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Comparison of Different Space Vector Modulation Types and Analyzing Their Effects on a Permanent Magnet Linear Synchronous Motor Load

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Abstract **-** A desirable three-phase voltage as output of three phase converters requires an appropriate modulation technique. Space vector modulation (SVM) technique is one of the most commonly used modulation types. It has some benefits compared to other modulation technique; therefore it is widely used in electric drive systems. SVM can be implemented in different ways, and each one has own advantages and disadvantages. In this paper, different ways of SVM implementation are introduced. Their design, differences, advantages, disadvantages and applications are analyzed and compared. To know the effect of SVM types on the load current, different kinds of SVM are applied to investigate the impacts of the load current in the case of supplying a permanent magnet linear synchronous motor (PMLSM).

Key Words - PWM ،SVM ،PMLSM ،THD ،Switching Losses ،Current Ripple

1. INTRODUCTION

Space phasor may be used, in the place of space vector, in electrical machines analyzing [1]. In three-phase inverter, there are different switching control and optimal voltage generation; all need pulse width modulation (PWM). Different kinds of modulation have been so far introduced and progressed [2-6]. Modulation method is an important part of the control structure and plays an important role in efficiency and quality enhancement of an electric drive system [7-11]. It provides the features such as wide range of linear operation, low content of high harmonics in voltage and current waveforms, minimal number of switching to decrease switching losses in the power components, appropriate operation in saturation and finally low ripples in outputs [2]. In the other hand One of the effective parameters in the content of harmonics in voltage and current and amplitude of ripples in electrical torque (rotational) or force (linear) motors in drive systems is the modulation technique. So, modulation techniques for providing new strategies have been introduced in order to decrease a number of drawbacks in control systems.

Based on the operation and implementation, two types of modulations are more common: sinusoidal PWM (SPWM) and space vector PWM (SVPWM or SVM) [7-13]. SPWM is based on the triangular carrier signal in which three reference signals are compared to the triangular carrier signal (common in three-phase). In this case logical command switching signals are generated. In SVM method, a reference signal determines the procedure for applying 6 nonzero vectors and 2 zero vectors [2, 14]. On contrary to SPWM, in SVM, separate unit for reference signal generation is not utilized. It also does not use a wide range of linear operation, and its modulation index can be about 91% compared with 78.5% in SPWM. More simple design and implementation, switching losses reduction in some types of SVM are other advantages of SVM. However, it is possible to implement all types of SPWM with SVM [1, 2, 14]. This is the reason for wide application of nearly all types of drive systems.

Also SVM is capable to reduce the drawbacks of DTC (or DFC in linear motors) such as decreasing amplitude of ripples in the torque-speed response and reducing the harmonics content in voltage and current waveforms. A constant switching frequency as an important feature of SVM technique can be applied as a solution in DTC (or DFC) drive systems [7-13]. Considering the widespread application of SVM, four strategies for implementation of SVM are designed in this paper. Differences in the vectors ordering cause the differences between these strategies. The ordering type influences the power supply parameters such as output ripples, harmonic distortion and switching losses. These strategies are applied to a motoring load (PMLSM) and their impacts upon the performance of the motor are investigated. In part 2, SVM technique and its implementation are explained. In part 3, four strategies for SVM generation are designed and their differences are compared. In part 4 four strategies are applied to supply a PMLSM as a load. In this part parameters of different types of SVMs are analyzed and their advantages and disadvantages are explained. Finally, a key point for desirable selection according to the system type and situation are introduced.

2. SVM Technique

A three-phase inverter with a motor load has been illustrated in Fig.1. To avoid the short-circuit, there are 8 possible states for switching and therefore there are 8 possible vectors for output voltage. These 8 vectors, consist of 2 zero and 6 nonzero voltages. They are called the basic voltage vectors. These vectors and 6 sections (P_n) that are limited with 6 nonzero voltages have been shown in Fig.2. Switching states for each voltage vector has been explained in Table 1[2].

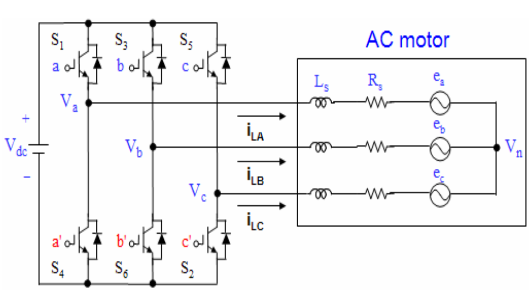
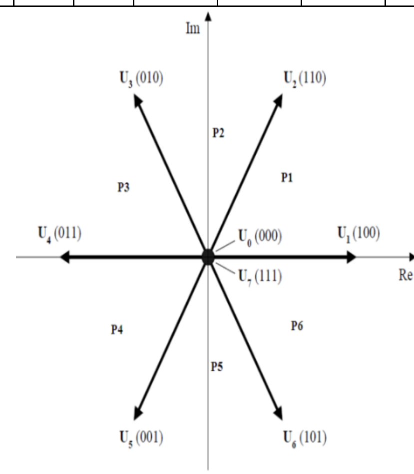


Fig.1. Three-phase inverter with motor load

Table.1. Switching states in three-phase inverter

Switching states			Phase voltage (*V_{DC})			Basic voltage vector
S_1	S_3	S_5	V_{an}	V_{bn}	V_{cn}	
0	0	0	0	0	**0**	U_0
1	0	0	2/3	-1/3	-1/3	U_1
1	1	0	1/3	1/3	-2/3	U_2
0	1	0	-1/3	2/3	-1/3	U_3
0	1	1	-2/3	1/3	1/3	U_4
0	0	1	-1/3	-1/3	2/3	U_5
1	0	1	1/3	-2/3	1/3	U_6
1	1	1	0	0	0	U_7



Fig, 2. Basic voltage vectors and sections

SVM is based on the combining 8 basic voltages to provide a desirable reference voltage vector. There are 6 nonzero voltage vectors and so there are 6 sections in space. Therefore, it is possible to introduce every reference voltage based on 2 nonzero adjacent voltages and zero voltages. Therefore, SVM can be implemented by the following three steps.

2.1. Determination of Reference Voltage Vector

Determining reference voltage vector requires two d-q voltage vectors components. These two vectors are determined in control system according to its control method. In Fig. 3, relation between d-q voltage components and reference voltage has been illustrated. Eqns. (1), (2) determine the amplitude and angle of reference voltage (V_{ref}) respectively. Determining precise reference voltage is an important step in control method.

Fig. 3. Reference voltage and its components

$$|V_{ref}| = \sqrt{(V_d)^2 + (V_q)^2} \qquad (1)$$

load. The advantage of this strategy is soft switching because the switching process is done in one sequence for all switches.

3.3. Alternating Method

According to the algorithm shown in Fig.8, in consecutive periods, U_o is applied during the 1^{st} period and U_7 during the 2^{nd} period. In this case, the effective frequency is halved and switching losses, which are proportional to the switching frequency will be 50%. Also there is a small asymmetric in the algorithm leading to a less harmonics and ripples in the load current.

3.4. Discrete Method

Discrete method is based on the fact that the switching losses are approximately proportional to the current being switched and hence it would be advantageous to avoid switching the inverter leg that carries the highest instantaneous current. The algorithm of this method has been shown in Fig.9, in which just one of the basic zero voltages U_0 or U_7 is used. Implementation of this method is simple and it has less losses; however, it increases the harmonics content and amplitude of the ripples in voltages and currents.

4. APPLICATION OF SVM STRATEGIES FOR SUPPLYING A MOTORING LOAD

To analyze and compare the efficiency and performance of four methods, they are simulated using MATLAB simulink considering a permanent magnet linear synchronous motor (PMLSM) as a load. The results have been analyzed. For the analysis amplitude of peak to peak ripples in the load currents, THD and switching losses are compared. A PMLSM is initially modeled and then four methods applied.

4.1. PMLSM Model

To model the PMLSM, first the stator three-phase windings are transformed into two-phase system. Then two-phase currents are transformed to the rotor frame and the stator voltage balance equation is written in the same frame. d-q model of PMLSM is as follow [12, 15].

$$u_d = R_r i_d + p\psi_d - \omega_r \psi_q \quad (6)$$

$$u_q = R_r i_q + p\psi_q + \omega_r \psi_d \quad (7)$$

$$\psi_d = L_d i_d + \psi_f \quad (8)$$

$$\psi_q = L_q i_q \quad (9)$$

Electromotive F_M is:

$$F_M = \frac{3\pi}{2\tau}\left[i_q \psi_f + \left(L_d - L_q\right) i_d i_q\right] \quad (10)$$

Mechanical motion equation is:

$$M\dot{V} = F_M - F_L - BV \quad (11)$$

The symbol definitions have been presented in Table 2.

Table 2. Symbols definition

parameter	symbol	unit
Rotor current in d-q axis	i_d, i_q	A
Rotor voltage in d-q axis	u_d, u_q	V
d-q inductances	L_d, L_q	H
Rotor resistance	R_r	î
Mover mass	M	Kg
Viscous fiction coefficient	B	N.s/m M

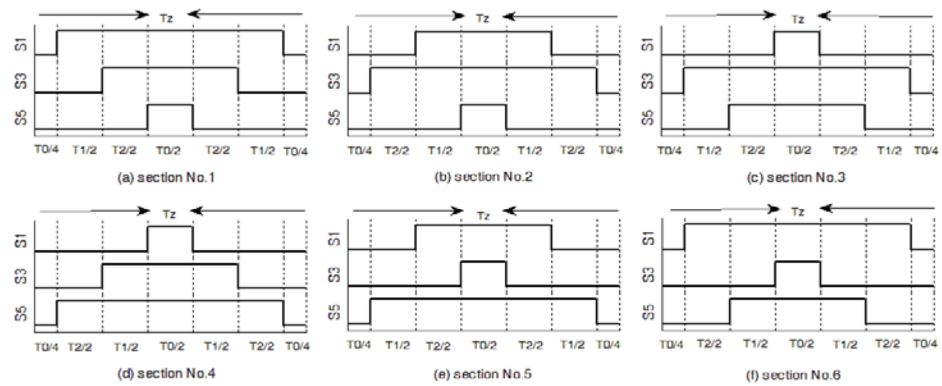


Fig. 6: Switching algorithm in symmetrical case in section 1

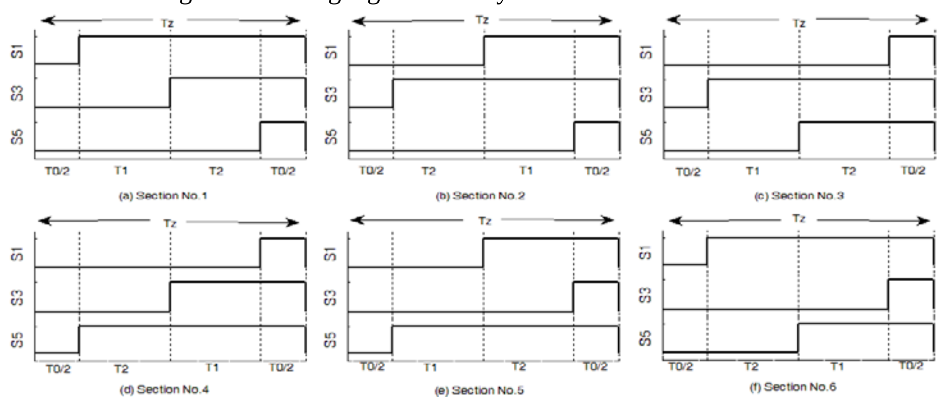


Fig. 7. Switching algorithm in direct case in section 1

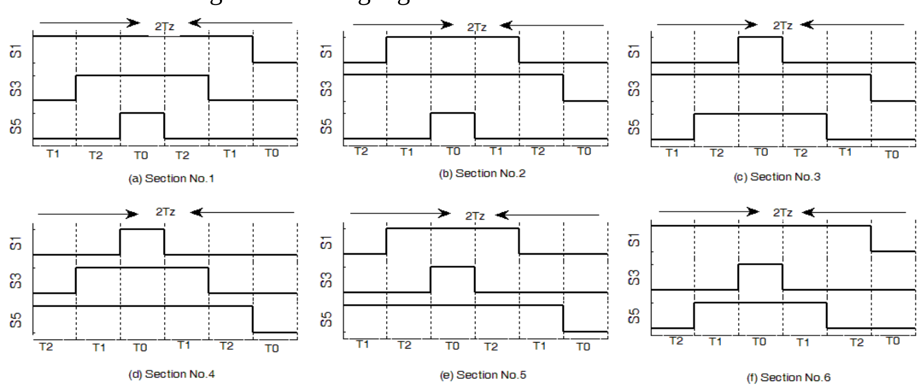


Fig. 8. Switching algorithm in alternating case in section 1

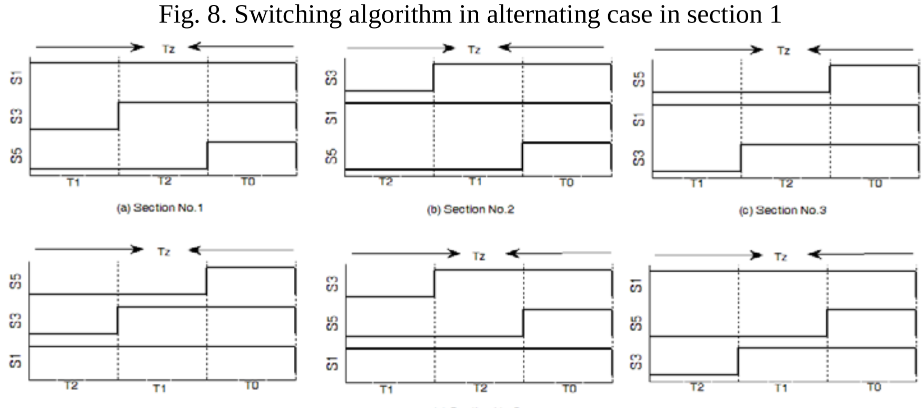


Fig. 9. Switching algorithm in discrete case in section 1

4.2 Load Current Ripple

The peak to peak value of the current ripple, at the load maximum current, is important in the design of inductive filters. On the other hand, ripples in the load current leads to the disturbance of the torque development, low efficiency of the system and losses increment in drive systems. Therefore, it will be desirable to have a power supply that generates the minimum ripples in the current without any additional equipment. Generally, the maximum output current ripple occurs when the volt-second across the output inductors is the largest [14]. Therefore, the ripple content is proportional to the duration times T_0, T_1, and T_2. In the symmetrical method these times are half compared to other methods, and the minimum peak to peak ripple is expected. In the alternating method the algorithm is almost symmetrical which leads to a low peak to peak ripple. Fig. 10 shows the phase current of the motor in four strategies. As it was explained theoretically, the first method has the lowest and the forth method the highest ripple.

4.3. Total Harmonic Distortion (THD)

THD of a periodic voltage, with Fourier series coefficients a_n, is defined as [14]:

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{\square} a_n^2}}{a_1} \tag{12}$$

A desirable SVM method generates the lowest THD. Whatever its harmonics order be higher. It is more desirable to have higher order harmonics due to lower size and cost of the filter. Fig. 11 shows the total harmonic distortion load current using four strategies. The most important parameter to determine the THD is the switching algorithm symmetry. Also the number of time division is important [16]. Therefore, the symmetrical case includes seven time divisions over a complete cycle and the maximum symmetry must have the lowest THD. Alternating method has nearly a symmetrical algorithm and therefore it must have low THD. Direct and discrete methods have the minimum symmetry leading to the highest THD.

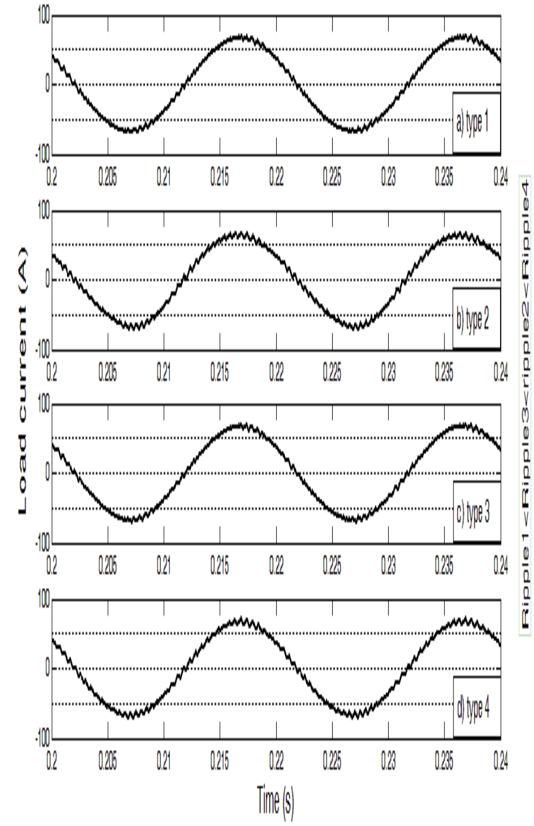


Fig. 10. Load phase current in four strategies

The direct method has the worse harmonic distribution. For example, its 2nd-order harmonic is 10% of the fundamental component and it requires a very costly filter. The amounts of THDs for different strategies have been presented in Table 3.

Table. 3. THD for different strategies

SVM method	%THD
Symmetrical	4.03
Direct	11.25
Alternating	7.91
Discrete	8.36

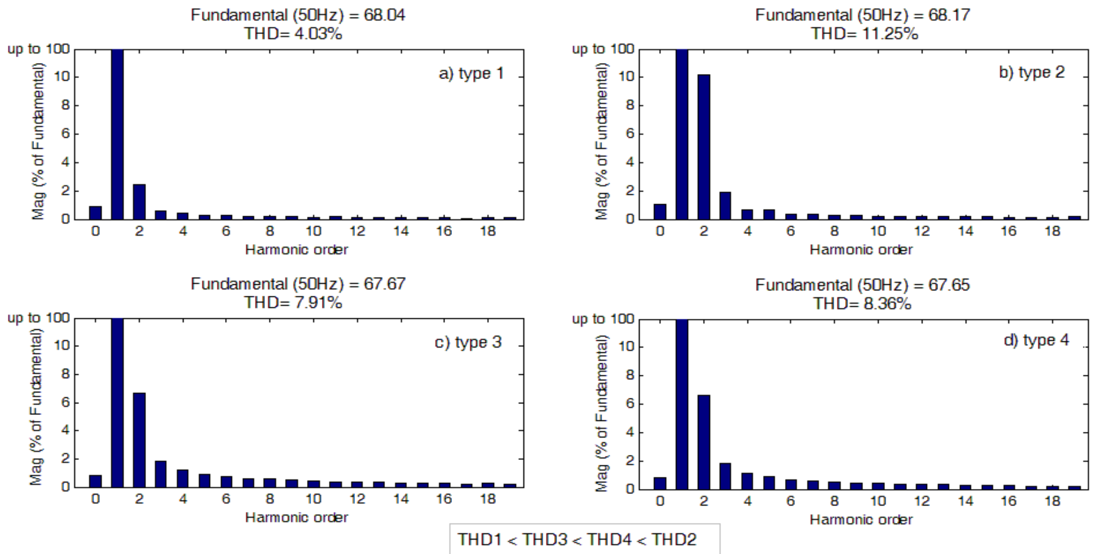


Fig. 11. THD for load current in four SVM strategies

4.4. Switching losses

The switching losses are assumed to be proportional to the product of the current through the switch and voltage dropt across the switch at the instant of switching. Switching losses depend on the current ripples, voltage ripples and power factor. As an approximation, the voltage and current seem to be ideal and losses are measured based on the number of commutations required in each switching algorithm and the current at the instant of switching [16]. Therefore, methods with the maximum number of commutations like symmetrical method have the highest losses, and methods with the least number of commutations like discrete method have the least losses. Other important task in switching losses is switching frequency. Alternating method with the half switching frequency has the half switching losses. Thus alternating has the lowest, and the losses increase in sequence of: discrete, direct and symmetrical methods. Table 4 compares different SVM methods.

Table.4. Comparison of different SVM methods

Performance Index	SVM method			
Lowest ripple	1	3	2	4
Lowest THD	1	3	4	2
Lowest losses	3	4	2	1
Lowest T_z division	4	2	3	1
Simplest structure	2	4	3	1

5. CONCLUSION

In this paper, four strategies for SVM implementation were proposed. Efficiency of these methods in respect to the power supply was analyzed from three different points of view: load current ripple, THD, and switching losses. They were modeled, simulated and compared with each others. It was shown that although application of some methods reduces the THD and amplitude of ripples in voltage and current, it increases the switching losses. Therefore, to select the desirable SVM method in system designing, at the load and desirable operation must be known. Then trade-off between the size of the heat sink and size of the filters must be considered. Based on the theoretical analyzing and simulation results, in low switching frequencies, use of the symmetrical method is desirable. its lowest THD, peak to peak ripples and low switching frequency compensates its highest losses. In high switching frequencies using alternating or discrete methods reduction of the switching losses is suggested. Also alternating method is more useful for low power factor application. Direct method has no special feature except it is useful in soft switching due to its special switching algorithm.

Appendix: Motor Parameters

Pole pairs	1
Pole pitch	42 mm
Stator resistance	2 □
d-q axis inductances	2.63 mH
Permanent magnet flux	0.17 Wb
Viscous friction coefficient	0.001 Ns/m
DC bus voltage	200 V
Load	4 N

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