Modeling and Analysis of Open and Closed Loop Induction Motor Fed PWM Inverter

Khadim M. Siddiqui and Kuldeep Sahay
Department of Electrical Engineering, Institute of Engineering & Technology, Lucknow, India
Email: siddiquikhadim@gmail.com, ksahay.iitd@gmail.com
V. K. Giri
Department of Electrical Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, India

Abstract—Squirrel Cage Induction Motors are the widely used motors for industries due to its robust design, simple construction and low operational costs. The squirrel cage induction motor fed into Sinusoidal Pulse Width Modulation (SPWM) inverter presents the greater advantages on cost and energy efficiency as compared with other industrial solutions for varying speed applications. In the present paper, an open and closed loop 0.5HP, 50Hz, 1725rpm squirrel cage induction motor fed into PWM inverter has been developed and analyzed in the recent MATLAB/Simulink environment. It has been observed from the obtained results of open and closed loop models, the closed loop model gives better results as compare to open loop with reduced harmonics. Four signature parameters of motor have been considered for the analysis purpose in both models (open/close). These are stator current, rotor current, rotor speed and developed electromagnetic torque. The torque control method has been used for controlling the induction motor in closed loop due to its advantages over field-oriented control method.

Index Terms—open loop model, close loop model, induction motor, PWM inverter, MATLAB/Simulink

I. INTRODUCTION

Nowadays, induction motors especially Squirrel Cage Induction Motor (SCIM) are widely used in various industries as well as in academic applications due to its simple construction, high reliability and the availability of power converters based on efficient control strategies [1]-[4].

Induction Motors (IM) are the most widely used motors for appliances, industrial control and automation. Hence, they are often called the workhorse of the motion industry. When power is supplied to an induction motor at the recommended specifications, it runs at its rated speed. However, many applications need variable speed operations. For example, a washing machine may use different speeds for each wash cycle. Historically, mechanical gear systems were used to obtain variable speed. Recently, electronic power and control systems such as PWM inverter have matured to allow these components to be used for motor control in place of mechanical gears [5]-[9]. These electronics devices such as PWM not only control the motor’s speed, but also improve the motor’s dynamic and steady state performance. In addition, electronics devices can reduce the system’s average power consumption and noise generation of the motor. The utilization of static frequency inverters comprehends currently the most efficient method to control the speed of induction motors [8].

The Induction Motor (IM) is being used in many 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 field is that its cost per KVA is approximately one fifty of its counterpart and it possesses higher suitability in complex environment [1]-[3].

Since, the Induction Machine modeling 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 [6]. In electric drive system elements, such machines is a part of the control system elements, which is to be controlled by the dynamic behavior of Induction Motor (IM) then the dynamic model of IM has to be considered [8]-[10].

The dynamic model considers the instantaneous effects of varying voltage/currents, stator frequency and torque disturbance [11]. The dynamic simulation of the IM is one of the key steps in the validation of the design process of the motor-drive system. Since, it is extremely needed with priority for eliminating inadvertent design mistakes and the resulting error in the prototype construction and testing [10].

In this present paper, the dynamic open and closed loop IM fed PWM inverter model are derived by using $d$ and $q$ variables with PWM inverter in a stationary rotating reference frame. From the open and closed loop simulation models the transient behavior of the motor has been observed. It has also been observed that from the stator current, rotor current, electromagnetic torque and rotor speed waveforms, the closed loop model gives better results as compare to open loop model.


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II. MATHEMATICAL MODELING OF THE MOTOR

In electrical engineering, direct-quadrature-zero (or dq0) transformation or zero-direct-quadrature (or 0dq) transformation is a mathematical transformation used to simplify the analysis of three-phase circuits. In the case of balanced three-phase circuits, application of the dq0 transform reduces the three AC quantities to two DC quantities. Simplified calculations can then be carried out on these imaginary DC quantities before performing the inverse transform to recover the actual three-phase AC results. It is often used in order to simplify the analysis of three phase induction machines or to simplify calculations for the control of three-phase inverters.

The mathematical modeling of IM and its simulink model are shown in Fig. 1 and Fig. 2. Induction Machine calculations for the control of three-phase inverters.

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

\[ V_s = R_s i_s + \frac{d\Psi_s}{dt} + \omega \Psi_{ss} \]  
(1)

where:

\[ \Psi_s = L_s i_s + L_i^' \]  
(2)

\[ V_s = R_s i_s + \frac{d\Psi_s}{dt} - \omega \Psi_{ss} \]  
(2)

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

\[ V_{q''} = R_i^' i_{q''} + \frac{d\Psi_{q''}}{dt} + (\omega - \omega) \Psi_{q''} \]  
(3)

where:

\[ \Psi_{q''} = L_i^' i_{q''} + L_i i_{q''} \]  
(4)

The Electromagnetic Torque is given in (7):

\[ T_e = 1.5p(\Psi_{q''} i_{q''} - \Psi_{i''} i_{q''}) \]  
(7)

The equations for the mechanical system are as shown below:

\[ \frac{d\omega}{dt} = \frac{1}{2H} (T_e - F\omega_s - T_n) \]  
(8)

\[ \frac{d\theta_s}{dt} = \omega_s \]  
(9)

The quadrature axis d-axis and q-axis which are obtained form abc to dq conversion

A. abc to dq Reference Frame

The following relationships describe the abc-to-dq reference frame transformations applied to the Induction Machine phase-to-phase voltages.

\[ \begin{bmatrix} V_{a'} \\ V_{b'} \\ V_{c'} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 \cos \theta & \cos \theta + \sqrt{3} \sin \theta \\ 2 \sin \theta & \sin \theta - \sqrt{3} \cos \theta \end{bmatrix} \begin{bmatrix} V_{a} \\ V_{b} \\ V_{c} \end{bmatrix} \]  
(10)

\[ \begin{bmatrix} V_{q'} \\ V_{d'} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 \cos \beta & \cos \beta + \sqrt{3} \sin \beta \\ 2 \sin \beta & \sin \beta - \sqrt{3} \cos \beta \end{bmatrix} \begin{bmatrix} V_{a'} \\ V_{b'} \end{bmatrix} \]  
(11)

In the preceding equations, \( \theta \) is the angular position of the reference frame, while \( \beta = \theta - \theta_s \) 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 stator voltage on the q-axis and d-axis are given in (1) and (2). The equations from ((1) to (7)) come into the category of Electrical system.
B. dq to abc Reference Frame

The following relationships describe the dq-to-abc reference frame transformations applied to the Induction Machine phase currents.

\[
\begin{bmatrix}
    i_{as} \\
    i_{bs} \\
    i_{cs}
\end{bmatrix}
= \begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\cos \theta + \sqrt{3} \sin \theta & -\sqrt{3} \cos \theta - \sin \theta \\
    2 & 2
\end{bmatrix}
\begin{bmatrix}
    i_{ds} \\
    i_{qs}
\end{bmatrix}
\]

(12)

\[
\begin{bmatrix}
    i'_{as} \\
    i'_{bs} \\
    i'_{cs}
\end{bmatrix}
= \begin{bmatrix}
    \cos \beta & \sin \beta \\
    -\cos \beta + \sqrt{3} \sin \beta & -\sqrt{3} \cos \beta - \sin \beta \\
    2 & 2
\end{bmatrix}
\begin{bmatrix}
    i'_{ds} \\
    i'_{qs}
\end{bmatrix}
\]

(13)

\[
i'_{as} = -i_{as} - i_{bs}
\]

(14)

\[
i'_{cs} = -i'_{as} - i'_{bs}
\]

(15)

where \(i_{as}, i_{bs}, i_{cs}\) are the stator currents in different phases, and \(i'_{as}, i'_{bs}, i'_{cs}\) are the rotor current in different phases.

III. PROPOSED OPEN LOOP SIMULATION MODEL OF 3-PHASE SQUIRREL CAGE INDUCTION MOTOR

This Squirrel cage IM block available in the Matlab/Simulink can operate in two modes; one is generator mode and the other is motor mode. The generator and motor mode depend on the sign of the mechanical torque. If mechanical torque is positive then the motor operates in motoring mode and negative in generating mode. The mechanical torque is applied on the machine shaft as shown in Fig. 2. The squirrel cage IM output block contains 21 output signals. We can demultiplex these signals by the Bus Selector block provided by the simulink library. In our model, we have chosen four outputs such as stator current, rotor current, rotor speed and developed electromagnetic torque.

One important point to be noted is that the neutral connections of the stator and rotor windings are not available in Matlab/Simulink. Therefore, we have assumed three-wire Y connections.

The proposed open-loop simulation model of the three-phase squirrel cage IM is as shown in Fig. 2. The applied mechanical rated torque on the shaft is 11.9 N-m as the full load torque. The scope block is used for result displaying purpose. The PWM inverter has been implemented and directly fed into the Induction motor.

The 0.5HP, 220V, 1725rpm IM is fed into a sinusoidal PWM inverter. The fundamental motor frequency is set at 50Hz and inverter frequency is set at 60Hz. The base frequency of the sinusoidal reference wave is 50Hz while the triangular carrier wave’s frequency is set to 1980Hz. The Maximum limited time step is set to 10µs. This maximum limited time is required due to the relatively high switching frequency (1980Hz) of the inverter. The PWM inverter is built entirely by standard Simulink blocks. Its output goes through Controlled Voltage Source (VSC) blocks before being applied to the Squirrel cage induction machine block’s stator side.

The machine’s rotor is short-circuited for squirrel cage IM. Its stator leakage inductance \(L_{ls}\) is set to twice its actual value to simulate the effect of smoothing reactor placed in between the inverter and the machine. The mechanical load torque has been applied to the machine’s shaft and set to its nominal value i.e. 11.9 N-m. The induction motor is started from standstill condition. The speed set point is set to 1.0pu, or 1725rpm. This speed is reached after 0.8s. It has been observed from obtained waveforms for rotor and stator currents are somewhat “noisy,” in spite of the use of a smoothing reactor. The noise is introduced by the PWM inverter and also can be observed in electromagnetic torque waveform.
(\(T_e\)). Though, the motor’s inertia prevents this noise from appearing in the motor’s speed. The RMS value of the fundamental component of the line voltage at the machine’s stator terminals is extracted from a built in Fourier block available in the Matlab’s Simulink tool box.

There are three reference frames has been possible in the three phase induction motor. In our case we have chosen stationary reference frame. For stationary reference frame, the value of rotor angle is set to 0 and the value of \(\beta\) is set to - \(\theta\). The reference frame plays a vital role. it 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 can choose one among the following reference frame transformations as per our requirement. The available and possible reference frames are as follows:

- Rotor reference frame (Park transformation)
- Stationary reference frame (Clarke or \(\alpha\beta\) transformation)
- Synchronous reference frame

The complete mathematical modeling of the motor and corresponding equations of the model has already been explained. The selection of reference frame affects the waveforms of all \(dq\) variables. It also affects the simulation speed and in definite cases the accuracy of the results. The following guidelines have been suggested in [3] for choosing the reference frame as follows:

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

After an extensive simulation of the developed model, there are some restrictions have been observed such as:

The Squirrel Cage Induction Machine block (used in simulink) does not include a representation of iron losses and saturation. Therefore, we must be careful when we connect ideal sources to the machine’s stator. If we select to give supply to the stator via a three-phase Y-connected infinite voltage source. So, we must use three voltage sources connected in Y. However, if we choose to simulate a delta source connection, we must be used only two voltage sources connected in series

The brief description about the induction motor parameters is as shown in Table II.

<table>
<thead>
<tr>
<th>Rotor Type: Squirrel Cage</th>
<th>Reference Frame: Stationary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor: 0.5HP</td>
<td>Line-to-Line Voltage: 400V</td>
</tr>
<tr>
<td>Frequency: 50Hz</td>
<td>Stator Resistance: 0.435Ω</td>
</tr>
<tr>
<td>Rotor Resistance: 0.816Ω</td>
<td>Mutual Inductance: 69.31×10^-3 H</td>
</tr>
<tr>
<td>No. of Pole: 4</td>
<td>Speed: 1725rpm</td>
</tr>
</tbody>
</table>

In our simulated model, we have chosen squirrel cage IM block in continuous systems. For increasing the accuracy, we can choose discrete systems. When we choose Squirrel Cage IM block in discrete systems, we need to use a small parasitic resistive load. This may be connected at the machine terminals for avoiding numerical oscillations. Large sample times will require larger loads. The minimum resistive load should be proportional to the sample time.

### A. Results of Open Loop PWM Inverter Fed Induction Motor Model

The results of open loop PWM inverter fed into induction motor are as shown in Fig. 3. There are four motor parameters have been considered such as stator current, rotor current, rotor speed and developed electromagnetic torque. In this paper, especially we are focusing on the transient characteristics of the motor. Therefore, the motor has been simulated only for 1 sec for clear visualization of the transient nature of the Induction motor.

The Fig. 3(a-d) shows that the stator current, rotor current, rotor speed and developed electromagnetic torque waveforms. The applied load torque on the shaft is set at 11.9 N-m and slip is set at 1. The motor is started from stall. The applied friction factor is zero. It has been observed from all the four waveforms that the transient time is lost after 0.8 sec. The first maximum peak has been observed in all four waveforms as shown in Fig. 3(a-d). The stator current first maximum peak transient value is high 87.07A, rotor current first maximum peak value is 74.53A, speed of Rotating Magnetic Field (RMF) in the motor is 1725rpm and the first maximum peak transient developed electromagnetic torque value is 90.64 N-m.

The stator current, rotor current and developed electromagnetic torque first maximum peak transient value is high due to the high switching frequency.
The developed electromagnetic torque waveform (Fig 3-d) illustrates that it is reached in the stable condition after 0.8 sec. It has also been observed that the strong oscillations in the developed electromagnetic torque at starting. If we zoom in on the torque in steady state, it will clearly be observed that noisy signal with a mean value 11.9N-m, corresponding to the load torque at nominal speed. Since, the stator is fed by a PWM inverter, a noisy torque has been observed. However, this noise is not visible in the speed because it is filtered out by the machine’s inertia. But, it can be seen in the stator and rotor currents.

IV. PROPOSED CLOSED LOOP SIMULATION MODEL OF 3-PHASE SQUIRREL CAGE INDUCTION MOTOR

The simulation model of closed loop squirrel cage induction motor fed into PWM inverter is as shown in Fig. 4. In this work, the torque control method has been used for controlling the induction motor. There are various modern control techniques are used for electric machines controlling purpose such as field oriented control or direct torque control technique. These techniques have been successfully used with D.C. machines. Similarly, these techniques can also be used with induction machine and can obtain same flexibility in the speed and torque control like DC machines. Though, the field control is an attractive control method but it has serious disadvantages such as it relies heavily on precise knowledge of the motor parameters. Therefore, the rotor time constant is particularly hard to measure accurately, and to make matter inferior because it varies with temperature. The torque control method is proficiently controls the induction motor. It estimates the electric torque and stator flux in the stationary reference frame and terminal measurements. The following relations are used for the torque control:

\[ \Psi_s = \int (V_s - R_s i_s) dt \]  
\[ \Psi_q = \int (V_q - R_q i_q) dt \]  
\[ \varphi_s = \sqrt{\Psi_s^2 + \Psi_q^2} \tan^{-1} \left( \frac{\Psi_q}{\Psi_s} \right) \]

The Electromagnetic Torque is given as follows:

\[ T_e = 1.5 p (\Psi_s i_q - \Psi_q i_s) \]
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 directly fed back and connected to the motor’s torque input. The value of the feedback constant $k$ has been computed as $6.693 \times 10^{-4}$.

A. Results of Closed Loop PWM Inverter Fed Induction Motor Model

The simulation results of developed closed loop model are as shown in Fig. 5. The four motor current parameters are 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. 0.8 sec. But, it has been observed in the torque controlled closed loop model, for the same values transient time is get decreased. In the open loop transient time lost after 0.8 sec and in closed loop transient time lost after 0.6 sec. It can be observed from Fig. 5(a-d). The first maximum peak transient values are same for stator current, rotor current and rotor speed as observed in the open loop also. Therefore; we can say that the proposed torque control method can be used proficiently for the control of induction motor.

V. Harmonic Analysis of Open and Closed Loop Models

The Total Harmonic Distortion (THD) analysis for open and closed loop models has been discussed for its output rotor current and input line-to-line voltage. The waveforms of rotor current for 500Hz maximum frequency is as shown in Fig. 6 and Fig. 7 for open loop and closed loop respectively. In this THD analysis, we have chosen maximum frequency 500Hz.
The THD in open loop rotor current is more in comparison to closed loop but for the line-to-line voltage, THD is same in both the cases (open/close). It is because we are not controlling input line-to-line voltage. 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 input-line-to-line voltage but THD in the rotor current will be less.

The fundamental component and Total Harmonic Distortion (THD) of the \( V_{ab} \) voltage are displayed above the spectrum window. The magnitude of the fundamental of the inverter voltage (310.9V) is compared well with the theoretical value (311V for \( m=0.9 \)) as shown in Fig. 6(b) and Fig. 7(b). The line-to-line RMS voltage is a function of the DC input voltage and of the modulation index \( m \) as given by the following equation:

\[
V_{LL,\text{rms}} = \frac{m}{2} \sqrt{\frac{3}{2}} V_{dc} = m \times 0.612 \times V_{dc}
\]  

(17)

Therefore, a DC voltage of 400V and a modulation factor of 0.90 yields the 220 V\(_{\text{rms}}\) output line-to-line voltage, which is the nominal voltage of the induction motor.

Harmonics are displayed in percent of the fundamental component in Fig. 6(b) and Fig. 7(b). It has been expected that the harmonics will occur around multiples of carrier frequency. The Highest harmonics around (30%) appear at 37 and 41 harmonics.

The magnitude of the fundamental frequency (50Hz) in open loop and closed loop is 64.69 and 65.65 respectively as shown in Fig. 6(a) and Fig. 7(a). As a result, THD has been decreased in closed loop as compare to open loop.

VI. CONCLUSIONS

In the present paper, an open loop and closed loop induction motor fed PWM inverter models have been developed and analysed its transient behavior. However, the PWM inverter influences the motor performance and might introduce disturbances 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 0.5HP, 4 pole, 50Hz 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 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 industry, especially in textile or paper mill.

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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. 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 60 research papers, guided 14 PG students; and supervising 6 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.