced.

In sector I, the reference vector is composed of voltage vector $\vec{V}_1$, $\vec{V}_2$ and zero voltage $\vec{V}_0$ as illustrated in Figure 6. Hence, it follows for a switching cycle in sector I:

$$\int_0^{T/2} \vec{V}_s \cdot dt = \int_0^{T_1/2} \vec{V}_1 \cdot dt + \int_{T_1/2}^{(T_1/2+T_2/2)} \vec{V}_2 \cdot dt + \int_{(T_1/2+T_2/2)}^{T/2} \vec{V}_0 \cdot dt \tag{3}$$

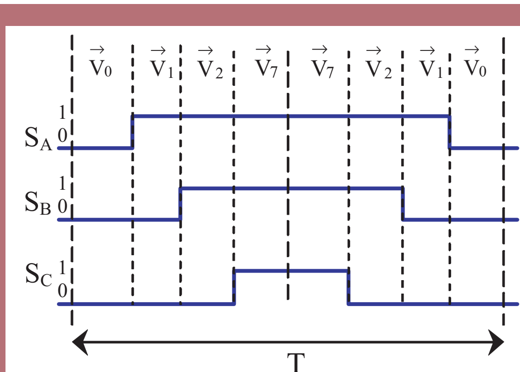


Figure 4: Switching sequence using $\vec{V}_0$ and $\vec{V}_7$

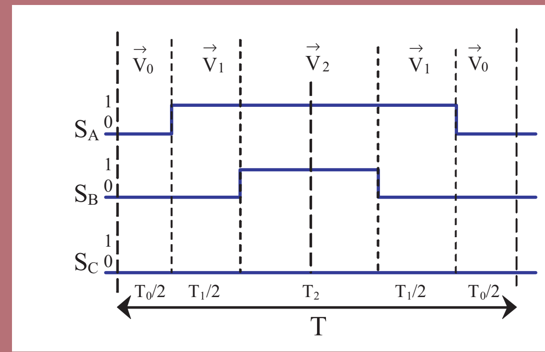


Figure 5: Switching sequence using zero vector only

Where T is the switching period and T_1 and T_2 are the active pulse times for voltage vectors $\vec{V}_1$ and $\vec{V}_1$ respectively. For a sufficiently high switching frequency, the reference space vector $\vec{V}_s$ is assumed constant during a switching cycle. Taking into account that $\vec{V}_1$ and $\vec{V}_2$ are constant and $\vec{V}_0 = 0$, one finds:

$$T\vec{V}_s = T_1\vec{V}_1 + T_2\vec{V}_2 \tag{4}$$

The reference space vector can be described in stationary coordinate (α,β), as follows:

$$\begin{cases} TV_{s\alpha} = T_1 \cdot \sqrt{\frac{2}{3}} \cdot E + T_2 \cdot \frac{E}{\sqrt{6}} \\ TV_{s\beta} = T_2 \cdot \frac{E}{\sqrt{2}} \end{cases} \tag{5}$$

From (5) we can obtain:

$$\begin{cases} T_1 = \frac{\sqrt{6} \cdot V_{s\alpha} - \sqrt{2} \cdot V_{s\beta}}{2 \cdot E} \cdot T \\ T_2 = \frac{\sqrt{2} \cdot V_{s\beta}}{E} \cdot T \end{cases} \tag{6}$$

Thus, for one cycle, SA switches for $\vec{V}_1$ and $\vec{V}_2$ while SB switches for $\vec{V}_2$ only. On the other hand, SC remains without switching. Then, one finds:

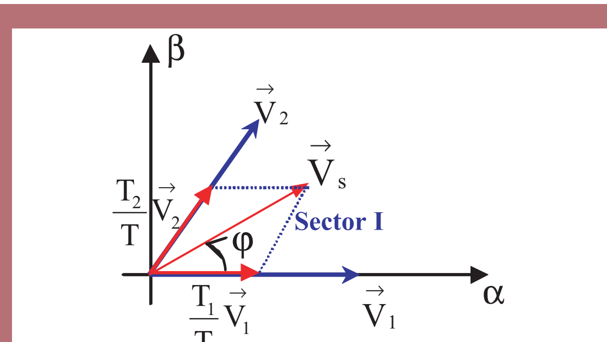


Figure 6: Determination of switching times

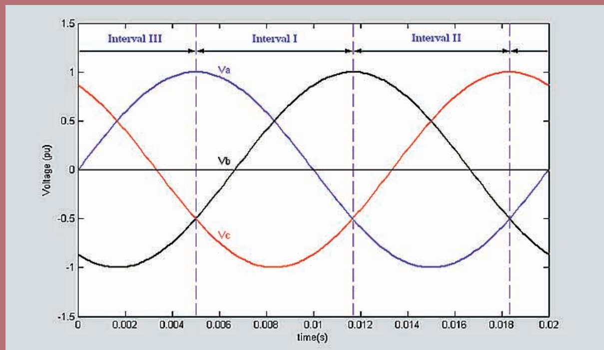


Figure 7: Intervals of 120°

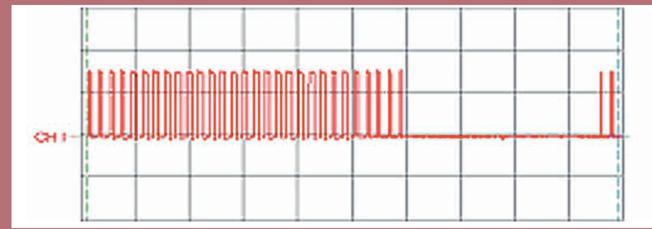


Figure 9: One of the gate control signals

$$\begin{cases} D_a = \dfrac{T_1 + T_2}{T} = \dfrac{\sqrt{6} \cdot V_{s\alpha} + \sqrt{2} \cdot V_{s\beta}}{2 \cdot E} \\ D_b = \dfrac{T_2}{T} = \dfrac{\sqrt{2} \cdot V_{s\beta}}{E} \\ D_c = 0 \end{cases} \qquad (7)$$

With 2/3 transformation, we obtain:

$$D_a = \frac{V_a - V_c}{E} \quad ; \quad D_b = \frac{V_b - V_c}{E} \quad ; D_c = 0 \qquad (8)$$

where V_a, V_b and V_c are the reference output voltages.

Taking into account the necessary changes in the other sectors, one finds (Table 1):

Table 1: Duty ratio in the 6 sectors

Sectors	Duty ratio
I and II	$D_a = \frac{V_a - V_c}{E}$; $D_b = \frac{V_b - V_c}{E}$; $D_c = 0$
III and IV	$D_b = \frac{V_b - V_a}{E}$; $D_c = \frac{V_c - V_a}{E}$; $D_a = 0$
V and VI	$D_a = \frac{V_a - V_b}{E}$; $D_c = \frac{V_c - V_b}{E}$; $D_b = 0$

According to this analysis, we can take into account only three intervals of 120 ° instead of six sectors of 60 °. These are identified as follows (Figure 7):

Interval I [sectors I II] : Va > Vc Vb > Vc.

Interval II [sectors III IV]: Vb > Va Vc > Va.

Interval III [sectors V VI]: Va > Vb Vc > Vb.

For each I, II and III interval, one of the three inverter phases - C, A and B respectively - remains without switching.

5.0 Experimental Results

Experimental results are presented in this section to demonstrate the validity of the proposed scheme. Experiments were performed on a 1HP induction motor. The motor parameters are listed in the Appendix.

Figure 8 shows the system configuration used in this experiment. The lookup table (EPROM) requires two external control signals: amplitude *Ai* and frequency *Fi*, converted with an A/D and a VCO respectively. An insulated gate bipolar transistor (IGBT) module is used to drive the induction motor. Since the duty ratio is incorporated in the software, the proposed scheme features a simple hardware design.

The fundamental frequency and the amplitude of the output voltage can be changed independently. The transition from one mode to another is without current transients.

Figure 9 shows the gate control signal of one inverter leg when the 33.3% non-switching portion of the inverter leg is clearly visible. This is well confirmed in Figure 9a.

Figure 10a shows the output voltage of one inverter leg and the corresponding sinusoidal current. It can be seen that, normally, the leg is set open in one-third the period compared to classical SVM (Figure 10b). Therefore, switching losses are reduced by 33.3%.

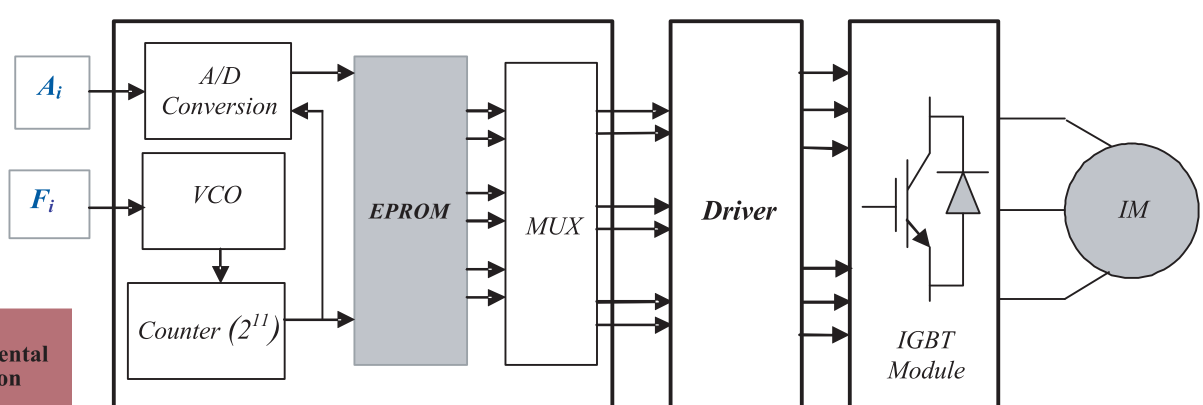
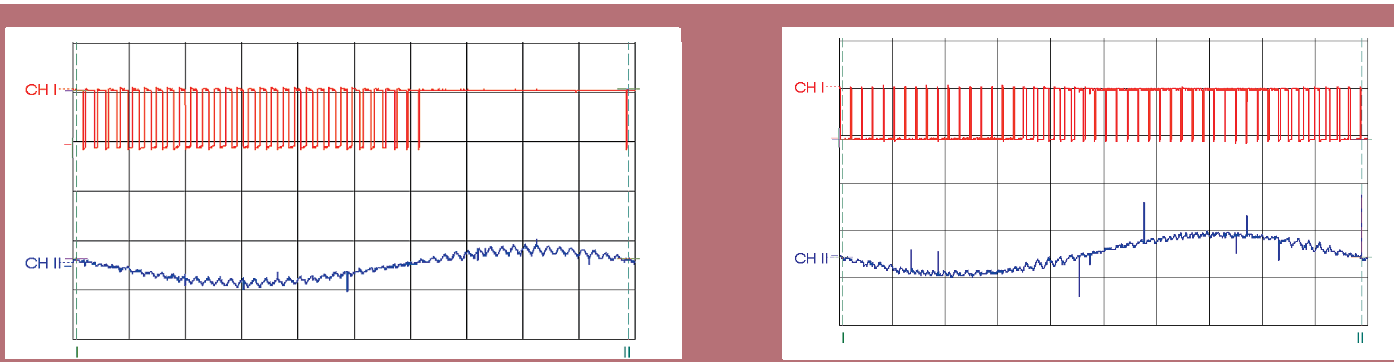


Figure 8: Experimental system configuration



(a) **(b)**

Figure 10: Output voltage of one leg and corresponding current
(a) Developed SVM
(b) Classical SVM

6.0 Conclusion

This paper presents a simplified space vector modulation control scheme for reduced switching losses in converter-fed drives. The proposed scheme reduces the switching power losses significantly more than the conventional SVM and gives the same performances, moreover, as those obtained with the SVM technique. The main advantages of the proposed scheme are:

- Only two inverter legs are controlled in each operation interval and the switching losses are reduced by 33.3%, and
- Low cost and easier digital implementation.

7.0 Appendix: Parameters of the motor

Un = 220V, In = 3.6A, Pn = 1 HP,

Nn = 1500 rpm, 3 Phases, 50 Hz.

8.0 References

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