ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 7, July 2015

Modelling and Simulation of Variable Speed Squirrel Cage Induction Motor Drives

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ABSTRACT: In the present time, the variable speed induction motors are being popularized with efficient performance by using different PWM techniques. These kinds of drives are replacing D.C. motors and thyrister bridges day by day in the industries. In the past, Many Pulse Width Modulated (PWM) inverter fed induction motor models has been proposed by researchers and used in the various adjustable speed drives applications. But, the harmonics in the voltage, current and electromagnetic torque remains create problem in this type of drives. For minimizing harmonics, they used 5 and 7 level inverters. But, the 3-level inverter is being more popular and extensively being used in many power electronics and drives applications rather that 5 and 7 level inverters. Therefore, in this work, we have developed 3-level inverter fed squirrel cage induction motor model with better performance. In the present paper, the open and closed loop 3 level inverter fed induction motor has been proposed and developed in the latest MATLAB/Simulink environment. It has been observed that the closed loop PWM model gives better results as compare to open loop model with reduced harmonics. The direct torque control method has been used along with PWM inverter for induction motor controlling purpose.

KEYWORDS: Squirrel Cage Induction Motor, IGBT inverter, Pulse Width Modulation, Direct Torque Control, Modelling and Simulation, MATLAB/Simulink.

I.INTRODUCTION

Induction motors, especially Squirrel Cage Induction Motor (SCIM) are being widely used these days in the industries along with different PWM techniques for variable speed applications. This kind of drives are often used in the appliances, industrial control and automation; hence called workhorse of the motion industry[1,3]. The Induction Motor having some important advantages over other motors such as simple construction, high reliability and the availability of power converters based on efficient control strategies. Since, induction machines are made and used in largest number of applications due to their varied modes of operation under both under steady state and dynamic states[3,6,12].

The induction machines may be used in some important applications in the place of D.C. machines. The most important feature which declares induction motor as a tough competitor to D.C. machines in the drives filed is that its cost per KVA is approximately one fifty of its counter-part and it possesses higher suitability in the hostile environment[1,3,5]. AC drives are more predominant than DC drives. AC drives requires high power variable voltage variable frequency supply. The research in Pulse width modulation schemes has been intensive in the last couple of decades. PWM techniques have been used to achieve variable voltage and variable frequency in AC-DC and DC-DC converters. The PWM techniques are widely used in different applications such as variable speed drives (VSD), static frequency changers (SFC), un-interruptible power supplies (UPS) etc. The main problems faced by the power electronic design engineers are about the reduction of harmonic content in inverter circuits. The classical square wave inverter used in low or medium power applications suffers from a serious disadvantage such as lower order harmonics in the output voltage. One of the solutions to enhance the harmonic free environment in high power converters is to use PWM control techniques. The objective of PWM techniques was to fabricate a sinusoidal AC output whose magnitude and frequency could both be restricted[6,9,10-11-12].

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ISSN (Online): 2278 – 8875

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Vol. 4, Issue 7, July 2015

The Pulse Width Modulation (PWM) inverters reduce harmonics in the output current as well as voltage by increasing the switching frequency and control the inverter output voltage as well as frequency by changing modulating wave. PWM inverters are more appropriate for speed control of induction motor instead of other techniques. The most popular technique is Sinusoidal PWM which is appropriate for linear modulation index upto 0.7855 only. Above this modulation index, SPWM produces more harmonics in output voltage and current. So, Space Vector PWM is suitable above 0.7855 modulation index. The main capability of SVPWM inverter is that it reduces THD as well as increases the basic value of inverter voltage. Consequently, induction motor works smoothly[6,8].

In the past, the 3 level PWM inverter fed induction motor drives has been proposed by various researchers. It has been observed that the THD in the current, voltage and electromagnetic torque was always the problem. Therefore, some researchers used 5 and 7 level inverters for minimizing harmonics. But, it has been seen that the 3 level inverter fed induction motor widely used in various applications[2,5,7,10]. Therefore, in this paper, our attempt is to minimize harmonics by using proposed models.

Since, the induction machine modelling has continuously attracted with the attention of researchers not only because such machines are made and used in largest number of applications but also due to their varied modes of operation both under steady state and dynamic states. In Electric Drive System elements, such machines is a part of the control system elements, which is to be controlled by the dynamic behaviour of Induction Motor (IM) then the dynamic model of IM has to be considered. The dynamic model considers the instantaneous effects of varying voltage/currents, stator frequency and torque disturbance[1,4].

In the present paper, the mathematical modelling of induction motor, open/closed loop induction motor fed PWM inverter model with THD analysis has been carried out for three level PWM inverter. This research paper is an attempt to minimize harmonics for 3 level PWM inverter by new proposed models.

II. MATHEMATICAL MODELLING OF THE INDUCTION MOTOR

The stator voltage on the *q*-axis and *d*-axis are given in equation 1 and 2. The equations from (1 to 7) come into the category of Electrical system.

$$V_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega \Psi_{ds} \quad (1) \qquad \text{Where, } \Psi_{qs} = L_s i_{qs} + L_m i'_{qr}$$

$$V_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} - \omega \Psi_{qs} \quad (2) \qquad \text{Where, } \Psi_{ds} = L_s i_{ds} + L_m i'_{dr}$$

The rotor voltage on *q*-axis and *d*-axis are given in equation (3) and (4).

$$V'_{qr} = R'_r i'_{qr} + \frac{d\Psi'_{qr}}{dt} + (\omega - \omega_r)\Psi'_{dr} \quad (3) \qquad \text{Where, } \Psi'_{qr} = L'_r i'_{qr} + L_m i_{qs}$$

$$V'_{dr} = R'_r i'_{dr} + \frac{d\Psi'_{dr}}{dt} - (\omega - \omega_r)\Psi'_{qr} \quad (4) \qquad \text{Where, } \Psi'_{dr} = L'_r i'_{dr} + L_m i_{ds}$$

$$L_s = L_{1s} + L_m \quad (5)$$

$$L'_r = L'_{1r} + L_m \quad (6)$$

The Electromagnetic Torque is given in equation (7):

$$T_e = 1.5 p(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) \quad (7)$$

The equations for the mechanical system are as shown below:

$$\frac{d\omega_m}{dt} = \frac{1}{2H}(T_e - F\omega_m - T_m) \quad (8)$$

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ISSN (Online): 2278 – 8875

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$$\frac{d\theta_m}{dt} = \omega_m \tag{9}$$

The *abc*-to-*dq* reference frame transformations applied to the Induction Machine phase-to-phase voltages are expressed by following equations:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2\cos\theta & \cos\theta + \sqrt{3}\sin\theta \\ 2\sin\theta & \sin\theta - \sqrt{3}\cos\theta \end{bmatrix}\begin{bmatrix} V_{abs} \\ V_{bcs} \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} V'_{qr} \\ V'_{dr} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2\cos\beta & \cos\beta + \sqrt{3}\sin\beta \\ 2\sin\beta & \sin\beta - \sqrt{3}\cos\beta \end{bmatrix}\begin{bmatrix} V'_{abr} \\ V'_{bcr} \end{bmatrix} \tag{11}$$

In the preceding equations, θ is the angular position of the reference frame, while $\beta = \theta - \theta_r$ is the difference between the position of the reference frame and the position (electrical) of the rotor. Because the machine windings are connected in a three-wire Y configuration, there is no homopolar (0) component. This also justifies the fact that two line-to-line input voltages are used inside the model instead of three line-to-neutral voltages.
The *dq*-to-*abc* reference frame transformations applied to the Induction Machine phase current are expressed by following equations.

$$\begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \frac{-\cos\theta + \sqrt{3}\sin\theta}{2} & \frac{-\sqrt{3}\cos\theta - \sin\theta}{2} \end{bmatrix}\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} i'_{ar} \\ i'_{br} \end{bmatrix} = \begin{bmatrix} \cos\beta & \sin\beta \\ \frac{-\cos\beta + \sqrt{3}\sin\beta}{2} & \frac{-\sqrt{3}\cos\beta - \sin\beta}{2} \end{bmatrix}\begin{bmatrix} i'_{qr} \\ i'_{dr} \end{bmatrix} \tag{13}$$

$$i_{cs} = -i_{as} - i_{bs} \tag{14}$$

$$i'_{cr} = -i'_{ar} - i'_{br} \tag{15}$$

Where i_{as}, i_{bs}, i_{cs} are the stator currents in different phases. i'_{ar}, i'_{br}, i'_{cr} are the rotor current in different phases.

III. PROPOSED OPEN LOOP SIMULATION MODEL OF PWM INVERTER FED SQUIRREL CAGE INDUCTION MOTOR MODEL

Variable speed controls of AC electrical machines make use by force-commutated electronic switches such as IGBTs, MOSFETs, and GTOs. Induction motors fed by pulse width modulation (PWM) voltage sourced converters (VSC) are nowadays gradually replacing the DC motors and thyristor bridges. With PWM, combined with modern control techniques such as field-oriented control or direct torque control, we can obtain the same flexibility in speed and torque control as with DC machines. Since, the IGBTs having superior characteristics rather than other power electronics switches in medium power applications. Therefore, in the present section we have developed an open and closed loop induction motor fed PWM inverter model with IGBT inverter in the Matlab/Simulink. This squirrel cage induction machine block can be operates in generator as well as motor mode. It depends upon the sign of mechanical torque(T_m). If T_m is positive as shown in fig. 1, machine acts as motor and if T_m is negative it acts as generator. The applied full load nominal constant mechanical torque at the machine's shaft is 15 Nm. The Simulink output block has one output but that contains 21 signals. We can de-multiplex these signals by the Bus Selector block provided by the Simulink library.

An open loop three-phase squirrel induction motor rated 3 HP, 50 Hz, 1490 rpm is fed with a sinusoidal PWM inverter is considered as shown in fig. 1. The base frequency of the sinusoidal reference wave is 50 Hz while the triangular carrier wave's frequency is set to 1650 Hz. This corresponds to a frequency modulation factor m_f of 33(50Hz*33=1650

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Hz). The Maximum time step has been limited to 10 µs. This is required due to the relatively high switching frequency (1650 Hz) of the inverter. It is recommended in [4] that the modulation factor m_f be an odd multiple of three and that the value be as high as possible. The PWM inverter is built entirely with standard Simulink blocks. The machine's rotor is short-circuited. Its stator leakage inductance L_{1s} is set to twice its actual value to simulate the effect of a smoothing reactor placed between the inverter and the machine. The motor is started from standstill condition. The speed set point is set to 1490 rpm under full load condition. This speed is reached after 0.1 s. it has been observed that the rotor and stator currents are quite "noisy," despite the use of a smoothing reactor. The noise introduced by the PWM inverter is also observed in the electromagnetic torque waveform. However, the motor's inertia prevents this noise from appearing in the motor's speed waveform.

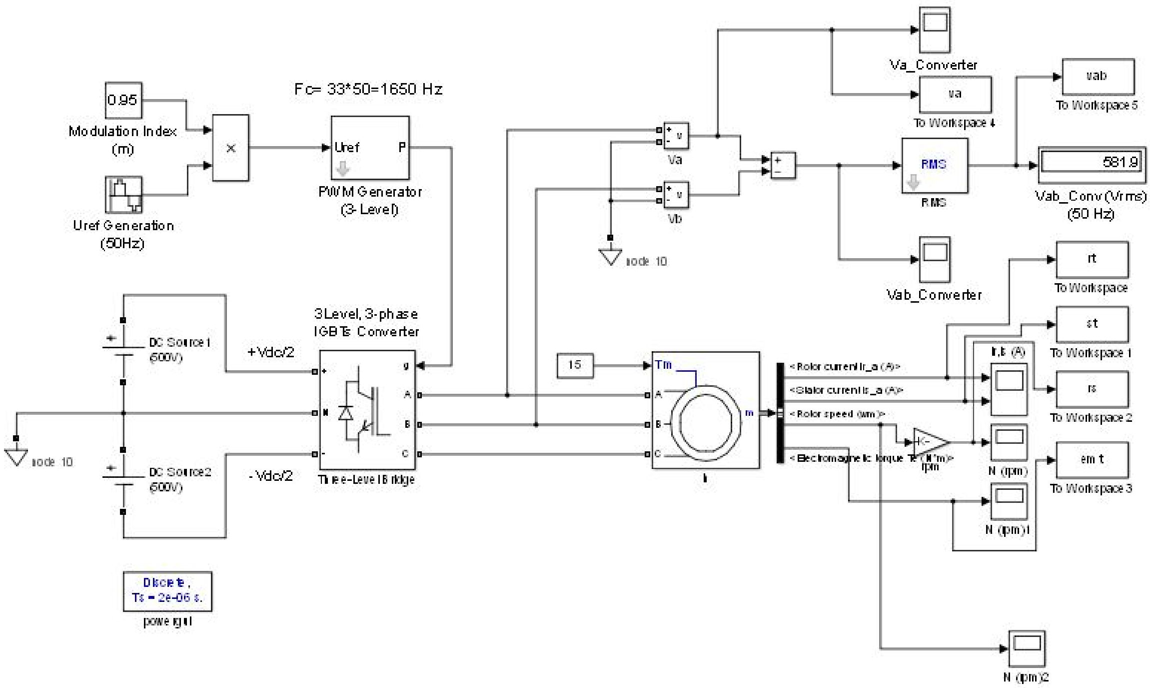

Fig. 1 Open Loop Simulink Model of Squirrel Cage Induction Motor Model

The reference frame is used to convert input voltages (*abc* reference frame) to the *dq* reference frame, and output currents (*dq* reference frame) to the *abc* reference frame. We may choose among the following reference frame transformations:

i) Rotor reference frame (Park transformation)
ii) Stationary reference frame (Clarke or αβ transformation)
iii) Synchronous reference frame

In our case, we have chosen stationary reference frame. The complete mathematical modelling and corresponding equations of the model has also been given earlier. The choice of reference frame affects the waveforms of all *dq* variables. It also affects the simulation speed and in certain cases the accuracy of the results. The following guidelines are suggested in [4].

i) Use the stationary reference frame if the stator voltages are either unbalanced or dis-continuous and the rotor voltages are balanced (or 0).
ii) Use the rotor reference frame if the rotor voltages are either unbalanced or discontinuous and the stator voltages are balanced.
iii) Use either the stationary or synchronous reference frames if all voltages are balanced and continuous.

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

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A pulse generator is used to control the inverter bridge. The efficient and common method is used for generating the PWM pulses. For generating the PWM pulses comparison of the output voltage to synthesize (50 Hz in this case) with a triangular wave at the switching frequency 1650 Hz (in this case). This method is implemented in the Discrete 3-phase PWM pulse generator block in the Matlab/Simulink. The line-to-line RMS output voltage is a function of the DC input voltage and of the modulation index *m* as given by the following equation:

V_{LL}_Converter = m * V_{dc}/2 * sqrt(3) / sqrt(2)
V_{LL}_Converter = m * V_{dc} * 0.6124
V_{LL}_Converter = 0.95 * 1000 * 0.6124 = 581.8 V (16)

Therefore, the obtained line-to-line voltage converter value matches to obtained theoretical value. It may be observed from the fig.1. Therefore, we can say that the simulated model is working perfectly.

A. Simulation Results of Open Loop Model

The simulation results in symmetrical or balanced supply (or called healthy mode) motor condition of the motor are as shown in fig 2. Four motor signatures are considered, those are stator current, rotor current, rotor speed and electromagnetic torque. In the healthy mode of the motor the slip is set at 1(s=1) and input mechanical torque is 15 N-m. It is observed from the obtained results, all the motor signatures are reached in the steady state condition after 0.1 seconds. The motor's speed is reached (i.e. 1490 rpm) in the steady state after 0.1 sec. It has been observed that in the starting of the motor, the first peak of the stator current and electromagnetic torque waveforms has highest amplitude after that it is being decreased and reached in the stable condition. The rotor speed is controlled by V/f control method of the induction motor. The model is simulated for 0.5 sec for clear visualization of transient characteristics. Therefore, the transient characteristics of the motor may be clearly observed and analysed. The electromagnetic torque waveform shows that it is reached in the stable condition after 0.1 sec. It has also been observed that the strong oscillations of the electromagnetic torque at starting. If we zoom in on the torque in steady state, we will observe a noisy signal with a mean value 15 N-m, corresponding to the load torque at nominal speed. If we zoom on the three motor currents, we can observe that all the harmonics (multiple of the 1650 Hz switching frequency) are filtered by the stator inductance; hence we can say that the 50 Hz component is dominant.

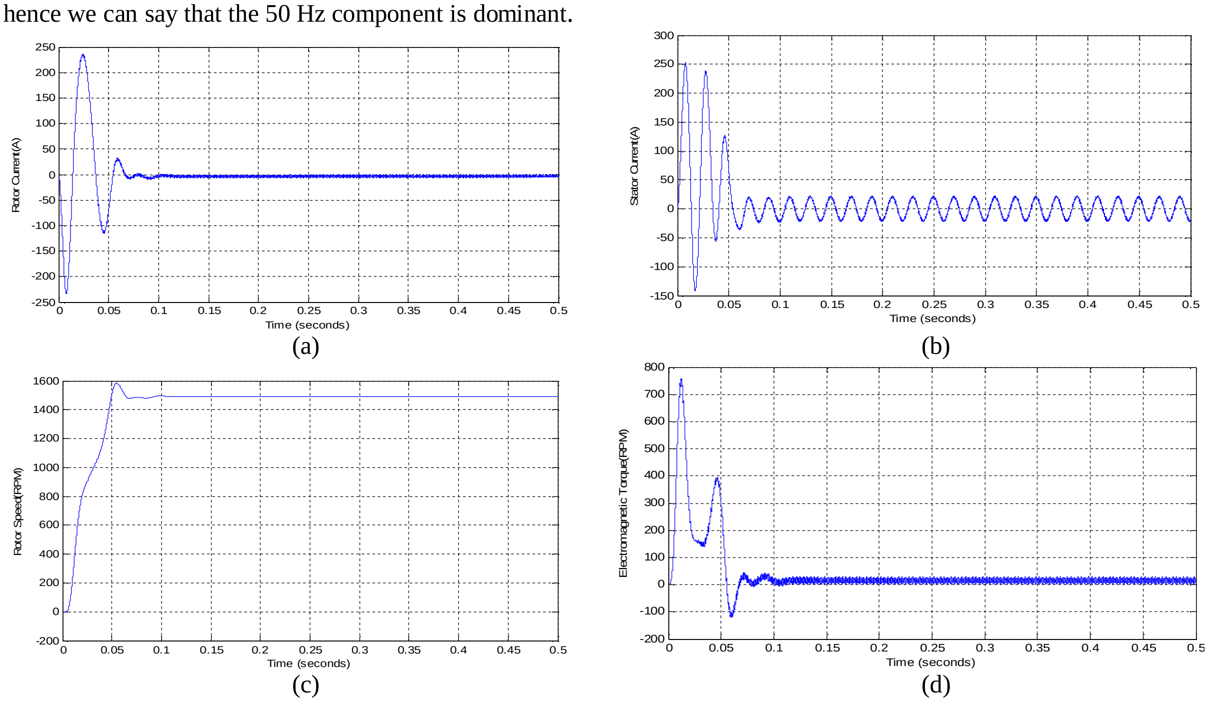

Fig. 2 Results of Open Loop Simulink Model, (a) Stator Current, (b) Rotor Current, (c) Rotor Speed, (d) Electromagnetic Torque

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

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IV.PROPOSED CLOSED LOOP SIMULATION MODEL OF PWM INVERTER FED SQUIRREL CAGE INDUCTION MOTOR

The closed loop induction motor fed PWM inverter Simulation model is as shown in fig. 3. It is simple open loop DC drive controlling an induction motor. The modern control techniques such as field oriented control or direct torque control technique can also be used with PWM inverter fed motor and can obtain same flexibility in speed and torque control like DC machines. The field control is an attractive control method but it has a serious drawback. It relies heavily on precise knowledge of the motor parameters. The rotor time constant is particularly difficult to measure precisely, and to make matter worse because it varies with temperature. The torque control method efficiently controls the induction motor. It estimates the stator flux and electric torque in the stationary reference frame and terminal measurements.

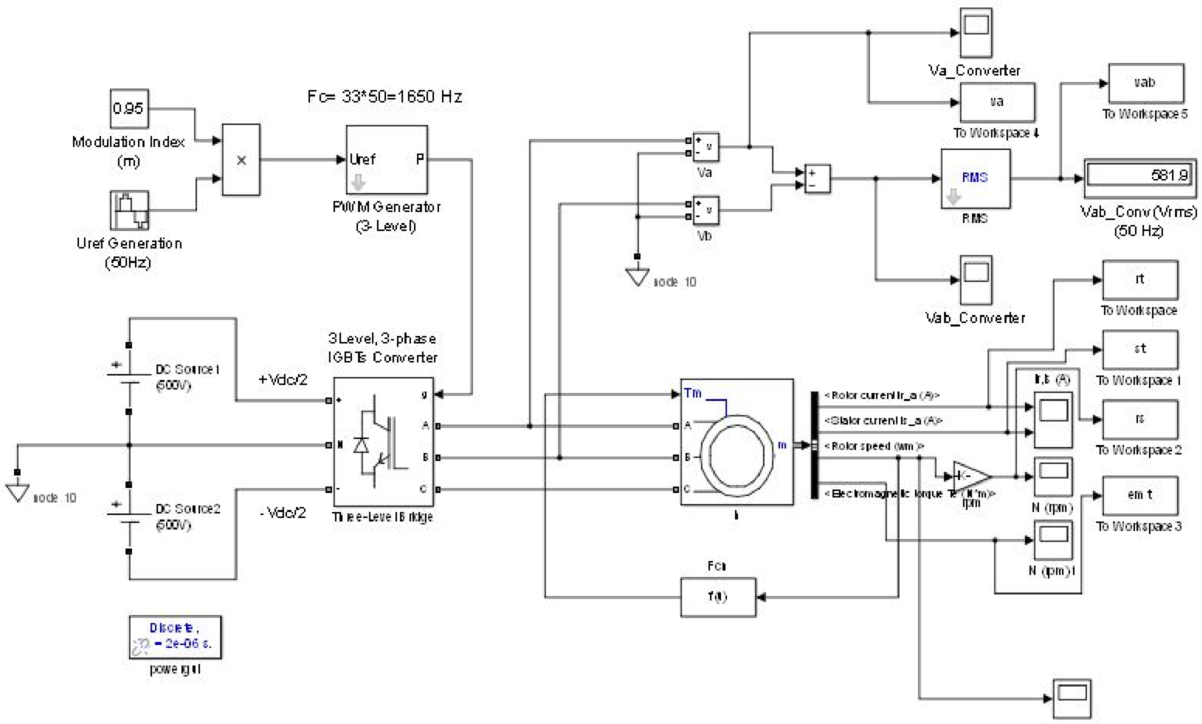

Fig. 3 Closed Loop Simulink Model of Squirrel Cage Induction Motor Model

The following relation is used for the torque control method:

$$\Psi_{ds} = \int(V_{ds} - R_s i_{ds})\, dt \quad (17)$$

$$\Psi_{qs} = \int(V_{qs} - R_s i_{qs})\, dt \quad (18)$$

$$\varphi_s = \sqrt{\Psi_{ds}^{2} + \Psi_{qs}^{2}} \leq \tan^{-1}\left(\frac{\Psi_{qs}}{\Psi_{ds}}\right) \quad (19)$$

The Electromagnetic Torque is given as follows

$$T_e = 1.5\, p(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds} \quad (20)$$

The estimated stator flux and electric torque are then controlled directly by comparing them with their respective demanded values using hysteresis comparators. The outputs of the two comparators are then used as input signals of an optional switching table. The rotor speed is fed back and directly connected to the torque input. The value of the feedback constant k is calculated as 6.156×10^{-4}.

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

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B. Simulation Results of Closed Loop Model

The simulation results of developed closed loop model are as shown in fig.4. The four motor current parameters are

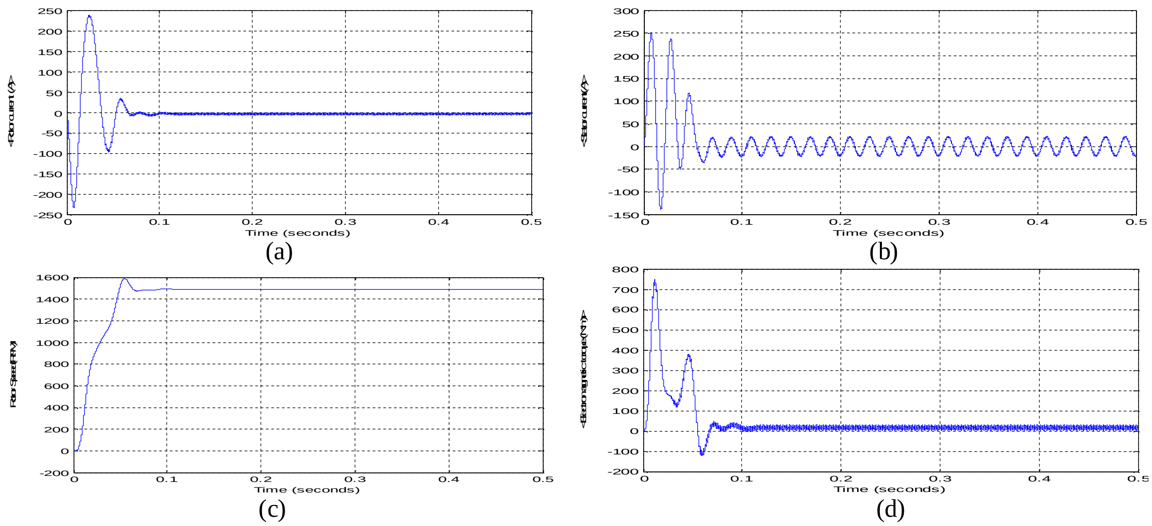

Fig. 4 Results of Closed Loop Simulink Model, (a) Stator Current, (b) Rotor Current, (c) Rotor Speed, (d) Electromagnetic Torque

compared with obtained results by open loop model. These motor signatures are stator current, rotor current, rotor speed and developed electromagnetic torque. As, we have observed from the obtained results in the open loop that motor signatures have been reached in the steady state condition after passing through the transient time i.e. 0.1 sec. But, it has been observed in the closed loop model, for the same values transient time is get decreased. In the open loop transient time lost after 0.1 sec and in closed loop transient time lost before 0.1 sec. It can be observed from fig.4 (a-d) Therefore; we can say that the proposed torque control method can be used proficiently for the controlling of induction motor.

V. THD ANALYSIS of OPEN AND CLOSED LOOP MODEL

The Total Harmonic Distortion (THD) analysis for open and closed loop models has been discussed for its stator current and line-to-line voltages. The waveforms of Stator current and line-to-line voltages for 4KHz maximum frequency is as shown in fig. 5 and fig. 6 for open loop and closed loop respectively.

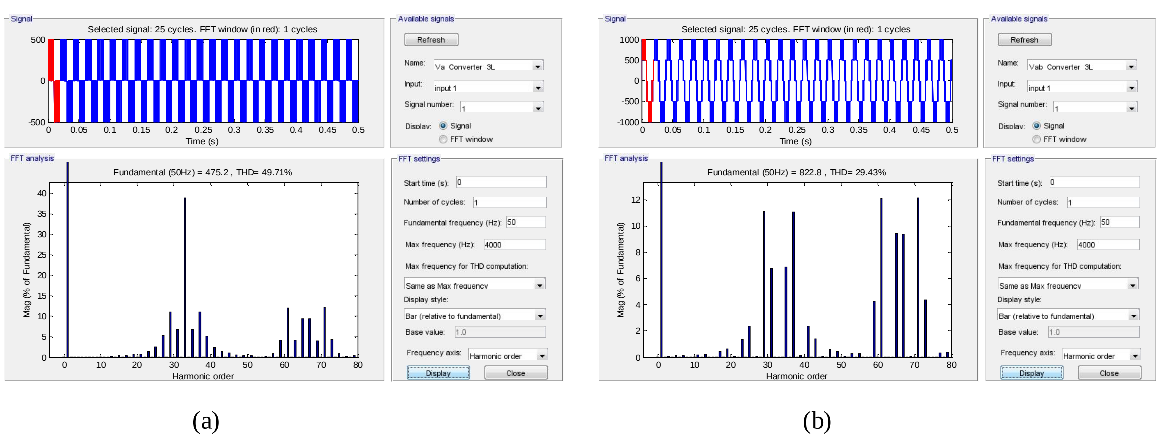

Fig. 5 Total Harmonic Distortion in Voltages(open/Closed Loop), (a) THD in Voltage V_a, (b) THD in Voltage V_{ab}

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

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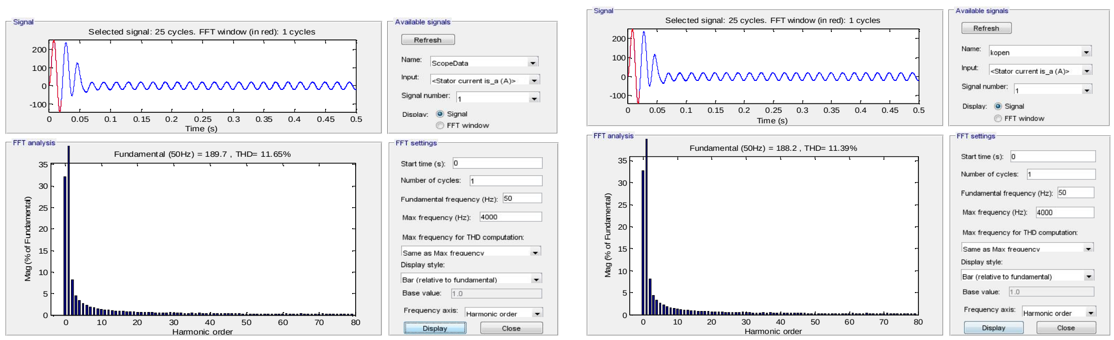
The THD in open loop stator current is more in comparison to closed loop but for the line-to-line voltages, THD is same in both the cases (open/close). It is because we are not controlling input line-to-line voltage here. Therefore, PWM inverter output voltage will be unchanged in open loop as well as closed loop. It has been observed that if the inverter is fed into induction motor then line voltage will be disturbed consequently rise in THD for line-to-line voltages but THD in the stator current will be less.



(a) (b)

Fig. 6 Total Harmonic Distortion in Stator Current , (a) THD in Open Loop Stator Current, (b) THD in Closed Loop Stator Current

In this kind of drives, we may control line-to-line voltages by varying modulation index is as shown in the Table I. The THD of the line to line voltages and corresponding fundamental values are as shown in Table 2. The THD is lowest when modulation index is set 0.95.

Table. I
THD Control in Voltages by Modulation Index

MI	THD (Va)	FM (Va)	THD (Vab)	FM (Vab)	RMS (Vab)
1	52.31	500.1	35.43	866	612.5
0.95	49.71	475.2	29.43	822.8	581.9
0.75	74.91	375.4	31.75	649.7	459.5
0.55	101.78	275.1	35.99	476.3	336.8
0.35	162.83	174.1	104.28	302.6	214

MI: Modulation Index, FM: Fundamental Magnitude

VI. CONCLUSIONS

In the present paper, an open loop and closed loop squirrel cage induction motor fed PWM inverter models have been developed and analysed its transient behaviour. However, the PWM inverter influences the motor performance and introduces disturbance into the main power line. But precisely designed interface system would be very useful in drive control applications. The extensive simulation has been carried out for 3 HP, 4 pole, 50 Hz induction motor and obtained simulation results has given ultimate solution for the wide range of speed control with reduced harmonics. It has been observed that the closed loop model has given better results as compare to open loop model with reduced harmonics. The torque control method has been used with PWM inverter for induction motor controlling purpose over field-oriented control technique due to its advantages discussed earlier. These models may be used in various power electronics and drives applications in industries. In future, these models may also be used in the different fault diagnosis purpose by advanced DSP based transformative techniques like Fast Fourier Transform and Wavelet Transform techniques.

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ACKNOWLEDGMENT

Authors acknowledge Technical Education Quality Improvement Program Phase-II, Institute of Engineering & Technology, Lucknow for providing financial assistantship to carry out the research work.

BIOGRAPHY

Khadim Moin Siddiqui is teaching-cum research Scholar in the Department of Electrical Engineering, IET, Lucknow. He received his B.Tech degree in Electronics Engineering from Azad Institute of Engineering & Technology, Lucknow, India, in 2007, the M.Tech degree in Power Electronics & Drives from Madan Mohan Malaviya Engineering College,(presently Madan Mohan Malaviya University of Technology) Gorakhpur, India, in 2011. He has published 15 International Journal papers and 8 papers presented in the conferences. He has total 04 years of teaching experience in AIET Lucknow, NIIT, Bangalore & JNU, Jaipur. His research area of interest includes Electrical Machines, fault diagnosis and health monitoring.

Kuldeep Sahay, Ph.D. is associated with Institute of Engineering & Technology, Lucknow since 1996, where, he is presently Professor in the Department of Electrical Engineering, An Autonomous Constituent Institute of Uttar Pradesh Technical University, Lucknow. He has authored numbers of research paper in National and International Journal having good citation and published a book. His research interests are in the area of Mathematical Modeling of Energy Storage System, Integration of Renewable Energy System with Grid. Prof. Sahay for his overall contribution in research and academics has been awarded "Shikha Rattan Puraskar" and "Rashtriya Gaurav Award" by India International Friendship Society, New Delhi in 2011.

V.K.Giri obtained his B.E. (Electrical) Degree from SVNIT (erstwhile, SVRCET), Surat (Gujrat) in 1988, M.E. (Measurement and Instrumentation) Hons. degree from University of Roorkee, Roorkee in 1997 and Ph.D. degree from Indian Institute of Technology Roorkee, Roorkee in 2003. He joined the Electrical Engineering Department of M.M.M Engineering College, Gorakhpur (UP) in 1989 as lecturer. Presently, he holds the position of Professor in the same department since, 2008. He has published more than 80 research papers, guided 14 PG students; and supervising6 Ph.D. theses. He has received many awards including the best paper awards of the Institution of Engineers (India) in 23rd Indian Engineering Congress in year 2008. He was elected as Fellow of the Institution of Engineers (I), Institution of Electronics and telecommunication. Engineers, and is a member of many professional bodies such as life member ISTE, member IEE and member CSI. He has also undertaken large number of consultancy, testing & sponsored projects from UGC, industries and other government departments. His research interests include Digital Signal Processing, Condition Monitoring of Machines, Control and Instrumentation, Biomedical Instrumentation, ECG, Data Compression and Telemedicine.