

# Simulation and Analysis of Indirect Field Oriented Control (IFOC) of Three Phase Induction Motor with Various PWM Techniques

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**Abstract:** The dynamics of the induction motor drive can be made independent of the position as well as speed control by using the field oriented control strategies. There are various techniques available under this category. One of such strategies is Indirect Field Oriented Control for the Induction Motor drive. The speed control is observed in closed loop control applications with different Pulse Width Modulation technique such as Hysteresis band controller, Sin-PWM (SPWM), Space Vector Pulse Width Modulation (SVPWM). The speed regulation is achieved with a PI controller which converts the command speed into the command torque and therefore the speed of the drive. Results of simulation are consistent with theory analyzed, and indicate that the model is accurate and practicable.

**Keywords:** Indirect Field Oriented Control, Space Vector Pulse Width Modulation (SVPWM), Hysteresis Current Controller, Sin-Triangle Pulse Width Modulation, Induction Motor.

## I. INTRODUCTION

At the present time, the field oriented control (FOC) technique is the widespread used in high performance induction motor drives [1, 2]. It allows, by means a co-ordinate transformation, to decouple the electromagnetic torque control from the rotor flux, and hence manage induction motor as DC motor. In this technique, the variables are transformed into a reference frame in which the dynamic behave like DC quantities. The decoupling control between the flux and torque allows induction motor to achieve fast transient response. Therefore, it is preferably used in high performance motor applications.

Nevertheless the performance of the output voltage of inverter that fed induction motor system is mainly determined by pulse width modulation (PWM) strategy. The simple implementation is to use current control based on hysteresis current controller. With this method, fast response current loop will be obtained and knowledge of load parameter is not required. However this method can cause variable switching frequency of inverter [3] and produce undesirable harmonic [4, 5]. Another method of PWM that have become popular and received great interest by researcher is SPWM. This technique has better dc bus utilization and easy for digital implementation but it contains 3<sup>rd</sup> order harmonics. In [6], SVPWM technique is used with the control strategy which

reduces the harmonics on the motor side. This paper presents a comparative performance of SVPWM towards the traditional Sin-PWM and hysteresis current controller to control high performance induction motor incorporated with indirect field orientation technique. The modelling and simulation of SVPWM system of induction motor is performed, the principle and algorithm is analyzed. This paper is organized as follows. The Hysteresis band controller, Sin- PWM, Space Vector PWM based Indirect Field Oriented Control is presented in section II. The comparison between performances of these systems is presented by simulation results in section III and finally some concluding remarks are stated in the last section.

## II. INDIRECT FIELD ORIENTED CONTROL OF THREE PHASE INDUCTION MOTOR

Three phase squirrel cage induction motor in synchronously rotating reference frame can be represent by following voltage equation:

$$V_{qs} = R_s I_{qs} + d\Phi_{qs} / dt + \dot{\Theta}_e \Phi_{ds} \quad \text{---(1)}$$

$$V_{ds} = R_s I_{ds} + d\Phi_{ds} / dt - \dot{\Theta}_e \Phi_{qs} \quad \text{---(2)}$$

$$V_{qr} = R_r I_{qr} + d\Phi_{qr} / dt + (\dot{\Theta}_e - \dot{\Theta}_r) \Phi_{dr} \quad \text{---(3)}$$

$$V_{dr} = R_r I_{dr} + d\Phi_{dr} / dt + (\dot{\Theta}_e - \dot{\Theta}_r) \Phi_{qr} \quad \text{---(4)}$$

and with  $V_{qr}, V_{dr} = 0$ , flux equation are:

$$\Phi_{qs} = L_{ls} I_{qs} + L_m (I_{qs} + I_{qr}) \quad \text{---(5)}$$

$$\Phi_{qr} = L_{lr} I_{qr} + L_m (I_{qs} + I_{qr}) \quad \text{---(6)}$$

$$\Phi_{ds} = L_{ls} I_{ds} + L_m (I_{ds} + I_{dr}) \quad \text{---(7)}$$

$$\Phi_{dr} = L_{lr} I_{dr} + L_m (I_{ds} + I_{dr}) \quad \text{---(8)}$$

Where  $V_{qs}, V_{ds}$  are the applied voltages to the stator,  $I_{qs}, I_{ds}, I_{qr}, I_{dr}$  are the corresponding d and q axis stator current and rotor currents.  $\Phi_{qs}, \Phi_{ds}, \Phi_{qr}, \Phi_{dr}$  are the rotor and stator flux component,  $R_s, R_r$  are the stator and rotor resistances,  $L_{ls}, L_{lr}$  denotes stator and rotor inductances, whereas  $L_m$  is the mutual inductance. The electromagnetic torque equation is

$$T_e = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r} (\Phi_{dr} I_{qs} - \Phi_{qr} I_{ds}) \quad \text{---(9)}$$

Where  $P$ , denote the pole number of the motor and rotor inductance  $L_r = (L_{lr} + L_m)$ . If the vector control is fulfilled, the q component of the rotor field  $\Phi_{qr}$  would be zero. Then the electromagnetic torque is controlled only by q-axis stator current and becomes:

$$T_e = \frac{3 P L_m}{2 L_r} (\Phi_{dr} I_{qs}) \quad \text{---(10)}$$

Fig. 2 (a), (b) and (c) shows the block diagram of indirect field oriented controlled of three phase induction motor with hysteresis current controller, SPWM and SVPWM. The flux command  $\Phi_{dr}^*$  indicates the right rotor flux command for every speed reference within the nominal value. From this the d-axis current reference  $I_{ds}^*$ , can be calculate using equation below

$$I_{ds}^* = \Phi_{dr}^* / L_m \quad \text{---(11)}$$

$$I_{qs}^* = \frac{T_e L_m}{P L_r \Phi_{dr}^*} \quad \text{---(12)}$$

Voltage decoupled equations become

$$V_{qsff} = R_s I_{qs}^* + \tilde{S}_e \dagger L_s I_{ds}^* \quad \text{---(13)}$$

$$V_{dsff} = R_s I_{ds}^* + \tilde{S}_e \ddagger L_s I_{qs}^* \quad \text{---(14)}$$

$$\tilde{S}_{sl} = \frac{I_{qs}^*}{\ddagger I_{ds}^*} \quad \text{---(15)}$$

Where  $L_s = L_{ls} + L_m$  is stator inductance,  $\tilde{S}_e$  is a synchronous speed,  $\dagger = (1 - L_m^2 / L_m L_r)$ ,  $\ddagger_r$  = rotor time constant. Decoupling circuit which has to be introduced into the control system of a voltage-fed rotor flux oriented induction machine, if decoupled flux and torque control is to be achieved. It is possible to omit decoupling circuit from the control system, without significant influence on dynamic response, if the sampling frequency and inverter switching frequency are high enough, usually above at least 1 kHz. If the inverter switching frequency is under 1 kHz, decoupling circuit should be included. However, application of decoupling circuit enables improvement of dynamics even at inverter switching frequency above 1 kHz. At higher switching frequencies current controllers are capable of suppressing interaction between d- and q-axis and decoupling circuit is in most cases omitted.

The rotor speed  $\tilde{S}_m$  is compared to rotor speed command  $\tilde{S}_m^*$  and the resulting error is process in the controller. The controller generates the q-axis reference current  $I_{qs}^*$ . For hysteresis current controller in Fig. 2(a), both stator reference current in d-axis and q-axis are converted to three phase stationary reference frame through Inverse Park Transformation and compared to the current from the feedback of the motor. Then the current errors are fed to hysteresis current controllers which generate switching

signal for the voltage source inverter. While for SPWM technique in Fig 1(b), both reference current in d-axis and q-axis is compared from the feedback from the motor current through Clark and Park Transformation. From the respective error the voltage command signal is generated through PI controller, summed with voltage decoupled equation and converted to three phase voltage. These voltages are compared with carrier signals block.

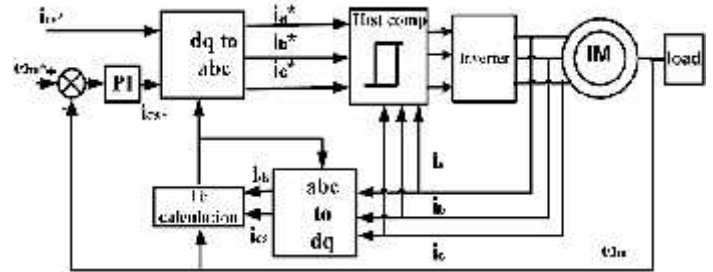


Fig. 1(a)

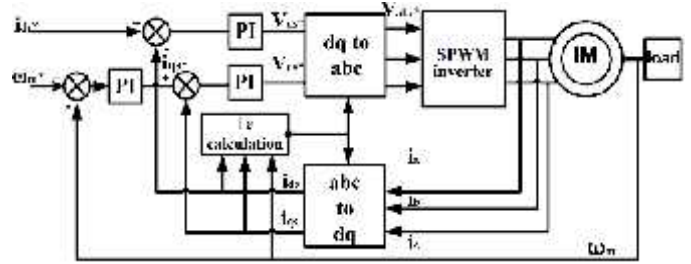


Fig. 1(b)

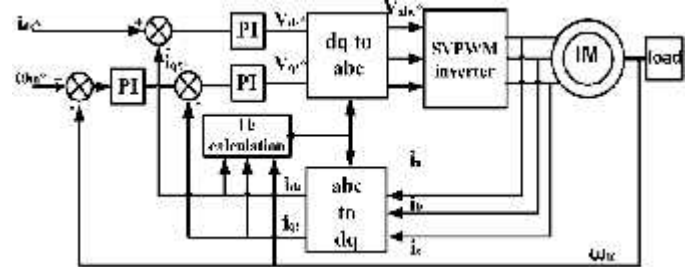


Fig. 1(c)

Fig. 1: (a) IFOC using Hysteresis band controller (b) IFOC using Sin-triangle PWM controller (c) IFOC using SVPWM technique

Similarly IFOC with SVPWM is implemented in Fig 1(c). SVPWM can be implemented by:

- Determine  $V_d$ ,  $V_q$ ,  $V_{ref}$  and angle
- Determine time duration  $T_1$ ,  $T_2$  and  $T_0$
- Determine the switching time of each transistor

In SVPWM block, the three phase voltage is transform into d-q axis using

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \text{--- (16)}$$

The SVPWM uses two neighboring effective vectors and null vectors of the eight basis space voltage vector and their different act time to obtain the equivalent space voltage vector that the motor needs, as shown in Fig 2.

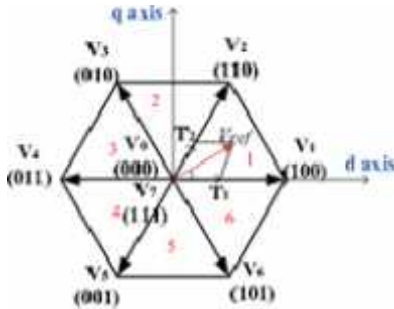


Fig. 2: Basic Voltage Vector and Reference Vector

Fig. 2 shows that there are six voltage vectors that can be selected to apply to the motor. The reference  $V_{ref}$  and angle of respective sector can be obtain as

$$|V_{ref}| = \sqrt{V_d^2 + V_q^2} \quad \text{--- (17)}$$

$$r = \tan^{-1} \left( \frac{V_q}{V_d} \right) \quad \text{--- (18)}$$

And switching time duration at any sector is as

$$T_1 = \frac{\sqrt{3} V_{ref} T_s [\sin(kf/3) \cos(r) - \cos(kf/3) \sin(r)]}{V_{dc}} \quad \text{--- (19)}$$

$$T_2 = \frac{\sqrt{3} V_{ref} T_s [-\sin((kf-1)/3) \cos(r) + \cos((kf-1)/3) \sin(r)]}{V_{dc}} \quad \text{--- (20)}$$

$$T_0 = T_s - T_1 - T_2 \quad \text{--- (21)}$$

Where  $k$  is a sector from 1 to 6,  $r$  is angle between  $0^\circ$  to  $60^\circ$  and  $T_s = 1/f_s$ , sampling frequency. SVPWM switching pattern for sector 1 and sector 6 is shown in Fig. 3 and switching time at any sector sequence is summarized in Table I. From this table a mathematical equation is built in function block in SIMULINK to generate a SVPWM waveform.

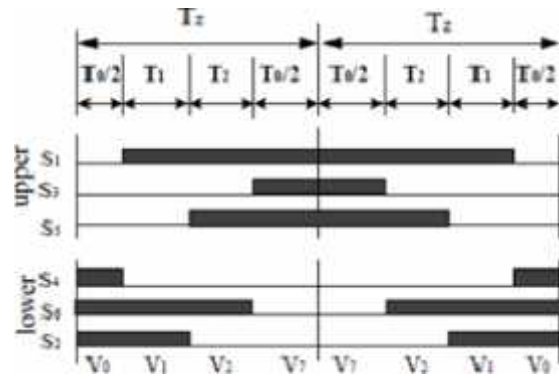


Fig. 3(b)

Fig. 3: Switching pattern for (a) sector 1 (b) sector 6

### III. SIMULATION AND COMPARATIVE ANALYSIS OF VARIOUS PWM TECHNIQUES

Simulation has been carried out using MATLAB/SIMULINK for 15 kW, 1470 rpm three phase induction motor which has following parameters:

L-L voltage(rms) , supply frequency(f), Number of poles(P)	400 V, 50 Hz, 4 poles machine
Stator resistance( $R_s$ ), Leakage stator inductance( $L_{ls}$ )	0.2147 , 0.991 mH
Rotor resistance( $R_r$ ), Leakage rotor inductance( $L_{lr}$ )	0.2205 , 0.991 mH
Mutual inductance ( $L_m$ )	64.19 mH

Simulink Model of IFOC induction motor drive for 15 kW rating is prepared using IFOC-Hysteresis band controller, IFOC- Sin-triangle PWM controller and IFOC SVPWM technique. The drive performance when motor speed changes from 1500 rpm to 750 rpm is simulated and the results obtained are as shown in Fig. 4 (a), (b) and (c).

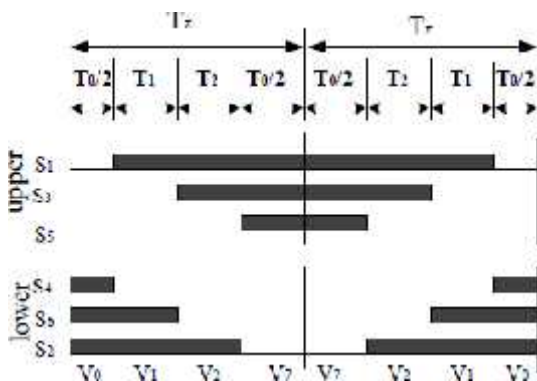


Fig. 3(a)

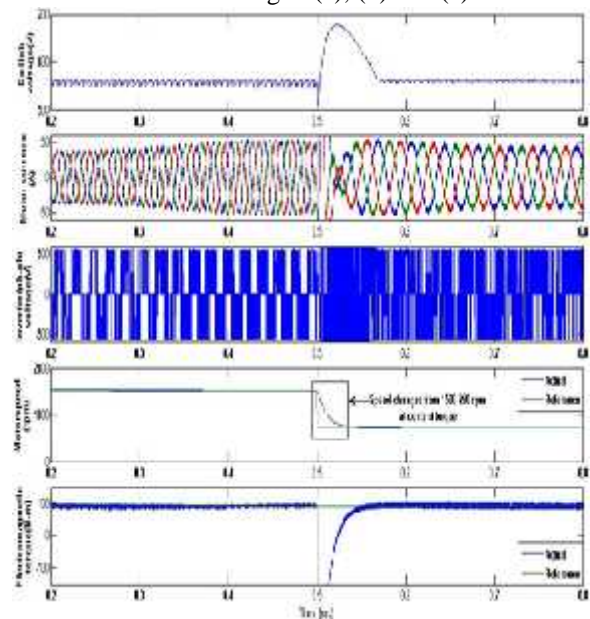


Fig. 4(a)

TABLE I SWITCHING TIME CALCULATION AT EACH SECTOR

Sector	Upper Switches ( $S_1, S_3, S_5$ )	Lower Switches ( $S_4, S_6, S_2$ )
1	$S_1=T_1+T_2+T_0/2, S_3=T_2+T_0/2, S_5=T_0/2$	$S_4= T_0/2, S_6= T_1+T_0/2, S_2= T_1+T_2+T_0/2$
2	$S_1= T_1+T_0/2, S_3= T_1+T_2+T_0/2, S_5=T_0/2$	$S_4= T_2+T_0/2, S_6= T_0/2, S_2= T_1+T_2+T_0/2$
3	$S_1= T_0/2, S_3= T_1+T_2+T_0/2, S_5= T_2+T_0/2$	$S_4= T_1+T_2+T_0/2, S_6= T_0/2, S_2= T_1+T_0/2$
4	$S_1= T_0/2, S_3= T_1 +T_0/2, S_5= T_1+T_2+T_0/2$	$S_4= T_1+T_2+T_0/2, S_6= T_2+T_0/2, S_2= T_0/2$
5	$S_1= T_2+T_0/2, S_3= T_0/2, S_5= T_1+T_2+T_0/2$	$S_4= T_1+T_0/2, S_6= T_1+T_2+T_0/2, S_2= T_0/2$
6	$S_1= T_1+T_2+T_0/2, S_3= T_0/2, S_5= T_1+T_0/2$	$S_4= T_0/2, S_6= T_1+T_2+T_0/2, S_2= T_2+T_0/2$

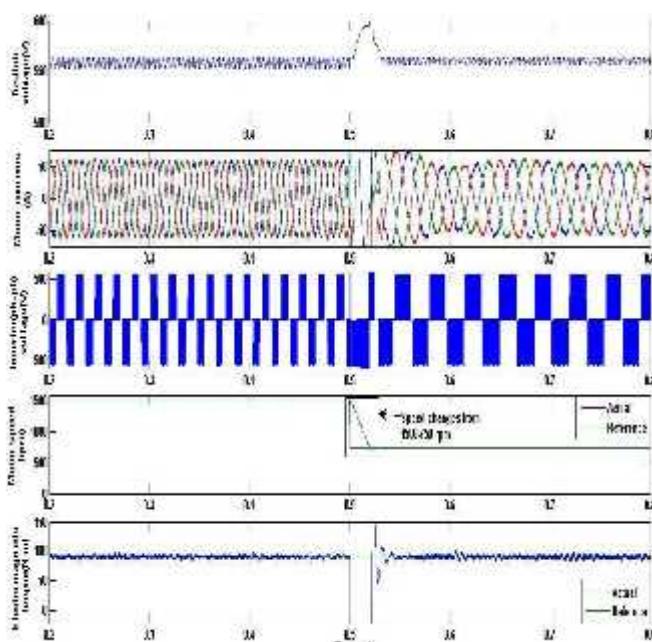


Fig. 4(b)

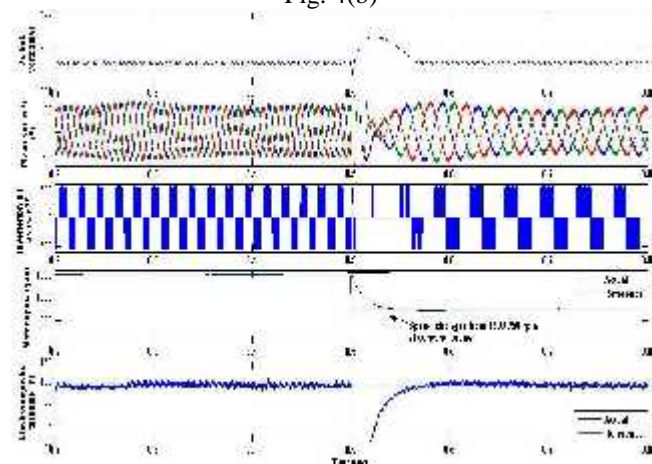


Fig. 4(c)

Fig. 4: Motor performance under speed changes from 1500 to 750 rpm (a) With IFOC- HB (b) IFOC-SPWM (c) IFOC-SVPWM

The IFOC induction motor drive is simulated at sampling time of  $10e-6$  in MATLAB with switching frequency of 7.5 kHz for SPWM and SVPWM. The reference speed command changes the speed at 0.5 sec of simulation at constant torque of 90 N-m. The torque ripple in each case is 15 N-m, 15 N-m, and 12 N-m respectively. Now simulation is carried out for changing load from full load (90-N-m) to No-load at constant speed of 900 rpm and results are as shown below

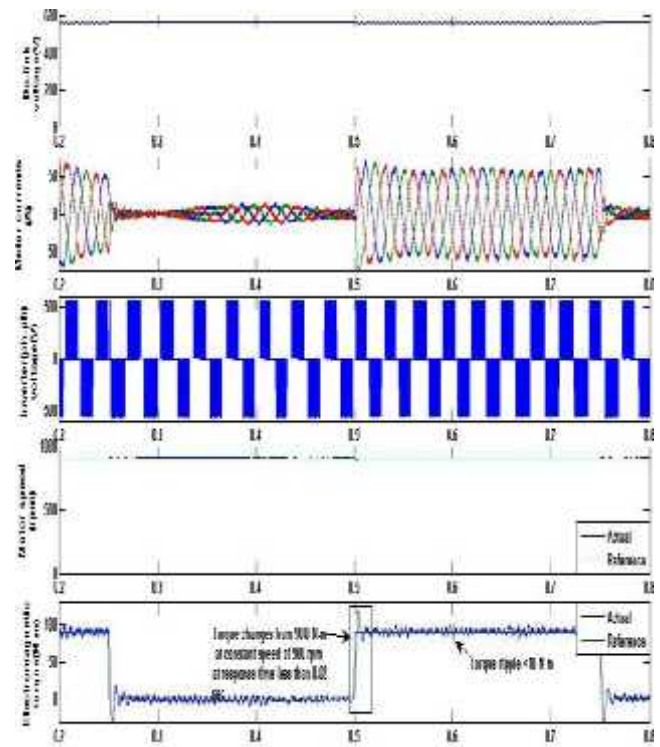


Fig. 5(a)

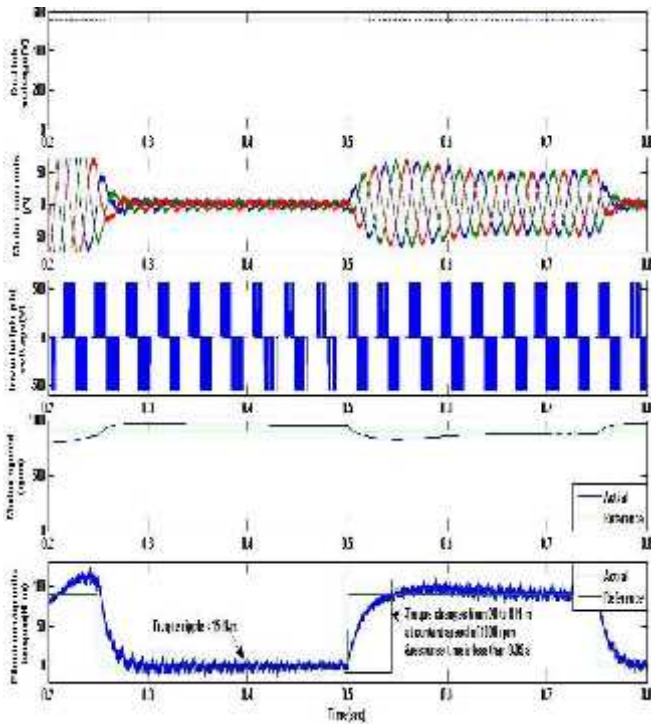


Fig. 5(b)

Fig. 5: Motor performance under Torque changes from 90 to 0 N-m (a) IFOC-SVPWM (b) IFOC-SPWM

FFT analysis of A-phase Stator current under steady state for IFOC using SPWM and IFOC using SVPWM techniques is shown in Fig. 6 (a) and (b).

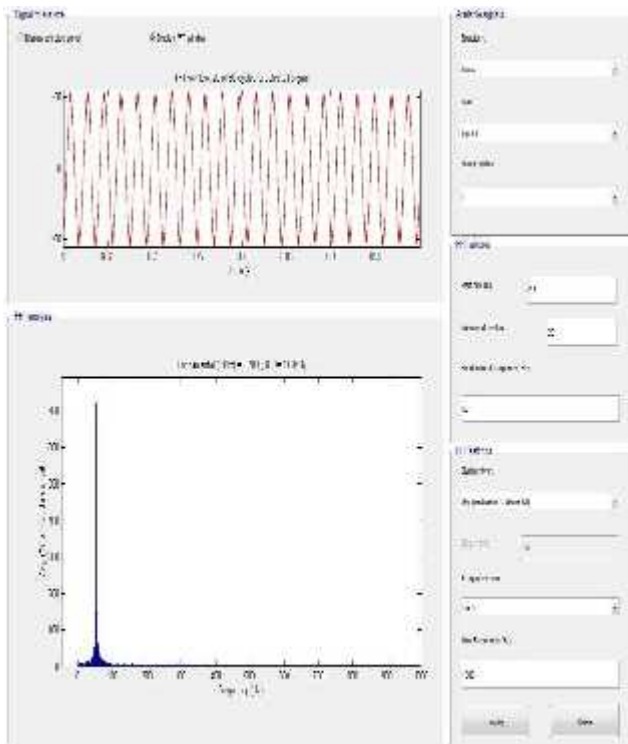


Fig. 6(a)

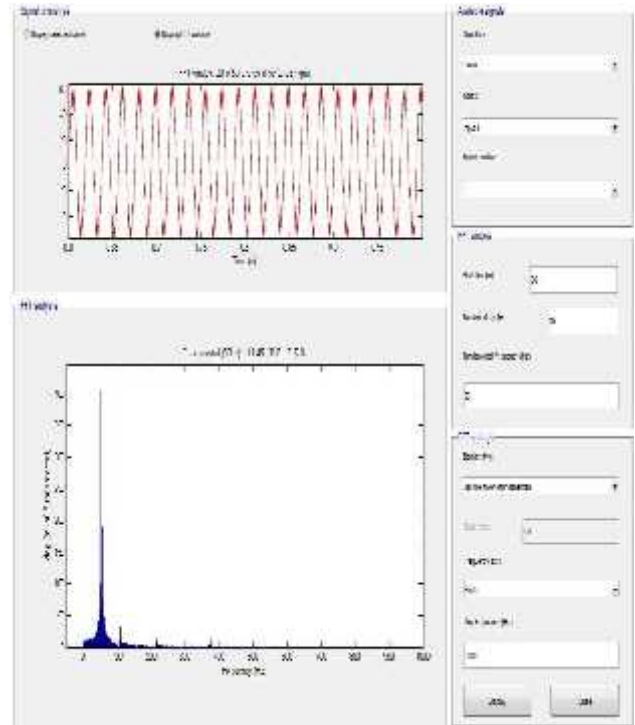


Fig. 6(b)

Fig. 6: FFT analysis and THD of A-phase Stator current under steady state for (a) IFOC-SPWM (b) IFOC-SVPWM

From FFT analysis it has been concluded that during the control of induction motor the frequency of current changes from 50 Hz to 52 Hz for IFOC-SPWM and to 51.86 Hz for IFOC-SVPWM. The above results are without any filter used. As frequency increases the hysteresis and eddy current loss also increases which reduce the efficiency of motor. The THD level for IFOC-SPWM and IFOC-SVPWM drive with 52 Hz as base frequency and for 20 cycles are 2.88% and 2.39 % respectively. The THD level for IFOC-SPWM and IFOC-SVPWM drive with 50 Hz as base frequency and for 20 cycles are 10.84% and 7.22 % respectively. From FFT analysis it is observed that IFOC-SPWM technique contains the third order harmonics while in SVPWM technique it is eliminated.

TABLE II OVERALL COMPARISONS OF IFOC DRIVES WITH DIFFERENT PWM TECHNIQUES

	Hysteresis Band	SPWM	SVPWM
Implementation	Easy	Medium	Complex
Switching frequency	Variable	Constant	Constant
Sampling Time	Can work on very small time for sampling one value	Can work on very medium time for sampling one value	Can work on very large time for sampling one value
THD level at 50 Hz	11.58%	10.84 %	7.22 %
Torque ripple (p-p)	15 N-m	15 N-m	12 N-m
DC-link Utilization	Low	High	Medium

#### IV. CONCLUSION

In this paper, an indirect field oriented control of three phase induction motor using hysteresis current band, SPWM and SVPWM technique has done using MATLAB/SIMULINK. The comparative performances between these techniques were presented. From the simulation results, SVPWM technique gives better performances in elimination of the stator current harmonics and reduction of the torque ripple while maintaining the other characteristic of the system.

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