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Comparison of PWM Strategies for Inverter-fed Induction Motor

Dimitar Stoilov Spirov

Abstract - **A system for frequency controlling of an induction machine has been designed and studied, with constant torque loading through the application of sine PWM, 7-segment space-vector PWM and 5-segment space-vector PWM. The three PWM schemes are analyzed through simulation.**

The modulation signals, DC bus voltage utilization, and output line voltage harmonic of these schemes are analyzed by the MATLAB software with different modulation index *M* and frequency modulation index k_f.

Keywords – **Induction machine, frequency control, PWM strategies, harmonic.**

I. Introduction

For being able to provide both voltage and frequency control, pulse-width modulated inverter has been widely applied to adjustable speed drives. Recent developments in the advanced technology of power devices increase the switching frequency of inverter control, thereby improving the performance of pulse-width modulated inverter [1].

However, high switching frequency operations of inverter contribute to bearing currents and cause adverse effects on motor insulation and electromagnetic interference in the applications of inverter-fed drives. Therefore, to reduce these side effects has become one of the main concerns for the development of modern inverter-controlled drives [1].

There are different algorithms for using PWM to modulate the inverter or rectifier. Many PWM schemes have been investigated extensively in literatures [2]-[6]. The goal in each modulation strategy is to lower the switching losses, maximize bus utilization, reduce harmonic content, and still achieve precise control. So the performance of a PWM scheme is usually judged based on the following criteria [7]: total harmonic distortion (THD) of output.

In this paper, space vector modulation (SVPWM) schemes are investigated. The modulation signals, DC bus voltage utilization, and output line voltage harmonic are analyzed with different modulation index *M* and frequency modulation index k_f. In addition, the simulation is implemented in MATLAB/SIMULINK.

A. Control Strategies

Sine pulse width modulation (SPWM).

The sine pulse width modulation (PWM) is obtained by comparing two signals – a modulating signal with frequency 10-20 kHz, and a three-phase sine system of voltages [8]. At the output of this system positive and negative pulses with variable frequency and width are obtained. Increasing the number of the pulses for half a cycle decreases the frequency of the output sine wave, and increasing the width of the pulse increase the amplitude. Fig. 1 shows the modulation waveform of the SPWM with $M=1$ and $k_f=25$.

The three sine voltages with frequency f_s (modulator wave), obtained by the system for regulation of the variables, are compared with a triangular signal, whose frequency defines the working frequency of the inverter f_m (carrier wave) and result modulated wave. The modulation index *M* is defined by $M=A_M/A_C$, were A_M is the amplitude of modulator wave, A_C is the amplitude of carrier wave. The frequency modulation index is defined by $k_f=f_s/f_m$. The value of k_f must be a round number and much greater than three, in order to decrease the losses due to high harmonics.

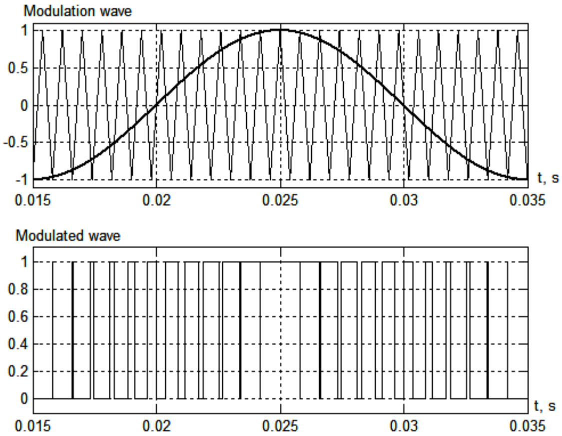

Fig. 1. Modulation waveform of SPWM

Space vector pulse width modulation (SVPWM)

For the presenting vector of the three-phase system of stator voltages while satisfying the requirements for invariability of the powers the following expression is obtained [8]:

$$\mathbf{u_s} = \frac{2}{3}\left(\mathbf{u_A} + a\mathbf{u_B} + a^2\mathbf{u_C}\right). \qquad (1)$$

There are eight combinations for switching the three bridges of the three-phase inverter (fig.2). From expression (1) the space vector of the voltage for each of these combinations may be obtained. Fig.2 shows the location of the space vectors in the complex plane. The six vectors are at 60° and the two zero vectors are in the beginning of the coordinate system.

D. Spirov is with the Department of Electrical Engineering, University of Food Technologies - Plovdiv, 26, Maritza Blvd., 4002 Plovdiv, Bulgaria, e-mail: dimitar_spirov@abv.bg

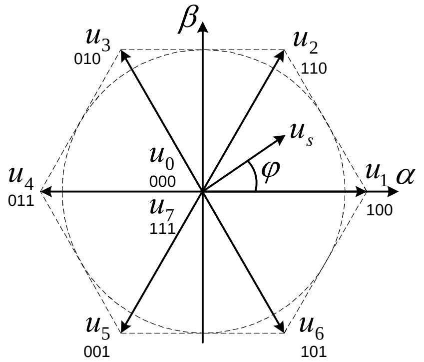

Fig.2. Location of the space vectors in the complex plane

The space vector modulation must describe the input space vector of the voltage $\mathbf{u_s}$ through the eight vectors obtained. One of the ways is to set the average voltage of the inverter for the period T_{pwm} equal to the average voltage of the input space vector for the same period. Thus, the space vector is modeled through the two borderline vectors of the sector in which it is located. The binary representation of the borderline vectors differs with one bit only, which means that only one transistor shall switch over.

Assuming that the modulating frequency of the inverter is great, and the changes of the input space vector within this period are small, the modulating scheme may be presented with the following expression:

$$T_{pwm}\mathbf{u_s} = T_1\mathbf{u_1} + T_2\mathbf{u_2} + T_0\mathbf{u_0}, \qquad (2)$$

where $\mathbf{u_1}$ and $\mathbf{u_2}$ are the two borderline vectors of the relevant sector, $\mathbf{u_0}$ is the zero vector, and T_1, T_2 and T_0 is the duration of the relevant vectors. To them the following expression applies:

$$T_{pwm} = T_1 + T_2 + T_0 . \qquad (3)$$

The length of the input space vector defines the amplitude of the output voltage, and the speed, with which the vector rotates, defines the frequency of the output voltage.

Fig. 3 illustrates the switching patterns and PWM waveform of PWM voltage in a carrier period using the reference vector in sector 1 as example for conventional 7-segment switching sequences.

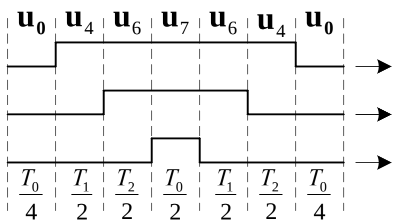

Fig. 3. Conventional 7-segment switching sequences of sector 1

The modulation waveform of the 7-segment SVPWM strategy has the saddle shape, which is shown in fig. 4 with *M=1* and k_f*=25*. It is a continuous function, linearly dependent on the modulation index and symmetrical with respect to the center of the periods. The continuity of the modulation waveform implies that in each leg of the inverter, switching occurs within all six sectors of the output voltage. And it is clear that there are 25 switching actions in each period for the classic strategy.

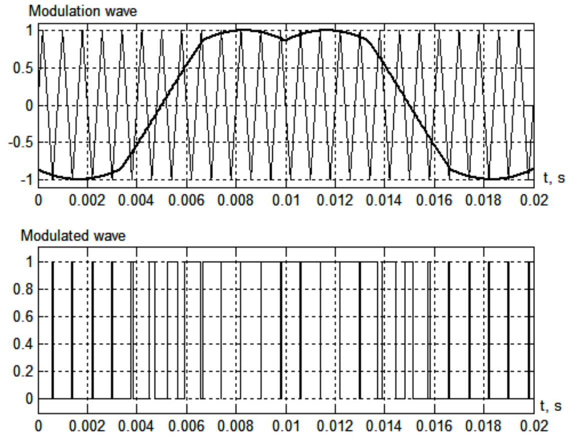

Fig. 4. Modulation waveform of 7-segment SVPWM

Another SVPWM technique is referred to as 5-segment algorithm [2]. Fig. 5 shows 5-segment algorithm switching sequences of sector 1. Only null vector $\mathbf{u_7}$ is used in each cycle. Its sequences are symmetrical too. This scheme lowers the switching times.

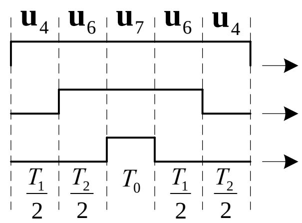

Fig. 5. 5-segment switching sequences of sector 1

Fig. 6 shows the modulation waveform of the 5-segment SVPWM with *M=1* and k_f*=25*. The waveform has the shape of saddle and symmetrical with respect to the center of the periods too. But it is discontinuous. It can be seen that within the total of one-third of the cycle of output voltage, the modulating waveform assumes the values of 0. Consequently, in a given leg of the inverter, switching occurs within the total of only two-thirds of the cycle and there are only 16 switching actions in each period. As a result, switching losses are significantly reduced in comparison with those in an inverter controlled by using a continuous modulating function.

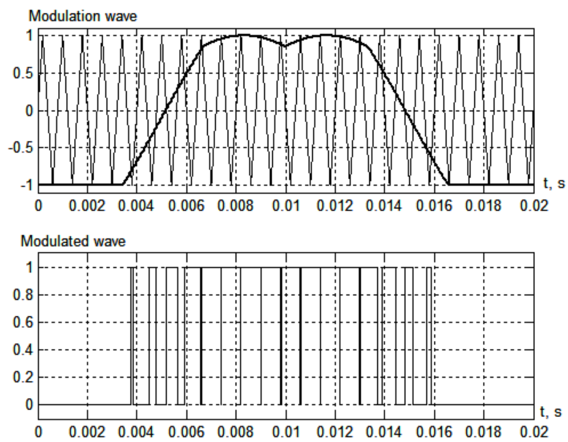

Fig. 6. Modulation waveform of 5-segment SVPWM

B. Simulation Results

The developed control system enables the realization of frequency control of an induction motor with the three methods of modulation of the input signal. The block scheme of the control system is given in Fig.7.

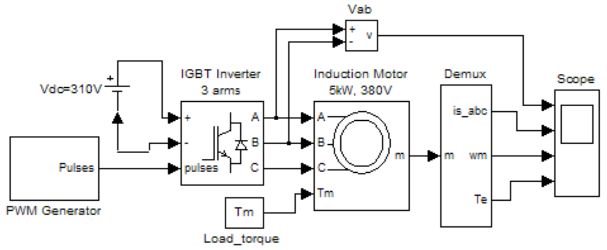

Fig.7. Block scheme of the control system

The operation of the induction motor type T112 M-2 BR//B14 will be researched, a motor, which is designed to drive the lifting mechanism. The technical data of the electric motor are given in Appendix. The T-shape equivalent circuit of the motor parameters determinate by a firm-producer calculating methodology accordingly different values of the slip are given in Appendix. The inertia coefficient *FI=2,0* is assumed.

The simulation results of line voltage U_{ab} and stator current I_{sa} are shown in fig. 8 – fig. 10 for the three PWM strategies with $M=1$, $k_f=25$ and DC link voltage $U_{dc}=310V$.

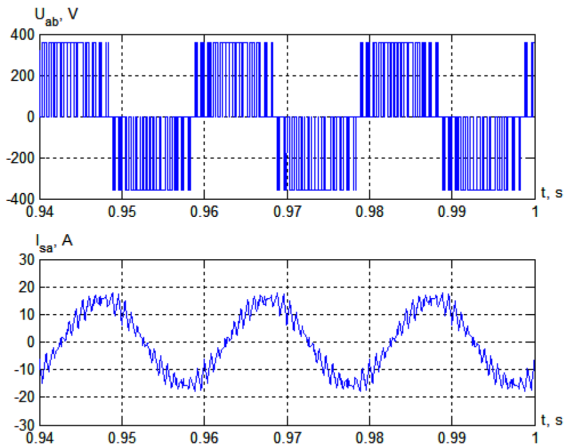

Fig. 8. Dependencies $U_{ab},I_{sa}=f(t)$ of SPWM

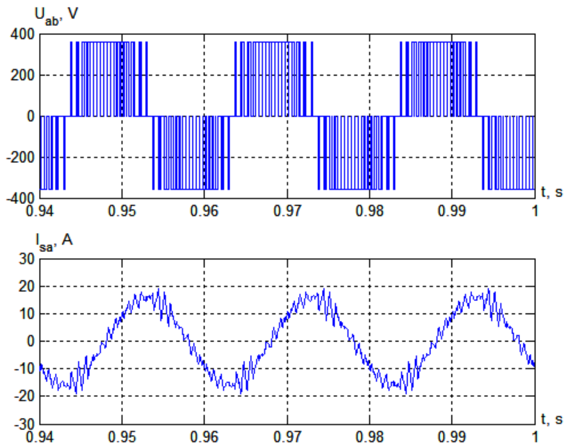

Fig. 9. Dependencies $U_{ab},I_{sa}=f(t)$ of 7-segment SVPWM

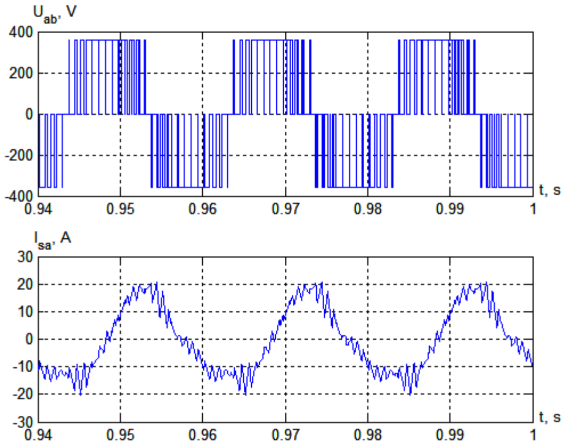

Fig. 10. Dependencies $U_{ab},I_{sa}=f(t)$ of 5-segment SVPWM

The total harmonic distortions of the voltage *THD* is define in accordance with the expressions as given in [8]:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_1} 100, \% . \quad (1)$$

In this calculation, U_n means the RMS (root mean square) voltage of harmonic n, where $n=1$ is the fundamental harmonic.

The results obtained for the fundamental harmonic of the voltage U_1 and total harmonic distortions of the voltage *THD* for the three methods of modulation with different modulation index *M* and frequency modulation index k_f are summarized in Table 1.

TABLE 1. VALUES OF U_1 AND THD FOR DIFFERENT K_F AND M FOR THE TREE PWM STRATEGIES

k_f	*M*	Sine PWM		7-segment SVPWM		5-segment SVPWM	
		U_1, V	*THD*, %	U_1, V	*THD*, %	U_1, V	*THD*, %
0,8	*25*	75,44	193,96	240,70	70,18	234,96	72,74
	50	119,99	141,21	245,73	67,97	252,20	65,15
1	*25*	79,04	188,29	287,41	50,00	281,66	52,49
	50	149,45	118,48	304,65	42,33	312,55	38,66
1,2	*25*	84,79	179,92	335,55	26,58	326,93	31,45
	50	164,54	108,78	349,92	16,33	343,45	21,45

From Table 1 it can be seen that the value of *THD* in SPWM can reach value twice greater than in SVPWM. When the modulation index *M* increases the *THD* of the output voltage decreases. The value of *THD* decreases when the frequency modulation index k_f increases. In SPWM, the *THD* changes little.

In addition, it can be seen that the fundamental voltage increases with the increase of modulation index *M*. In SVPWM, the U_1 changes little.

The value of *THD* in 5-segment SVPWM is greater than in 7-segment SVPWM in $M=25$, but is lower in $M=50$. In the over-modulation region ($k_f=1,2$), the value of *THD* in 5-segment SVPWM is greater than in 7-segment SVPWM in $M=25$ and $M=50$.

The harmonic spectrum of SPWM, 7-segment SVPWM and 5-segment SVPWM are shown in fig. 11 – fig. 13.

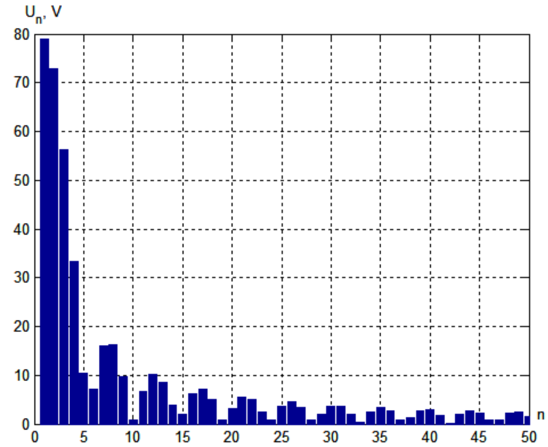

Fig 11. Harmonic spectrum of SPWM with k_f=1, M=25

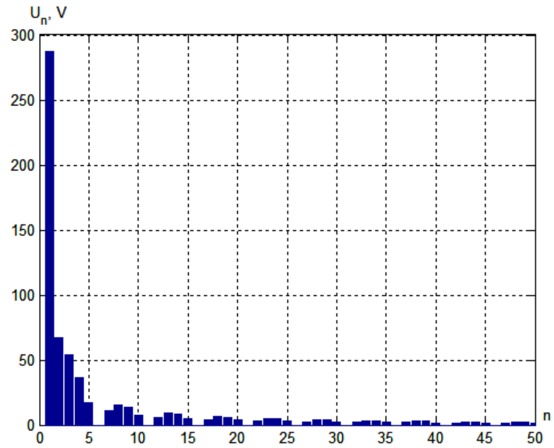

Fig. 12. Harmonic spectrum of 7-segment SVPWM with k_f=1, M=25

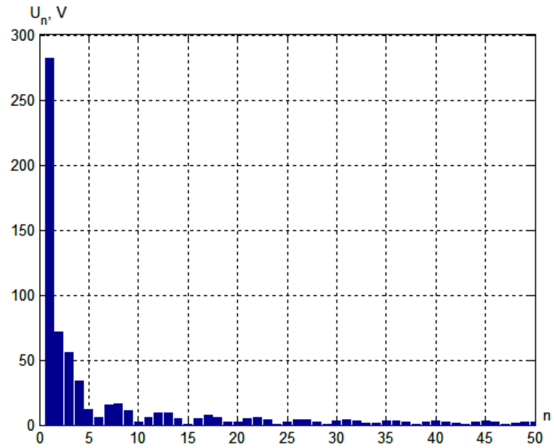

Fig. 13. Harmonic spectrum of 5-segment SVPWM with k_f=1, M=25

II. CONCLUSION

A system for frequency controlling of an induction machine has been designed and studied, with constant torque loading through the application of sine PWM, 7-segment space-vector PWM and 5-segment space-vector PWM.

The comparison study shows that all three PWM schemes can obtain almost the same output voltage in linearity modulation or over-modulation region. Consequently, the switching loss of the SPWM scheme is the lowest and the 7-segment SVPWM scheme performs better in terms of *THD* of the output line voltage. The experimental results demonstrate the validity and efficiency of three PWM schemes and the simulation.

APPENDIX

Technical data of induction motor type T112 M-2 BR//B14

$P_N=5kW$; $U_N=380V$; $I_N=9,774A$; $f_N=50Hz$; $p_p=1$; $n_N=2827min^{-1}$; $M_N=16,887Nm$; $J_m=0,01153kg.m^2$.

Parameters of induction motor type T112 M-2 BR//B14 $s_N=0,0575$:

$R_s=1,35\Omega$; $R_r=1,25\Omega$; $X_{\sigma s}=2,164\Omega$; $X_r=2,206\Omega$; $X_m=87,909\Omega$

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