Simulation of Indirect Vector Controlled Induction Motor Drive

Kulraj Kaur, SSSR Sarathbabu Duvvuri and Shakti Singh

1Electrical and Electronics Engineering Deptt., LPU, Jallandhar, Punjab, India
2Electrical and Inst. Engineering Deptt., Thapar University, Patiala, Punjab, India
3Electrical and Inst. Engineering, Thapar University, Patiala, Punjab, India
E-mail: kulraj.15720@lpu.co.in, sarath.duvvuri@thapar.edu, shakti.singh@thapar.edu

Abstract
The paper emphasis a solution for induction motor speed control. In this paper we present the simulation results of vector speed control of an induction motor. In this case, indirect methods were simulated using MATLAB (SIMULINK). A squirrel cage induction motor model was used taking the reference coordinates as the rotor magnetic field. The accuracy of results is given by the precision of motor model used. This paper describes the use of the MATLAB simulation toolbox “SIMULINK” for dynamic modeling of vector controlled motor drive system. The dynamic and transient performance is studied through simulation and the results are presented. The principle of vector control of AC machine enables the dynamic control of AC motors, and induction motors in particular to a performance level comparable to that of a DC machine. The basic equations describing the dynamic behavior of an induction machine in rotating reference frame are designed. Based on these equations the structure of the vector controlled induction motor drive is designed. The procedure is evaluated through extensive computer simulation. The complex nature of the vector controlled scheme places a heavy computational burden on the controller. The power circuit is developed using Insulated Gate Bipolar Transistors (IGBTs). This structure generates the desired reference voltage by acting on both the amplitude and the angle of its components. The motor reaches the reference speed rapidly and without overshoot, load disturbances are rapidly rejected and variations of some of the motor parameters are fairly well dealt with.

Keywords: vector control, induction motor, scalar control, rotor equations, reference frame

Introduction
Modern industrial processes place stringent requirements on industrial drives by way of efficiency, dynamic performance, flexible operating characteristics, ease of diagnostics and communication with a central computer. These coupled with the developments in micro-electronics and power devices have led to a firm trend towards digital control of drives. There is a wide variety of applications such as machine tools, elevators; mill drives etc., where quick control over the torque of the motor is essential. Such applications are dominated by DC drives and cannot be satisfactorily operated by an induction motor drive with constant Volt-Hertz (V/f) scheme. Over the last two decades the principle of vector control of AC machines has evolved, by means of which AC motors and induction motors in particular, can be controlled to give dynamic performance comparable to what is achievable in a separately excited DC drive. In recent decades, many investigations have been done by researchers to control AC motors similar to that of separately-excited dc machines that lead them to vector control theory [1]. Vector control made the ac drives equivalent to dc drives in the independent control of flux and torque. The major disadvantage of the indirect vector control scheme is that it is machine parameter dependant, since the model of the machine is used for flux estimation. The machine parameters are affected by variations in the temperature and the saturation levels of the machine. Any mismatch between the parameters in the motor and that instrumented in the vector controller will result in the deterioration of performance in terms of steady state error and transient oscillations of rotor flux and torque. These types of oscillations are not desired for some exact uses. Regarding the importance of sensitivity of vector control drive to the motor parameters, many investigations have been carried out in this field. In [2] the effects of rotor resistance and mutual inductance variations on output torque and rotor flux have been discussed qualitatively. In the other work the effect of the machine parameters variations on its outputs, referring to simulation results has been investigated and two techniques for rotor resistance estimation have been described [3]. Krishnan in [4] has derived approximate equations for parameter sensitivity of indirect vector control; and finally in some references, motor parameter estimation and compensation techniques and their effect on machine outputs have been described [5]-[9]. In this paper exact equations of parameter sensitivity have been derived. Using derived equations, the effect of parameter variations on the outputs of the machine can be determined. In the next sections, first the basic equations of indirect vector control are presented, and then sensitivity analysis of this type of control carried out and analytical functions for output torque and rotor flux sensitivity are derived.

Indirect vector control rotor field oriented induction machine
The analysis of vector control structures highlights several possibilities to control the instantaneous values of the electromagnetic torque of the induction machine. The position of rotor flux can be estimated directly or indirectly. The
indirect estimation schemes of the rotor flux position ensure a good behaviour in all speed range, and they are the common solution in practice. In the indirect method [4], it is necessary to determine the rotor time constant in order to realize effectively the orientation of the rotor flux space vector. This can be seen from the following equations [7]:

\[ \tau_r \frac{di_{mr}}{dt} + [1 - j \omega_m \tau_r] i_{mr} = i_s \]  \hspace{1cm} (1)

Where

\[ \tau_r = \frac{L_r}{R_r} \] is the rotor time constant

\[ L_r, R_r \] is the rotor inductance and resistance respectively

\[ i_{mr} \] - Rotor magnetization current space

\[ i_s \] - Stator current space vector

\[ \omega_m \] - Electric rotor speed.

Equation (1) is determined taking into consideration the coordinates of the stator, transforming it to the rotor flux coordinates by multiplying with the unit vector \( e^{-j\rho} \) and separating the result into real and imaginary parts, we get

\[ \tau_r \frac{di}{dt} + i_{mr} = i_{ds} \]  \hspace{1cm} (2)

\[ \tau_r \frac{d\rho}{dt} = \omega_m - \omega_1 + \frac{i_{qs}}{\tau_r i_{mr}} \]  \hspace{1cm} (3)

Figure 1 shows the current phasor diagram in the rotatory reference frame. The synchronous speed of the stator current space vectors is:

\[ \omega_1 = \omega_{mr} + \frac{d\delta}{dt} \]  \hspace{1cm} (4)

Where \( \delta \) is the torque angle

In steady state, the torque angle is constant i.e. \( \omega_1 = \omega_m \) and the vectors \( i_s \) and \( i_{mr} \), rotate in synchronism. The components \( i_{qs} \) and \( i_{ds} \) can be controlled independently thus uncoupling the magnetic rotor flux from the torque, a similar behaviour as a separately excited dc motor. This is the basic principle of field orientation control (FOC). The indirect vector speed control with rotor time constant \( \tau_r \) estimation is shown in figure 2 [6]. In the direct method [5], a rotor flux observer (rotor flux model) is needed in order to implement closed loop flux control such that a reference flux value is set and the estimated flux is the feedback signal.

The basic equations describing the dynamic behaviour of an induction machine in a rotating reference frame aligned to the rotor flux axis [1, 2] can be given as

\[ T_r (di_{mr}) / dt + i_{mr} = i_{sd} \]  \hspace{1cm} (5)

\[ d(\rho) / dt = \omega_1 = \omega_1 + \omega_2 = \omega_1 + i_{sq} / T_i i_{mr} \]  \hspace{1cm} (6)

\[ Jd(\omega_1) / dt = 2 / 3P[L_m / (1 + \sigma)]i_{mr}i_{sq} - m_{load} \]  \hspace{1cm} (7)

As evident in the above equations, the electromagnetic torque is directly proportional to \( i_{sd} \) component of the stator current, if \( i_{mr} \) is kept constant. The ideal method of vector control implementation is to control the stator current by controlling \( i_{sq} \) and \( i_{sd} \) separately. While a current controlled inverter using hysteresis controller is easy to realise, it has the following disadvantages:

1. The switching frequency depends on the nature of the load.
2. The current ripple is high.
3. Performance at higher speeds is unsatisfactory.

These disadvantages can be overcome by using a constant switching frequency Pulse Width Modulated (PWM) inverter to control the stator current by a voltage source inverter. This calls for the translation of stator voltage equations to the rotor flux reference frame.

The possibility to use the squirrel cage motor in high performance control systems in which a dynamic response similar to that given by dc motor opens up new applications in industry for this type of motors.

There exist two vector control methods:

- The direct field orientation method where field sensors or models are used to calculate the magnitude and position of the rotor flux vector subsequently orienting it in a system of rotatory orthogonal coordinates.
- The indirect method in which the slip angular speed is used to obtain the position of the rotor flux vector henceforth orienting it.

In both methods, it is necessary to determine correctly the orientation of the rotor flux vector, lack of which leads to degradation in the speed control of the motor. In the indirect method, the rotor flux obtained from an adaptable reference model was compared to a rotor flux obtained from a fixed reference model thus estimating the rotor time constant. This new value is substituted in the oriented field equations thus

![Figure 1 Phasor diagram representation](image-url)
not disorienting the magnetic field framework that rotates at the same speed as the rotor magnetic flux.

The indirect vector controller is derived from the dynamic equations of the induction machine in the synchronously rotating reference frames. The rotor equations of the induction machine are given by:

\[ R_l i_{dr} + p \lambda_{dr}^e = 0 \]  
\[ R_l i_{dq} + p \lambda_{dq}^e - \omega_s \lambda_{dq} = 0 \]

Where
\[ \omega_s = \omega_e - \omega_r \]
\[ \lambda_{dq}^e = L_m i_{dq} + L_r i_{dq} \]
\[ \lambda_{dr}^e = L_m i_{dr} + L_r i_{dr} \]

In these equations, the various symbols denote the following:
\( R_l \), the referred rotor resistance per phase;
\( L_m \), the mutual inductance per phase;
\( L_r \), the stator referred rotor self inductance per phase;
\( i_{dr} \) and \( i_{dq} \), the referred direct and quadrature axes currents, respectively;
\( p \), the differential operator;
\( \omega_s \) and \( \omega_r \) are synchronous speed and electrical rotor speed both in rad/sec,
\( \lambda_{dq}^e \) and \( \lambda_{dr}^e \) are rotor direct and quadrature axes flux linkages, respectively.

The resultant rotor flux is assumed to be on the direct axis, to reduce the number of variables in the equations. Hence, aligning the d axis with rotor flux phasor yields:

\[ \lambda_r = \lambda_{dr}^e \]  
\[ \lambda_{dq}^e = 0 \]  
\[ p \lambda_{dq}^e = 0 \]

Substituting equations (6) to (8) in (1) and (2) and using equations (4) and (5), the followings are obtained for \( i_f \) and \( \omega_{sl} \):

\[ i_f = \frac{1}{L_m} [1 + p T_r] \lambda_r \]  
\[ \omega_{sl} = \frac{L_m i_r}{T_r} \lambda_r \]

Where
\[ i_f = i_{ds} \]
\[ i_r = i_{qs} \]

The q and d axis currents are labeled as torque (\( i_f \)) and flux (\( i_r \)) producing components of the stator current phasor, respectively. \( T_r \) denotes the rotor time constant. Also using equations (6) to (8), we can summarize the induction machine torque equation as:

\[ T_e = \frac{3}{2} \frac{p L_m}{2} \left( \lambda_r i_r \right) = \frac{3}{2} \frac{p L_m}{2} \lambda_r i_r = K_{te} \lambda_r i_r \]

Where \( K_{te} \) is torque constant and is equal to:

\[ K_{te} = \frac{3}{2} \frac{p L_m}{2} \]

Note that the torque is proportional to the product of the rotor flux linkages and the stator q axis current. This resembles the torque expression of dc motor, which is proportional to the product of the field flux linkages and the armature current. If the rotor flux linkage is kept constant, then the torque is simply proportional to the torque producing component of the stator current (\( T i \)), as in the case of the separately excited dc machine, where the torque is proportional to the armature current when the field current is constant. The rotor flux linkage and torque equations given in (9) and (14), respectively, complete the transformation of the induction machine into an equivalent separately excited dc machine from a control point of view.

Figure 2 Simulation model of indirect vector controlled induction motor drive system simulation and experimentation

Computer modelling and simulation is widely used to study the behaviour of various complex systems. With proper simulation techniques, a significant amount of experimental cost could be saved in the prototype development. Among several simulation software packages, SIMULINK [7] is one of the most powerful techniques for simulating dynamic systems due to it’s graphical interface and hierarchical structure and in addition SIMULINK uses MATLAB as a Tool for mathematical purposes which further enhances the modelling process. This software permits the design of special user blocks, which can be added to the main library. Figure 3 shows the block diagram in the d-q synchronous reference frame of the reluctance synchronous machine without damper windings, by considering a two pole machine. The vector control aspects are studied using synchronously rotating...
reference frame. The main part of the dynamic vector controlled reluctance synchronous motor model is the two-axis motor model block which consists of electrical torque, machine voltages and mechanical equations. The (3-2) phase transformation block converts the 3 phase supply to 2-phase but the reverse transformation block converts the 2-phase rotating reference frame into 3-phase stationary equivalent. The load torque \( T \) is simply represented as a constant value, though it can be represented as a variable quantity. In order to start simulating the system, the parameters must be known. They can be either calculated or measured as in this investigation. The parameters of the motor, used for simulation are as shown in Table.

**Table I** Induction machine parameters.

<table>
<thead>
<tr>
<th>S.no</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Voltage(V)</td>
<td>220</td>
</tr>
<tr>
<td>2</td>
<td>Frequency (Hz)</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>Inertia</td>
<td>0.089</td>
</tr>
</tbody>
</table>

**Figure 2** Motor specifications.

**Table II**: Speed Controller

<table>
<thead>
<tr>
<th>S.no</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Proportional gain (Kp)</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>Integral gain (Ki)</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>Derivative gain (Kd)</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 3** Controller parameters.

**Results and Discussions**

Vector controlled motor (kW) has been simulated and the dynamic responses have been obtained. The simulation results for speed-time, torque-time and current-time are as shown in figures 3-5 respectively. Figure 3 shows the speed response for the motor with different load torque \( (T) \) when the reference speed is 200 (rad sec) while keeping the voltage-frequency ratio \((v/f)\) constant. Figure 6 shows the starting torque produced by the motor when the motor started from rest, and figure 5 shows the speed/torque characteristics of the drive.

To validate the simulation results, the prototype of the proposed scheme is worked upon in the laboratory and tests are conducted on it. The motor is run at speed of 1425 rpm in both simulations as well as in experimentation. It can be observed that the simulation results match reasonably with the experimental results. It has been observed that the design of proposed method is flexible for making it suitable for retrofit applications.

**Figure 4** Speed response with time variation.

**Figure 5** Current responses with time variation.

**Figure 6** Speed response with time variation.

**Figure 7** Torque variation with time.

**Figure 8** Experimental speed and voltage response.
The experimental set up is shown as under:

Conclusions
A design procedure has been given for various control loops of a vector controlled drive. The design procedure is verified using computer simulation. The simulation results helps to decide the hardware and software structure for the vector controlled induction motor drive. The total system includes an electronic controller for the signal processing involved in vector control, PWM inverter, motor and the load. Although the hardware and software have been dealt with in the context of a vector controlled induction motor drive, they are general purpose in nature. These can be used for control of other machine types such as wound field as well as permanent magnet synchronous motors. It is also possible to use the same hardware and software for the implementation of other control schemes like direct self- control of induction machines.

The operation of 3.75 KW drive was also investigated experimentally. The simulation has been validated using the actual control of induction motor. The simulation results have shown a reasonably close agreement with experimental results. The results demonstrate that the drive can be operated in a wide speed and load range.

References