Vector Control of Induction Motor using Sophisticated Look-up Table

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Abstract

High-performance variable speed drives require a better transient performance compared with the steady-state operation. Nowadays, vector control and direct torque control (DTC) are popular methods for high performance drives. Though these methods give better performance, the vector control needs reference frame transformations and direct torque control gives large steady state ripples. To overcome these problems, this paper presents a new vector control method for voltage-source inverter fed induction motors using look-up tables. The proposed method combines the principles of both vector control and DTC. The proposed method uses a predetermined look-up table instead of a much more time consuming pulse width modulation (PWM) procedure in conventional vector control to produce inverter gate signals. This approach gives a quick torque response like vector control and gives reduced ripple in steady state compared to DTC. To validate the proposed method numerical simulations have been carried out and compared with the existing algorithms. The simulation results confirm the effectiveness of the proposed method.

Keywords: Induction Motor Drive, Look-up table, Vector Control

Introduction

High performance induction motor drives require decoupled torque and flux control. This control is commonly provided through vector control [1]. Almost 38 years ago, in 1971 F. Blaschke presented a paper on vector control for induction motor. Although vector control schemes are capable of controlling the torque and flux of the induction motor independently, they require reference frame transformation, which increases the complexity of the system. With the advent of vector control scheme, the technique was completely developed and several papers have been published on
vector control [3-6].

In 1985, Takahashi introduced direct torque control (DTC) scheme [7]. In contrast to vector control, DTC method requires the knowledge of stator resistance only; thereby decreasing the associated sensitivity to parameters variation and the elimination of speed information. DTC as compared to FOC is also advantageous in other aspects like absence of co-ordinate transformation and PWM modulator. DTC is also very simple in its implementation because it needs only two hysteresis comparators and a lookup table for both flux and torque control. A detailed comparison between vector control and DTC has given in [8]. Though, DTC gives fast transient response, it gives large ripple in steady state.

Hence to overcome the drawbacks of vector control and DTC, this paper presents a new vector control scheme, which combines the principles of both vector control and DTC. For the current controllers, several look-up tables have given in [9]. This paper also presents, a sophisticated look-up table based vector control algorithm. The proposed method does not require reference frame transformations and give good steady state and transient responses.

Mathematical Modeling of Induction Motor
The voltage expressions of a three-phase induction motor in stator reference frame are given as in (1)

\[ \vec{v}_s = R_s \vec{i}_s + \frac{d\vec{\lambda}_s}{dt} \]  
(1)

\[ \vec{v}_r = R_r \vec{i}_r - j \omega_r \vec{\lambda}_r + \frac{d\vec{\lambda}_r}{dt} \]  
(2)

The dynamic equations of the induction motor can be represented by using flux linkages as variables, which involves the reduction of a number of variables in the dynamic equations. The stator and rotor flux linkages in the stator reference frame are defined as in (2).

\[ \vec{\lambda}_s = L_s \vec{i}_s + L_m \vec{i}_r \]  
(3)

\[ \vec{\lambda}_r = L_m \vec{i}_s + L_r \vec{i}_r \]  
(4)

The electromagnetic torque and electromechanical expressions of the induction motor are given by

\[ T_e = \frac{3}{2} P \frac{L_m}{L_r} (\lambda_{dr} \vec{i}_q - \lambda_{qdr} \vec{i}_s) \]  
(5)

And

\[ T_e = T_L + J \frac{d\omega_m}{dt} = T_L + \frac{2}{P} J \frac{d\omega_r}{dt} \]  
(6)

Vector Control of Induction Motor
Though the induction motor has a very simple structure, its mathematical model is complex due to the coupling factor between a large number of variables and the non-
linearities. The vector control offers a solution to circumvent the need to solve high order equations and achieve an efficient control with high dynamic. The vector control consists in controlling the components of the motor stator currents, represented by a vector, in a rotating reference frame \( d,q \) aligned with the rotor flux. In the vector control algorithm, the machine torque and rotor flux linkage are controlled through stator current vector control. The stator current vector is decomposed into a torque producing component \( (i^*_{qs}) \) and flux producing component \( (i^*_{ds}) \) in a rotating reference frame respectively. The flux component is along a machine flux linkage vector, and the torque component is perpendicular to the flux component. This decouples the torque control from the flux control. The electromagnetic torque expression for an induction motor is given as

\[
T_e = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r} \Re \left( \bar{J} \lambda_r \cdot \bar{i}_s \right) = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r} (\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}) \tag{7}
\]

For decoupling control, the q-axis flux component must be equal to zero. Then the torque expression can be modified as given in (8).

\[
T_e = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r} (\lambda_{dr} i_{qs}) \tag{8}
\]

Hence, the total rotor flux equal to \( \lambda_r = \lambda_{dr} \) and given as in (9).

\[
\lambda_r = \lambda_{dr} = L_m i_{ds} \tag{9}
\]

From (9), it can be observed that the rotor flux is directly proportional to \( i_{ds} \) and is maintained constant. Hence, the torque linearly depends on \( i_{qs} \), and provides a torque response as fast as the current \( (i_{qs}) \) response. Then, the slip frequency is \( i_{qs} \) and added to the rotor speed to generate unit vectors. The block diagram of indirect vector controlled induction motor drive is as shown in Fig.1.

![Block diagram of indirect vector controlled induction motor drive](image-url)
The d-q axes currents then transformed from rotating to stationary and then converted from two-phase to three-phase currents. Then, the reference three-phase currents are compared with the actual three-phase stator currents in the hysteresis band type current controller, from which the pulses can be generated and given to the voltage source inverter.

**Proposed Vector Control Algorithm for Induction Motor**

The electromagnetic torque expression for an induction motor, which is given in (7), can be represented as

\[
T_e = \frac{3}{2} P \frac{L_m}{L_r} \left| \mathbf{\lambda}_r \right| \left| \mathbf{\vec{i}}_s \right| \sin \eta
\]  

(10)

where \( \eta \) is the angle between stator current and rotor flux linkage vectors as shown in Fig. 2.

From (10), it can be observed that the torque dynamics depends on the variation of \( \eta \). Hence, fast torque control can be achieved by rapidly changing \( \eta \) in the required direction. This is the essence of “proposed vector control”. During a short transient, the rotor flux is almost unchanged, thus rapid changes of electromagnetic torque can be produced by rotating the d and q components of stator current vector in the required direction according to the demanded torque. By ignoring the stator resistance drop, the stator voltage expression can be represented as

\[
\bar{v}_s \equiv \frac{d\mathbf{\lambda}_s}{dt}
\]

(11)

Fig. 2 Representation of stator current vector and rotor flux linkage space vectors

From (3) and (4), the stator flux linkage space vector can be represented as given in (12).

\[
\mathbf{\lambda}_s = L_d \mathbf{i}_s + \frac{L_m}{L_r} \mathbf{\lambda}_r \left( \mathbf{\lambda}_s - \frac{L_m^2}{L_r} \mathbf{i}_s \right)
\]

(12)

Then the stator voltage expression can be represented as given in (13).
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\[
\bar{v}_s = \frac{d\bar{\lambda}_s}{dt} = L_s \frac{d\bar{i}_s}{dt} + \frac{L_m}{L_r} \frac{d\bar{\lambda}_r}{dt} - \frac{L_m^2}{L_r} \frac{d\bar{r}_s}{dt} \quad (13)
\]

As the rotor time constant is high, the rotor flux linkage space vector will move slowly. Hence, for short time durations, the rotor flux linkage vector is assumed as constant. This simplifies the voltage expression as follows.

\[
\bar{v}_s = \frac{d\bar{\lambda}_s}{dt} = \left( L_s - \frac{L_m^2}{L_r} \right) \frac{d\bar{i}_s}{dt} = \sigma L_s \frac{d\bar{i}_s}{dt} \quad (14)
\]

For a short time interval of \( \Delta t \), the stator current expression can be represented as given in (15).

\[
\Delta \bar{i}_s = \frac{1}{\sigma L_s} \bar{v}_s \Delta t \quad (15)
\]

Thus, the stator current space vector moves by \( \Delta \bar{i}_s \) in the direction of the stator voltage space vector at a speed proportional to magnitude of voltage space vector (i.e. dc link voltage). By selecting step-by-step the appropriate stator voltage vector, it is then possible to change the stator current in the required direction. Decoupled control of the torque and stator flux is achieved by acting on the radial (flux component current \( \bar{i}_{ds} \)) and tangential components (torque component current \( \bar{i}_{qs} \)) of the stator current vector in the locus. These two components are directly proportional to the components of the stator voltage vector in the same directions. By assuming a slow motion of the rotor flux linkage space vector, if a forward active voltage vector is applied then it causes rapid movement of \( \bar{i}_s \) and torque increases with \( \eta \). On the other hand, when a zero voltage vector is used, the \( \bar{i}_s \) becomes stationary and the electromagnetic torque will decrease, since \( \bar{\lambda}_r \) continues to move forward and the angle \( \eta \) decreases. If the duration of zero voltage space vector is sufficiently long, then the rotor flux linkage space vector will overtake the stator current vector, the angle \( \eta \) will change its sign and the torque will also change its direction. Thus, it is possible to change the speed of stator current vector by changing the ratio between the zero and non-zero voltage vectors.

By considering the three-phase, two-level, six pulse voltage source inverter (VSI), there are six non-zero active voltage space vectors and two zero voltage space vectors as shown in Fig.3. The six active voltage space vectors can be represented as

\[
\bar{V}_k = \frac{2}{3} V_{dc} \exp \left[ j(k-1)\frac{\pi}{3} \right] \quad k = 1,2,...,6 \quad (16)
\]

Depending on the position of stator current vector, it is possible to switch the appropriate voltage vectors to control both d and q axes stator currents. As an example if stator current vector is in sector I, then voltage vectors \( \bar{V}_2 \) and \( \bar{V}_6 \) can increase \( \bar{i}_{ds} \) and \( \bar{V}_3 \) and \( \bar{V}_5 \) can decrease the \( \bar{i}_{ds} \). Similarly \( \bar{V}_2 \) and \( \bar{V}_3 \) can increase the torque component current \( \bar{i}_{qs} \) and \( \bar{V}_5 \) and \( \bar{V}_6 \) can decrease the \( \bar{i}_{qs} \). Similarly the suitable voltage vectors can be selected for other sectors.
The block diagram of proposed vector control algorithm is as shown in Fig.4.

As in conventional vector control, the proposed vector control algorithm generates d- and q- axes commands. Then as in DTC, the proposed algorithm uses hysteresis current controllers and switching table. Thus, the proposed algorithm eliminates time consuming PWM procedure. The generated \( d \) and \( q \) axis current commands are compared with their actual current values obtained from the measured phase currents. The current errors are used to produce \( d \) and \( q \) flags as inputs to the switching table. A third input to the table determines the sector through which the current vector is passing. It is produced by having the \( d \) and \( q \) axis currents and the rotor position. The switching table provides the proper voltage vectors by deciding on the status of the
inverter switches. In field oriented control, the current decoupling network is a feedforward (indirect) method to produce flux orientation. In proposed control system, Current decoupling means to determine the reference current space phasor \( \tilde{i}_{ds}, \tilde{i}_{qs} \), based on reference rotor flux \( \tilde{\lambda}_r \) and torque \( \tilde{\tau}_e \). Based on the outputs of hysteresis controllers and position of the stator current vector, the optimum switching table will be constructed. This gives the optimum selection of the switching voltage space vectors for all the possible stator current vector positions. As in DTC, the stator flux linkage and torque errors are restricted within their respective hysteresis bands, which are \( 2\Delta\tilde{i}_{ds} \) and \( 2\Delta\tilde{i}_{qs} \) wide respectively. If a flux component current \( (\tilde{i}_{ds}) \) increase is require then \( S_d = 1 \); if a flux component current decrease is required then \( S_d = 0 \). The digitized output signals of the two level flux hysteresis controller are defined as,

\[
\text{If } \tilde{i}_{ds} \leq \tilde{i}_{ds}^* - \Delta I_s \text{ then } S_d = 1
\]

\[
\text{If } \tilde{i}_{ds} \geq \tilde{i}_{ds}^* + \Delta I_s \text{ then } S_d = 0
\]

If a torque component current \( (\tilde{i}_{qs}) \) increase is required then \( S_q = 1 \), if \( \tilde{i}_{qs} \) decrease is required then \( S_q = -1 \), and if no change in \( \tilde{i}_{qs} \) is required then \( S_q = 0 \). The digitized output signals of the three level torque hysteresis controller for the anticlockwise rotation or forward rotation can be defined as,

\[
\text{If } \tilde{i}_{qs} \geq \tilde{i}_{qs}^* \text{ then } S_q = 1
\]

\[
\text{If } \tilde{i}_{qs} \geq \tilde{i}_{qs}^* \text{ then } S_q = 0
\]

And for clockwise rotation or backward rotation

\[
\text{If } \tilde{i}_{qs} \leq \tilde{i}_{qs}^* \text{ then } S_q = -1
\]

\[
\text{If } \tilde{i}_{qs} \leq \tilde{i}_{qs}^* \text{ then } S_q = 0
\]

Depending upon the \( S_d, S_q \) and the position of the stator current vector, the suitable switching voltage vector is determined from the lookup table, which is given in Table 1.

**Table 1** Optimum voltage switching vector lookup table

<table>
<thead>
<tr>
<th>Sector</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_d )</td>
<td>( S_q )</td>
<td>( \tilde{v}_2 )</td>
<td>( \tilde{v}_3 )</td>
<td>( \tilde{v}_4 )</td>
<td>( \tilde{v}_5 )</td>
<td>( \tilde{v}_6 )</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>( \tilde{v}_7 )</td>
<td>( \tilde{v}_0 )</td>
<td>( \tilde{v}_7 )</td>
<td>( \tilde{v}_0 )</td>
<td>( \tilde{v}_7 )</td>
</tr>
<tr>
<td>-1</td>
<td>( \tilde{v}_6 )</td>
<td>( \tilde{v}_1 )</td>
<td>( \tilde{v}_2 )</td>
<td>( \tilde{v}_3 )</td>
<td>( \tilde{v}_4 )</td>
<td>( \tilde{v}_5 )</td>
</tr>
<tr>
<td>1</td>
<td>( \tilde{v}_3 )</td>
<td>( \tilde{v}_4 )</td>
<td>( \tilde{v}_3 )</td>
<td>( \tilde{v}_6 )</td>
<td>( \tilde{v}_1 )</td>
<td>( \tilde{v}_2 )</td>
</tr>
</tbody>
</table>
Simulation Results
To verify the proposed algorithm, a numerical simulation has been carried out using MATLAB-Simulink. The induction motor parameters are: \( R_s = 4.1 \, \Omega \), \( R_r = 2.5 \, \Omega \), \( L_s = 0.545 \, \text{H} \), \( L_r = 0.542 \, \text{H} \), \( L_m = 0.51 \, \text{H} \), number of poles = 4 and \( J = 0.04 \, \text{Kg-m}^2 \). The results of conventional vector control and proposed vector control algorithms are presented and compared. The simulation studies have been carried for various conditions such as starting, steady state, load change and speed reversal with a PI type speed controller. The results of conventional vector control algorithm are given in Fig. 5 – Fig. 10 and the results of proposed algorithm are given in Fig.11 – Fig.16.
Fig. 7 transients during load change in conventional vector control algorithm

Fig. 8 transients during speed reversal (speed is changed from +1000 rpm to -1000 rpm)
**Fig. 9** transients during speed reversal (speed is changed from -1000 rpm to +1000 rpm)

**Fig. 10** Harmonic distortion of stator current in conventional vector control algorithm

**Fig. 11** starting transients in proposed vector control algorithm
Fig. 12 steady state plots in proposed vector control algorithm

Fig. 13 transients during load change in proposed vector control algorithm

Fig. 14 transients during speed reversal in proposed algorithm (speed is changed from +1000 rpm to -1000 rpm)
From the simulation results it can be observed that the proposed algorithm gives good performance as in conventional vector control algorithm. As the proposed algorithm eliminates the reference frame transformation and PWM procedure, the complexity involved in proposed algorithm is less. The steady state ripple in current is little more than that of conventional vector control algorithm. Thus, the proposed algorithm is simple and gives good performance.

**Simulation Results**
A novel vector control algorithm is presented in this paper for the VSI-fed induction
motor drive. The proposed algorithm combines the basic principles of vector control and direct torque control algorithms. It uses the instantaneous errors in d-and q axes stator currents and sector information to select the suitable voltage vector. Hence, the proposed algorithm uses a predetermined look-up table instead of a much more time consuming PWM procedure in conventional vector control algorithm. The proposed algorithm is validated through simulation results. From the results, it can be concluded that the proposed method is simple and gives good transient performance with slightly increased steady state ripple in stator current.

References
