A Combined Stator Vector Control – SVM-Direct Torque Control for High Performance Induction Machine Drives

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Introduction

Electrical drives based on induction motors are the most widely used electromechanical systems in modern industry. Due to their reliability, ruggedness, simple mechanical structure, easy maintenance and relatively low cost, induction motors are attractive for use in a new generation of electrical transportation systems, such as cars, buses and trains. However, from the control point of view, they represent a complex multivariable nonlinear problem and constitute an important area of application for control theory. In fact, induction motors constitute a class of highly coupled and multivariable systems with two control inputs (stator voltages) and two output variables (rotor speed and flux modulus), required to track desired reference signals. Traditionally, rotor field-oriented control (RFOC) has permitted fast transient response by decoupling torque and flux control. This control strategy exploits the fact that in a suitable rotating frame, aligned with the rotor flux space vector, the torque and flux dynamics are decoupled and the induction motor can be efficiently controlled using linear techniques. However, RFOC has several disadvantages such as high computational requirement, high parameter dependence and speed signal for the coordinate transformation. Also, the direct torque control (DTC) technique has gained wide acceptance in motor drive. Although the DTC is a simple control scheme with low computational requirement and has merits like inherent sensorless operation and reduced parameter sensitivity, it has some drawbacks such as operation with variable switching frequency and large torque ripple, due to the hysteresis control and the switching table method. To overcome these problems, the variable switching frequency problem and the torque ripple can be addressed by Proportional-Integral (PI) controllers plus space vector modulation (SVM)]. However, the calculation of the voltage command vector requires the derivative of the stator flux vector, which is kept moving and can be a potential source of errors [1–7].

This paper presents an alternative scheme for torque and stator flux control of an induction machine. The proposed scheme investigates the basic DTC idea, which considers the torque of induction machine proportional with the slip frequency if the amplitude of stator flux vector is kept constant. For that, stator flux orientation technique is used to avoid the requirement of the derivative of stator flux vector and to develop the relationships between the controlled variables and the machine torque. Hence, with the combined stator vector control (SVC) and DTC methods, the torque and stator flux vector can be regulated with PI controllers, and the required voltage vector can be applied to the induction machine by the SVM technique. Furthermore, the estimation of the torque and stator flux is based on voltage mode estimator with minimized sensors numbers. In fact, speed sensor is eliminated and only DC-bus voltage sensor and two AC current sensors are needed.

Proposed stator vector - direct torque control (SVDTC)

The dynamic model of the induction machine can be represented in the \((d,q)\) frame as:

\[
\begin{align*}
\dot{\psi}_{ds,q} &= R_s i_{ds,q} + \frac{d\psi_{d,q}}{dt} - \alpha \omega \psi_{q,s}, \\
0 &= R_r i_{dr,qr} + \frac{d\psi_{dr,qr}}{dt} - \alpha \omega \psi_{d,q}, \\
\dot{\psi}_{ds,q} &= L_s i_{ds,q} + L_{dr} i_{dr,qr}, \\
\dot{\psi}_{dr,qr} &= L_r i_{dr,qr} + L_{qr} i_{ds,q}, \\
T_{em} &= p(\psi_{d,s} i_{q,s} - \psi_{q,s} i_{d,s})
\end{align*}
\]

where \((v_{ds}, v_{qs})\) – stator voltages; \((\psi_{ds}, \psi_{qs})\) – stator fluxes; \((\psi_{dr}, \psi_{qr})\) – rotor fluxes; \((i_{ds}, i_{qs})\) – stator currents; \((i_{dr}, i_{qr})\) – rotor currents; \(R_s\) and \(R_r\) – stator and rotor resistances; \(L_s\) and \(L_r\) – stator and rotor inductances; \(L_{dr}\) – mutual inductance; \(p\) – number of pole pairs; \(\omega_s\) and \(\omega_m\) – stator
and rotor angular speed; \( \omega_l \) – slip angular speed \((\omega_b - \omega_h)\); \( T_{em} \) – electromagnetic torque.

It is known that the stator field-orientation method is based on the alignment of stator flux vector with the \( d \)-axis and setting the stator flux to be constant equal to its rated value, which means:

\[
\psi_{ds} = \psi_s; \psi_{qs} = 0.
\]  

(6)

Then, (1) and (5) can be simplified to:

\[
v_{ds} = R_i i_{ds} + \frac{d\psi_s}{dt}; \quad v_{qs} = R_i i_{qs} + \omega_s \psi_s,
\]

(7)

and the rotor currents and rotor fluxes can be expressed as:

\[
i_{ds} = \frac{1}{L_s} (\psi_s - L_s i_{ds}); \quad i_{qs} = \frac{-L_s}{L_s} i_{qs},
\]

(9)

\[
\psi_{ds} = L_s \left( \psi_s - \sigma L_s i_{ds} \right); \quad \psi_{qs} = \frac{-\sigma L_s L_r}{L_r} i_{qs},
\]

(10)

where \( \sigma = 1 - L_{ds}^2 / (L_s L_r) \) – the total leakage constant.

By substituting (9) and (10) in (2) and considering the Laplace operator \( s = d/dt \), (11) can be obtained:

\[
\begin{align*}
\psi_s(s) &= \frac{\sigma T_s}{1 + \sigma T_s} \left[ \frac{1}{\sigma T_r} + s \right] i_{ds}(s) + i_{qs}(s) \omega_{ds}(s), \\
i_{qs}(s) &= \frac{\sigma T_s}{1 + \sigma T_s} \left[ \sigma \omega_r(s) + \frac{1}{\sigma L_s} \psi_s(s) - I_{ds}(s) \right],
\end{align*}
\]

(11)

where \( T_s = L_s / R_s \) and \( T_r = L_r / R_r \) – the stator and rotor time constant, respectively.

Thus, by expressing \( i_{ds} \) and \( i_{qs} \) according to the stator flux, the stator voltages become:

\[
\begin{align*}
V_{ds}(s) &= \frac{\psi_s(s)}{G_{ds}(s)} + E_d(s), \\
V_{qs}(s) &= \omega_s(s) \psi_s(s),
\end{align*}
\]

(12)

where

\[
\begin{align*}
G_{ds}(s) &= \frac{T_s (1 + \sigma T_s)}{1 + (T_r + T_s) s + \sigma T_r T_s s^2}, \\
E_d(s) &= -\frac{\sigma R_s T_r}{1 + \sigma T_s} I_{qs}(s) \omega_{ds}(s).
\end{align*}
\]

(13)

Hence, it can be seen that the stator flux can be regulated by the \( d \)-component of stator voltage. Fig. 1 shows the relationship between \( \psi_s \) and \( V_{ds} \); a second-order equivalent system with a disturbance \( E_d \).

From (11), the \( q \)-component of stator current can be expressed as:

\[
I_{qs}(s) = \frac{K_n \psi_s(s) \omega_{ds}(s)}{(1 + \sigma T_s s + \sigma T_r T_s s^2)},
\]

(14)

where \( K_n = (1 - \sigma) T_c / L_s \).

Hence, (8) becomes:

\[
T_{em}(s) = \frac{pK_n \psi_s^2(s) \omega_{ds}(s)}{(1 + \sigma T_s s + \sigma T_r T_s s^2)}.
\]

(15)

From the basic DTC principle, if the amplitude of stator flux vector is kept constant and equal to its reference value \( \psi_s^* \), the machine torque is proportional with the slip angular speed. Therefore, with the small values of the slip angular speed, (15) can be simplified to:

\[
T_{em}(s) = G_{em}(s) (\omega_s(s) - \omega_n(s)),
\]

(16)

where

\[
G_{em}(s) = \frac{pK_n \psi_s^2(s)}{(1 + \sigma T_s s + \sigma T_r T_s s^2)}.
\]

(17)

Thus, the machine torque can be regulated by controlling the rotating speed of the stator flux vector. Fig. 2 shows the relationship between \( T_{em} \) and \( \omega_s \); a second-order equivalent system with a disturbance \( \omega_n \).

Fig. 2. Closed-loop control of electromagnetic torque

**Space vector pulse-width modulation technique (SVM)**

Since the controllers produce the voltage command vector, appropriate space voltage vector can be generated with Space Vector Modulation (SVM) and fixed switching frequency can be achieved. The SVM technique is used to create a reference vector by modulating the cyclic ratios of switches in each of the six sectors shown in Fig. 3.

However, with the SVM method, the reference voltage should be limited to ensure that the voltage command is lower or equal to the maximum inverter voltage:
\[ V_{ref} \leq V_{\text{max}} = \frac{V_{dc}}{\sqrt{3}}, \quad (18) \]

where \( V_{\text{max}} \) – the maximum available inverter voltage; \( V_{dc} \) – the DC-bus voltage of the inverter.

The space voltage vector is produced by two active vectors, which limit the sector, and two zero vectors. For example, if the reference voltage is located in sector 1, it can be expressed as:

\[
\tilde{V}_{\text{ref}} = \frac{T_0}{T_s} \tilde{V}_1 + \frac{T_1}{T_s} \tilde{V}_2 + \frac{T_7}{T_s} \tilde{V}_7, \quad (19)
\]

where \( T_0, T_1, T_2 \) and \( T_7 \) – the time intervals of \( \tilde{V}_0, \tilde{V}_1, \tilde{V}_2 \) and \( \tilde{V}_7 \), respectively, within the sampling period \( T_s \).

From Fig. 3, it can be obtained:

\[
\begin{align*}
V_{\text{ref}} T_s \cos \delta &= \tilde{V}_1 T_1 + \tilde{V}_2 T_2 \cos \frac{\pi}{3}, \\
V_{\text{ref}} T_s \sin \delta &= \tilde{V}_1 T_1 \sin \frac{\pi}{3}.
\end{align*}
\quad (20)
\]

Thus, \( T_1, T_2 \) and \( T_0 \) (or \( T_7 \)) can be expressed as:

\[
T_1 = \frac{\sqrt{3} V_{\text{ref}}}{2 \tilde{V}_1} T_s \sin \left( \frac{\pi}{3} - \delta \right), \quad T_2 = \frac{\sqrt{3} V_{\text{ref}}}{2 \tilde{V}_2} T_s \sin \delta,
\quad (21)
\]

\[
T_0 = T_7 = 0.5 \left( T_s - T_1 - T_2 \right). \quad (22)
\]

**Structure of the induction machine drive**

The complete scheme that allows torque and flux control has been developed, and it is shown in Fig. 4. It includes the PI regulators for the torque, stator flux and machine speed (deducted by the usual method). Compared to the usual SVM-direct torque control, the stator angular speed is a signal command generated by the torque controller, not an estimated variable as in the other schemes, and allows to generate the \( q \)-component of stator voltage vector. The \( d \)-component of the same vector is generated directly from the stator flux controller.

Also, to avoid involvement of more machine parameters, the unknown variables are estimated in the \((\alpha, \beta)\) frame using the Concordia transformation:

\[
\begin{bmatrix}
I_{\alpha s} \\
I_{\beta s}
\end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix}
1 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
I_{\alpha s} \\
I_{\beta s} \\
I_{\gamma s}
\end{bmatrix}, \quad (23)
\]

\[
\psi_{\alpha s} = \int (V_{\alpha s} - R I_{\alpha s}) \, dt, \quad \psi_{\beta s} = \int (V_{\beta s} - R I_{\beta s}) \, dt, \quad (24)
\]

\[
\psi_{x s} = \sqrt{\psi_{\alpha s}^2 + \psi_{\beta s}^2}, \quad \theta_{x s} = \arctan \left( \frac{\psi_{\beta s}}{\psi_{\alpha s}} \right),
\quad (25)
\]

\[
T_{\text{ems}} = \rho \psi_{x s} I_{\beta s} - \psi_{x s} I_{\alpha s}. \quad (26)
\]

With the DC-bus voltage sensor and the actual inverter switch positions \((s_0, s_1, s_2)\), the stator voltage vector can be determined using:

\[
v_{ax} = \frac{V_{dc}}{\sqrt{6}} (2s_a - s_b - s_c), \quad v_{bx} = \frac{V_{dc}}{\sqrt{2}} (s_b - s_c). \quad (27)
\]

Since the controllers produce the stator voltage vector in \((d,q)\) frame, the voltage vector should be transferred from the stator flux reference frame to the stationary frame by (28) before using SVM algorithm.

\[
\begin{bmatrix}
v_{ax}^* \\
v_{bx}^*
\end{bmatrix} = \begin{bmatrix}
\cos \theta_{x s} & -\sin \theta_{x s} \\
\sin \theta_{x s} & \cos \theta_{x s}
\end{bmatrix} \begin{bmatrix}
v_{ds}^* \\
v_{qs}^*
\end{bmatrix}. \quad (28)
\]

**Simulation result**

The proposed scheme has been implemented with Matlab/Simulink in order to evaluate its performance. The induction machine used for the simulations has the following parameters: 1.5\( kW \), 50Hz, \( p = 2 \), \( R_s = 4.58\Omega \), \( R_r = 4.468\Omega \), \( L_s = 0.253H \), \( L_r = 0.242H \).

For comparison, both SVDTC and conventional DTC for induction motor are simulated with step change in torque from 0 to 10N.m (without speed controller). Fig. 5 shows torque and flux amplitude.

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Torque (N.m)</th>
<th>Stator flux (Wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>2.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3.0</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>4.0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Fig. 4.** Bloc diagram of the proposed induction machine control

**Fig. 5.** System response during step change in torque from 0 to 10N.m. (a) Conventional DTC – (b) SVDTC
Conclusion

This paper has provided a novel direct torque control method to improve high performance drive of an induction machine. The proposed control combines the basic ideas of both stator vector control (SVC) and direct torque control (DTC). With SVC, the amplitude of stator flux vector is kept constant and the relationship between the machine torque and the slip angular speed is fully developed. Thus, the electromagnetic torque can be regulated as in the case of direct torque control, and the PI controllers and SVM technique can be used to obtain a fixed switching frequency and low torque ripple. Furthermore, the estimation of the machine torque and stator flux is based on voltage mode estimator with minimized sensors numbers, and only DC-bus voltage sensor and two AC current sensors are needed.

The simulation results indicate that SVDTC of induction machine can achieve precise control of the stator flux and machine torque. Compared to conventional DTC, presented method is easily implemented, and the steady performances of ripples of both torque and flux are considerably improved.

References


In this paper, a novel direct torque control method has been proposed for high performance induction machine drives. The control system enjoys the advantages of stator vector control and direct torque control and avoids some of the implementation difficulties of either of the two control methods. The stator flux orientation is used to keep constant the amplitude of stator flux vector, and to develop the relationship between the machine torque and the slip angular speed. At this stage, the electromagnetic torque can be regulated as in the case of direct torque control. The proportional–integral controllers and space vector modulation technique are used to obtain a fixed switching frequency and low torque ripple. Simulation experiments results indicate that, with the proposed scheme, a precise control of the stator flux and machine torque can be achieved. Compared to conventional direct torque control, presented method is easily implemented, and the steady performances of ripples of both torque and flux are considerably improved. Ill. 5, bibl. 7 (in English; summaries in English, Russian and Lithuanian).