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ANALYSIS AND IMPROVEMENT IN TOTAL HARMONIC DISTORTION OF STATOR CURRENT AND VOLTAGE OF INDUCTION MACHINES WITH DIFFERENT PWM TECHNIQUES

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***Abstract**- Three phase induction motor with variable voltage and variable frequency is invariably obtained from a three phase voltage source inverter (VSI). Due to the revolutionary improvement of power semiconductor technology, it is possible to control AC drives with superior performance. A number of PWM techniques are widely used to obtain required variable voltage and variable frequency in the line side of the inverter where most widely used and efficient schemes are carrier based sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM). Due to easier digital realization and better dc bus utilization, SVPWM has been treated as a reliable control scheme rather than other techniques. In this paper, model of SPWM and SVPWM techniques are employed in three phase inverter fed by induction motor in MATLAB Simulink environment. The simulation study has been focused with space vector PWM which generates less total harmonic distortion (THD) in both line voltages and fundamental component of input current corresponding to the sinusoidal PWM and also utilizes DC bus voltage more effectively. Simulation study reveals an improve results associated with this research work. All the simulation results are also provided in the paper.*

Keywords: Pulse width modulation techniques, Total harmonic distortion, Three-phase inverter, Induction Machines, MATLAB Simulink

1. INTRODUCTION

Due to the revolutionary improvement in power semiconductor technology, the use of AC drives in industries and traction works are increased. So, variable frequency is needed to AC drives for different load conditions. This variable frequency for AC drives can be obtained by controlling the switching frequency of the converter. As a result, different types of switching techniques are investigated in the literature. Among these switching techniques, pulse width modulation (PWM) technique is intensively used in the last couple of decades for achieving variable voltage and variable frequency. It can be widely used in different applications such as static frequency changers (SFC), variable speed drives (VSD) and in uninterruptible power supplies (UPS) etc. In all applications harmonic contents are the main problem which to be reduce for getting better performance and reduction of harmonic contents are the main issue for power electronic design engineers. PWM switching schemes not only useful in reducing THD, effective DC bus utilization, but also it helps to reduce some extra secondary issues like electromagnetic interference (EMI), switching losses, better spreading of harmonics over the spectrum [1]. There are different types of PWM techniques where the most widely used techniques are carrier based sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM) due to efficient in reducing THD. For generating PWM signals for three phases, three phase reference modulating signals are compared with a common triangular carrier wave in SPWM. On the other hand, a revolving reference voltage vector is used as reference voltage without using three phase modulating waves in the Space Vector PWM. This reference voltage is the key parameter to control the magnitude and frequency of the fundamental component in the line side [2, 3]. Numerous advantages in practice are analyzed among the PWM schemes which are based on the concept of voltage space vectors [4, 5]. Also field oriented control can be applied in PMSM based on Space Vector Pulse Width Modulation [6]. The main focus of this paper is to develop the simple MATLAB Simulink model by using both SPWM and SVPWM schemes and study the comparison of the total harmonic distortion and better utilization of the DC bus in three phase voltage source inverter. From the analysis of the simulation results in both SPWM and SVPWM, it reveals that SVPWM schemes gives better performance in reducing

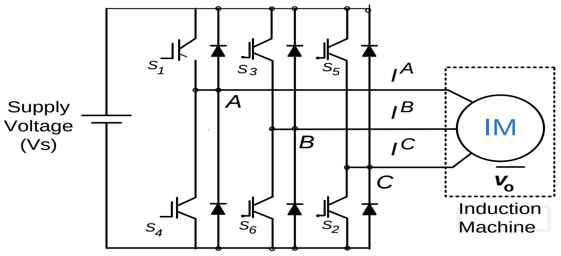


Fig. 1: Three-Phase Voltage Source Inverter (VSI) topology

total harmonic distortion (THD) and giving the better DC bus utilization.

2. SPWM AND SPACE VECTOR PULSE WIDTH MODULATION

The topology of the three phase voltage source inverter is shown in Figure 1. The output voltage of three phase voltage source inverter (VSI) is controlled by sinusoidal pulse width modulation (SPWM), also called Sine Coded Pulse Width Modulation. In this technique,

$$\text{Modulation Index, } M = \frac{A_r}{A_c} \tag{1}$$

Where, A_r = Reference signal magnitude and
A_c = Carrier signal magnitude.

Figure 2 shows the sinusoidal pulse generation technique for the three phase inverter. In SPWM, three phase quantities are treated as separately.

All quantities are given in below

$$V_A = V_m \sin \omega t \tag{3}$$

$$V_B = V_m \sin(\omega t - 2\pi/3) \tag{4}$$

$$V_C = V_m \sin(\omega t - 4\pi/3) \tag{5}$$

There are 2^3=8 permissible switching states in three phase inverter for 180˚ conduction mode where six active states and another two are zero state. When the load terminal are connected through the lower or upper devices then it is depicted as zero state [7].

Considering state 2, when switches 1, 3 and 2 are closed then the phase A, phase B are connected to the positive bus and phase C is connected to the negative bus. Therefore, the circuit solution implies that

$$V_{AN} = \frac{1}{3}V_s,\ V_{BN} = \frac{1}{3}V_s \text{ and } V_{CN} = -\frac{2}{3}V_s \tag{2}$$

The switching sequence of the three phase inverter is in order of 1-6-5, 4-6-5, 4-3-5, 4-3-2, 1-3-2, 1-6-2; where each switches conducts over 180˚ in a period. Switching sequence exist 60˚ apart from one to another. In Table 1 switching patterns and output vectors are presented.

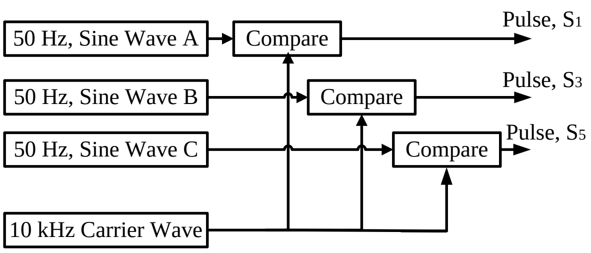


Fig. 2: Sinusoidal Pulse width modulation Technique.

Table 1: Switching patterns and output vectors

Voltage Vectors	Switching States			Phase to neutral Voltage			Phase to Phase Voltage		
	A	B	C	V_{AN}	V_{BN}	V_{CN}	V_{AB}	V_{BC}	V_{CA}
V0	0	0	0	0	0	0	0	0	0
V1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V2	1	1	0	1/3	1/3	-2/3	0	1	-1
V3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V4	0	1	1	-2/3	1/3	1/3	-1	0	1
V5	0	0	1	-1/3	1/3	2/3	0	-1	1
V6	1	0	1	1/3	-2/3	1/3	1	-1	0
V7	1	1	1	0	0	0	0	0	0

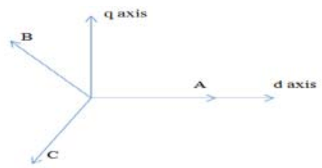


Fig. 3: Relationship between three-phases (ABC) vs. stationary d-q reference frame

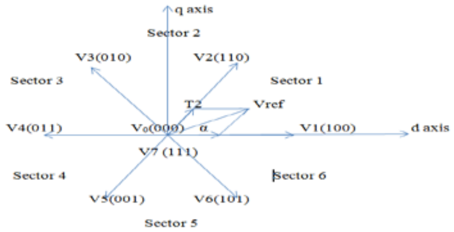


Fig. 4: Basic switching vectors and sectors in SVPWM schemes

On the other hand, in SVPWM, 3-phase quantities are treated using single equation known as space vector [8].

The space vector of a three-phase voltage is defined as,

$$V_{space} = \frac{2}{3}[V_A(t) + V_B(t)e^{j\frac{2\pi}{3}} + V_C(t)e^{j\frac{4\pi}{3}}] \tag{6}$$

$$V_{space} = \frac{2}{3}V_s[S_A + aS_B + a^2 S_C] \tag{7}$$

The magnitude and angle of the rotating space vector can be found by means of Clark's Transformation in the stationary reference frame. For implementing the SVPWM, three phase voltage in ABC reference frame can be transformed into the stationary dq reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Figure 3 and in figure 4 basic switching vectors and sectors are presented.

$$f_{dqo} = K_s f_{ABC} \tag{8}$$

3. STEPS FOR IMPLEMENTING SVPWM

Following the steps, space vector pulse width modulation can be implemented.

Step 1: Determine V_d, V_q, and V_{ref} and angle (α).

Step 2: Determine the time duration T1, T2, and

Step 3: Determine the switching time of each transistor (Switch 1 to switch 6).

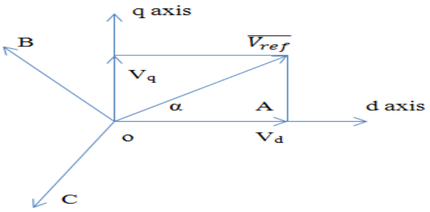


Fig. 5: Voltage space vector and its components in dq frame.

From the Figure 4, V_d, V_q, and V_{ref} and angle (α) can be determined as follows:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} \tag{9}$$

$$\left|\overline{V_{ref}}\right| = \sqrt{V_d^2 + V_q^2} \tag{10}$$

$$\alpha = \tan^{-1}\left(\frac{V_q}{V_d}\right) = \omega t = 2\pi f t \tag{11}$$

Where, f = fundamental frequency. Voltage space vectors and its components in d-q frame are indicated in Figure 5. The interval for each voltage vector is determined by equating volt-second integral of V_s with the sum of all voltage vectors with in a cycle. The time constant is as below

$$T = T_o + T_1 + T_2 + T_7 \tag{12}$$

Let, $T_0 = T_7$ and It can calculate all the required time intervals. If the angle between the reference voltage and the adjacent vector is α, it can be shown that for any sector the time intervals T1 and T2 are given by

$$T_1 = \frac{3}{2} T V_s \left(\cos\alpha - \frac{2}{\sqrt{3}} \sin\alpha\right) \tag{13}$$

$$T_2 = \sqrt{3} T V_s \sin\alpha \tag{14}$$

From equation (15)

$$T_7 + T_o = T - (T_1 + T_2) \tag{15}$$

By using the equations (12) to (15), it can find out the switching pattern for three phases in different sectors which are depicted in Figure 6.

Sector 1

Sector 2

Sector 3

Sector 4

Sector 5

Sector 6

Fig. 6: Switching pulses pattern of each transistor (one to six) in six different sectors

4. SIMULATION RESULTS FOR SPWM

The output voltage and the stator current of the induction machine are depicted in Figure 7.

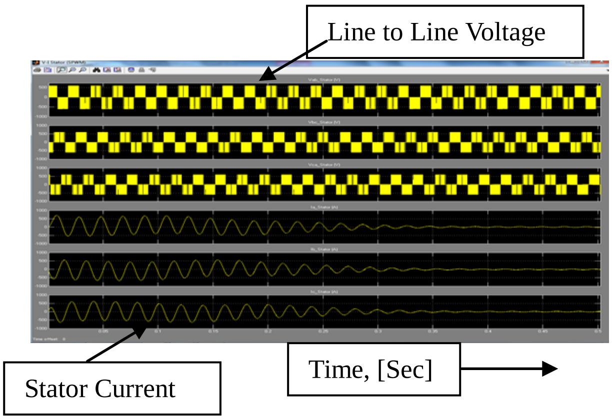
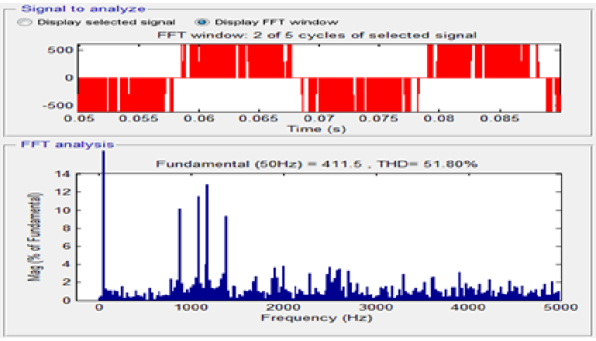


Fig. 7: Line to line voltage and each phase currents of the stator of induction machine with respect to time

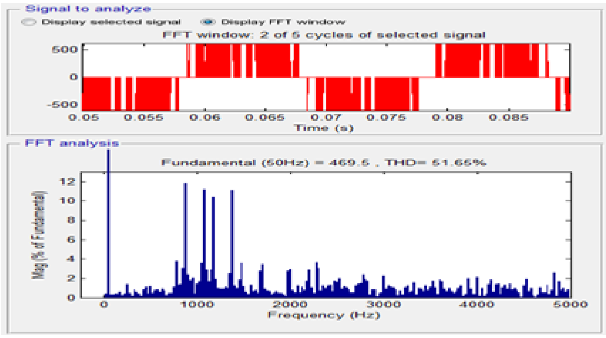
4.1 FFT ANALYSIS (SPWM)

4.1.1 FFT ANALYSIS OF VOLTAGES IN SPWM

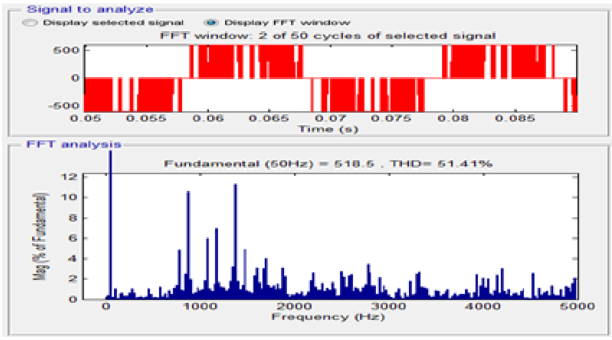
FFT analysis reveals the following total harmonic distortion (THD) for the case of output line voltage in different modulation index. The results of total harmonic distortion (THD) analysis are presented in figure 8 (a) to 7 (c) for different modulation index.



(a) for M = 0.8 (SPWM)



(b) for M = 0.9 (SPWM)



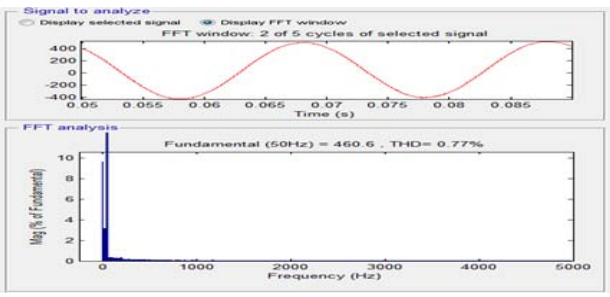
(c) for M = 1.0 (SPWM)

Fig. 8: Total Harmonic Distortion (THD) analysis for output voltages in SPWM: (a) for M=0.8, (b) for M=0.9 and (c) for M=1.0.

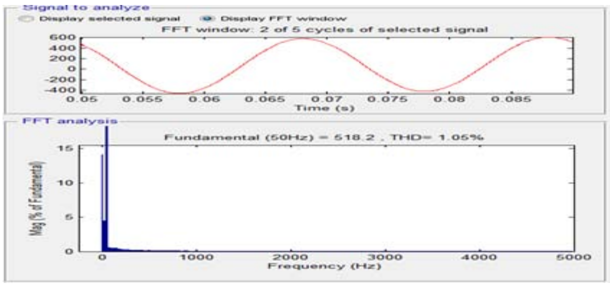
4.1.2. FFT ANALYSIS OF INPUT CURRENT IN SPWM

FFT analysis reveals the following total harmonic distortion (THD) for the case of fundamental component of stator current in different modulation index.

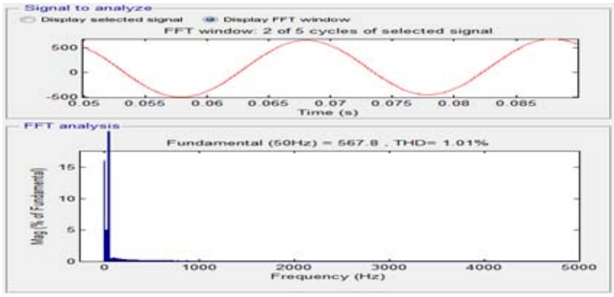
The results of total harmonic distortion (THD) analysis for stator current with SPWM are presented in Figure 9 (a) to 9(c) for different modulation index



(a) for M=0.8 (SPWM)



(b) for M=0.9 (SPWM)



(c) for M=1.0 (SPWM)

Fig. 9: Total Harmonic Distortion (THD) analysis of fundamental component of stator current in sinusoidal pulse width modulation (a) for M=0.8, (b) for M=0.9 and (c) for M=1.0

5. SIMULATION RESULTS OF SVPWM

By simulating the model for space vector modulation, results are elaborated in Figure 10 and reveal the line to line voltage and each phase currents of the stator of induction machine with respect to time.

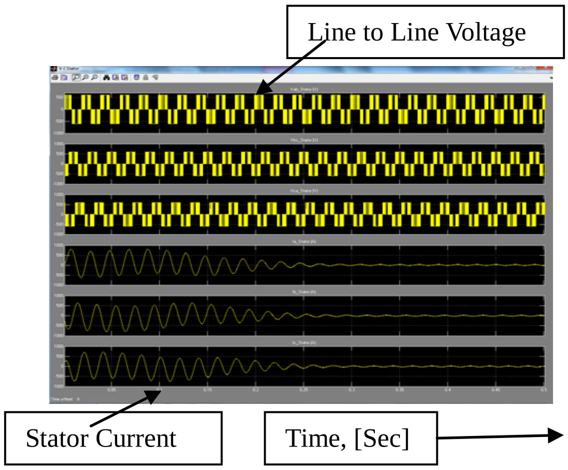


Fig. 10: SVPWM: line to line voltage and each phase currents of the stator of induction machine.

Table 2: Simulation Parameters for SVPWM.

SL. No.	Parameter Names	Values
1	DC Supply Voltage, V_{DC}	600V
2	Chopping Frequency, f	10 KHz
3	Fundamental frequency, f	50 Hz
4	Phase	0º

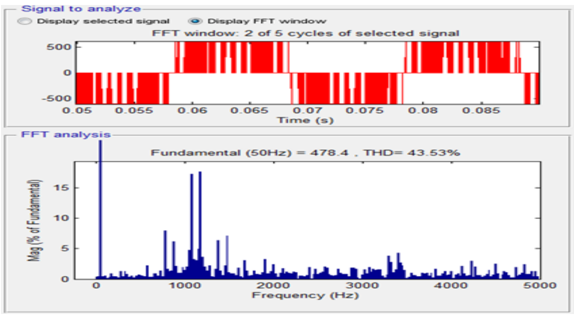
Table 3: Simulation Parameters for Sinusoidal Pulse width modulation

SL. No.	Parameter Names	Values
1	DC Supply Voltage, V_{DC}	600V
2	Carrier Frequency, fc	10 KHz
3	Fundamental frequency, f	50 Hz
4	Phase of output voltage	0º
5	Constant Mechanical Torque	0.5 Nm
6	Step Time	0.5
7	Initial value, Final value	0, 190
8	Sample Time	0
9	Induction Machine Parameters	80HP, Voltage(L-L) 440, Frequency 50 Hz

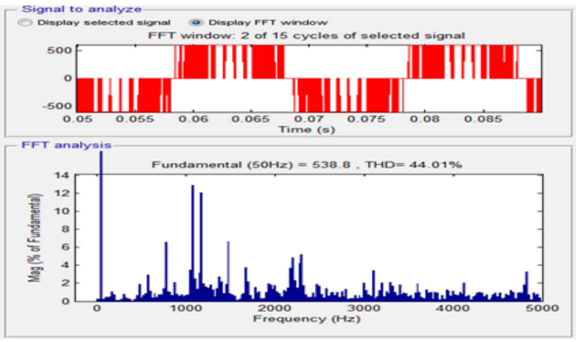
5.1 FFT ANALYSIS (SVPWM)

5.1.1 FFT ANALYSIS OF VOLTAGES IN SVPWM

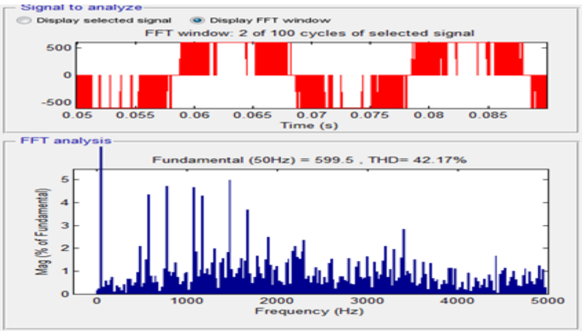
Space vector PWM FFT analysis reveals the following total harmonic distortion (THD) for the case of output line voltage in different modulation index. The results of total harmonic distortion (THD) analysis are presented in Figure 11 (a) to 11 (c) for different modulation index.



(a) for M=0.8 (SVPWM)



(b) for M=0.9 (SVPWM)

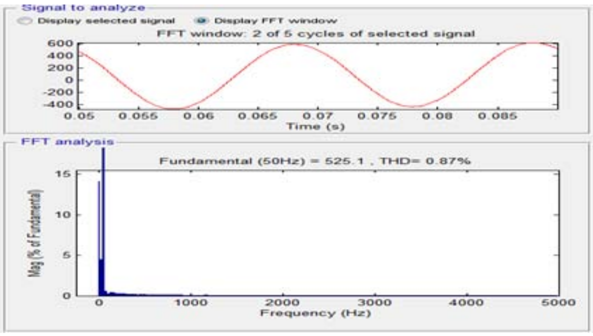


(c) for M=1.0 (SVPWM)

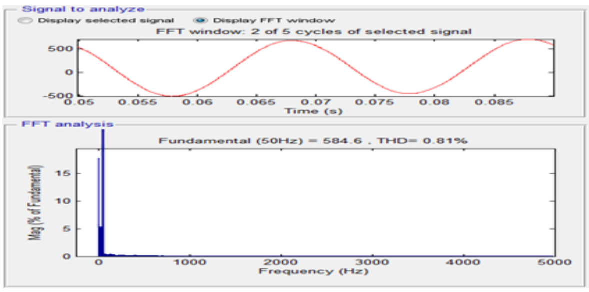
Fig. 11: THD% analysis for output voltages in SVPWM (a) for M=0.8, (b) for M=0.9 and (c) for M=1.0.

5.1.2 FFT ANALYSIS OF INPUT CURRENT IN SVPWM

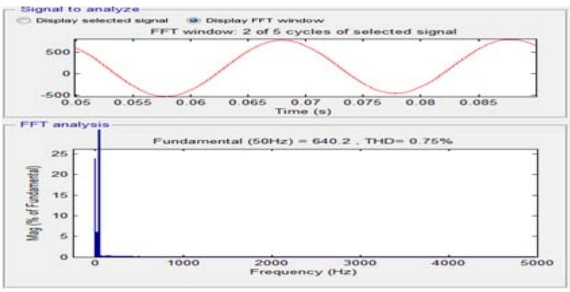
FFT analysis in SVPWM depicts the following total harmonic distortion (THD) for fundamental component of stator current. The results of total harmonic distortion (THD%) analysis for stator current with SVPWM are presented in Figure 12 (a) to 12 (c).



(a) for M=0.8 (SVPWM)



(b) for M=0.9 (SVPWM)



(c) for M=1.0 (SVPWM)

Fig. 12: Total Harmonic Distortion (THD) analysis of fundamental component of stator current in space vector pulse width modulation (a) for M=0.8, (b) for M=0.9 and (c) for M=1.0.

6. COMPARISON OF TOTAL HARMONIC DISTORTION BETWEEN SPWM AND SVPWM

The comparative study of FFT analysis for both SPWM and SVPWM for the output line voltage is represented in Table 4 and fundamental component of stator current is in Table 5.

Table 4: FFT analysis between SPWM and SVPWM for Line voltage

Mod. Tech. (M.I)	SPWM		SVPWM	
	Output Line Voltage (Peak) (V)	THD (%)	Output Line Voltage (Peak) (V)	THD (%)
0.8	411.5	51.80	478.4	43.53
0.9	469.5	51.65	538.8	44.01
1.0	518.5	51.41	599.5	42.17

Table 5: FFT analysis between SPWM and SVPWM in the case of fundamental components of stator current

Mod. Tech. (M.I)	SPWM		SVPWM	
	Stator Current I_A (A)	THD (%)	Stator Current I_A (A)	THD (%)
0.8	460.6	0.77	525.1	0.87
0.9	518.2	1.05	584.6	0.81
1.0	567.8	1.01	640.2	0.75

The results described in the Table 4 shows, for modulation index 0.8, output line voltage is 411.5 V and THD 51.80% in SPWM control, whereas in SVPWM output line voltage 478.4 V and THD is 43.53%. Therefore improves the THD in SVPWM compare to SPWM with better DC bus utilization. Similarly, for modulation index 0.9 and 1.0, THD also been improved with increasing DC bus voltage. On the other hand, THD of stator current in induction machine is improved for modulation index 0.9 and 1.0 except 0.8 in case of SVPWM which are putted in Table 5. It is because of lower modulation index. So for getting the best results high modulation index are mostly acceptable. However, the results found from the comparative study are very much encouraging.

7. CONCLUSION

In this investigation, the simulations are carried out in MATLAB Simulink environment. This inquisition discloses the several informations which are expected for reducing the THD. In SVPWM, THD of output line voltages are reduced for all the modulation index utilized in the simulation and it is ranges from approximately 9% to 10% corresponds to SPWM with better DC bus utilization. On the other hand, THD of fundamental components of current are reduced in SVPWM compare to SPWM same with the better DC bus utilization. Finally it can be summarized that this investigation reveals the better performance in focusing to THD with SVPWM compare to SPWM.

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