Indirect Rotor Field Orientation Vector Control for Induction Motors Without Voltage and Current Sensors

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ABSTRACT: This paper presents a vector-controlled implementation strategy that can be realized in the absence of voltage and current sensors. It is proposed that, in order to decouple the torque and flux in the determination of the three-phase voltage reference commands, both stator and rotor currents in the stationary and rotating frames can be derived from the corresponding rotor flux-oriented vector control requirements and motor dynamic equations. A sensitivity analysis to study the effect of parameter deviation or mismatch is also investigated. Simulation results are presented to demonstrate the feasibility and performance of the proposed methodology.

Key-words:- Vector control, Induction motor control, Sensor.

1 Introduction
Indirect field orientation control (IFOC) strategy is widely used for implementing high performance induction motor drive systems, and has been increasingly adopted as the standard industry solution [1-3]. In such scheme, current sensors are used to measure the motor currents and two current controllers have to be designed to regulate the motor currents and to infer the M/T-axis voltage reference command. These sensors and controllers not only increase the overall system’s cost, but also increase the design complexity in terms of drift compensation and gain correction, particularly if the scheme is to be used over the whole speed and torque load ranges.

Conventional slip frequency control scheme does not use voltage/current sensors [4]. However, such scheme is essentially a scalar controller. Inevitably, its dynamic performance is poor due to the coupling between torque and flux. Yamamura S. etc. integrated the scalar scheme with vector control, and proposed the slip frequency vector control strategy to obtain good dynamic responses [5]. But in this method, current sensors and their controllers have to be used to regulate the motor currents.

This paper presents a novel IFOC implementation method for induction motor drives without voltage/current sensors. It also eliminates the two current feedback loops and their associated controllers, resulting in overall design simplicity and cost reduction. In order to realize the decoupled control between the torque and flux, the stator current is separated into two orthogonal components of torque current and flux magnetizing current, and these components are then regulated independently. Furthermore, it can be shown that if the rotor current is known, the voltage applied to the motor can be determined using motor equations. Nevertheless the rotor current cannot be measured directly in induction motors. However, for rotor field orientation drives, one could calculate the rotor current based on the vector control scheme and motor dynamic equations. Thus, the voltage applied to the motor can be controlled precisely. On the other hand, one has to note that as there are no voltage and current feedbacks, the performance of the drive might deteriorate due to parameter deviations/mismatch and disturbances in the input DC link voltage. It is shown from the simulation results that even though there are large mismatches, the proposed algorithm could, with the exception at very low speeds, produce good dynamic and steady state performances over a wide range of speed. The effect of DC link voltage disturbance can be neglected in many practical application cases.

2 Induction Motor Model and the Proposed Control Methodology
According to the rotor field orientation theory [4], [6], the stator current of squirrel-cage induction motor can be decomposed into two orthogonal components in the synchronous rotating rotor flux-oriented reference frame which are, namely, the torque current $i_{TS}$, which is to generate the electromagnetic torque, and the magnetizing current $i_{MS}$, which is to excite the motor flux. Their magnitudes are governed by
The subscript s and r indicate the stator and rotor variables, M, T represent the variables in the rotor field orientation rotating reference frame. \( R_r, L_M, L_S \) and \( L_r \) are the motor rotor resistance, mutual inductance, stator inductance and rotor inductance, respectively. \( \lambda_r \) and \( T_r \) are the respective rotor flux and electromagnetic torque. \( P \) is the number of pole pairs. \( p \) is the \( d/dt \) operator.

In most cases, the flux magnitude should be kept at some constant level, particularly when the motor runs below its base speed. So, equation (1) can be rewritten as

\[
\begin{align*}
    i_{TS} &= \frac{4T_v}{3P\lambda_r} \\
    i_{MS} &= \frac{1 + (L_r / R_r) p}{L_M} \lambda_r 
\end{align*} 
\]

(2)

The current angle \( \theta_2 \) in M-T axis is

\[
\theta_2 = \arctan \frac{i_{TS}}{i_{MS}} 
\]

(3)

On the other hand, the slip frequency is [4]

\[
\omega_s = \frac{R_r i_{TS}}{L_r i_{MS}} 
\]

(4)

The rotor flux angle in stationary reference frame can be expressed as

\[
\theta_1 = \int (\omega_r + \omega_s) dt 
\]

(5)

where \( \omega_r \) is the rotor mechanical speed. Thus, the stator current can be expressed in the stationary reference frame as:

\[
\begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_{MS} \\ i_{TS} \end{bmatrix} 
\]

(6)

where \( \theta = \theta_1 + \theta_2 \)

On the hand, in the rotor flux-orientated reference frame, the rotor side voltage-current equations of squirrel-cage induction motor can be described as

\[
\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} L_M P & 0 \\ L_M \omega_s & 0 \end{bmatrix} \begin{bmatrix} i_{MS} \\ i_{TS} \end{bmatrix} + \begin{bmatrix} R_r + L_r p & 0 \\ L_r \omega_S & R_r \end{bmatrix} \begin{bmatrix} i_{Mr} \\ i_{Tr} \end{bmatrix} 
\]

(7)

The 1st row of eq. (7) can be rewritten as

\[
\begin{align*}
    i_{TS} &= \frac{4T_v}{3P\lambda_r} \\
    i_{MS} &= \frac{1 + (L_r / R_r) p}{L_M} \lambda_r 
\end{align*} 
\]

(8)

In the rotor field orientation control, \( \lambda_r = \lambda_{Mr}, \lambda_{Tr} = 0 \). In most cases, flux magnitude should be kept at some constant levels: \( |\lambda_r| = \cos nt \), or \( p\lambda_r = 0 \). Base on these requirements and the flux definition, the rotor current can be obtained as

\[
\begin{align*}
    i_{Mr} &= -p\lambda_M / R_r = -p\lambda_r / R_r = 0 \\
    i_{Tr} &= (\lambda_{Tr} - L_m i_{TS}) / L_r = (0 - L_M / L_r) i_{TS} 
\end{align*} 
\]

(9)

Using coordinate transformation, the rotor current can be expressed in the stationary reference as

\[
\begin{bmatrix} i_{a r} \\ i_{b r} \end{bmatrix} = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 \\ \sin \theta_1 & \cos \theta_1 \end{bmatrix} \begin{bmatrix} i_{Mr} \\ i_{Tr} \end{bmatrix} 
\]

(10)

The phasor diagram of the stator and rotor current \( (i_s, i_r) \) in \( \alpha-\beta \) axis and M-T axis is shown in Fig. 1.

Based on the motor voltage-current equations in stationary reference frame which are shown below,

\[
\begin{bmatrix} u_{\alpha s} \\ u_{\beta s} \end{bmatrix} = \begin{bmatrix} R_S + L_S p & 0 \\ 0 & R_S + L_S p \end{bmatrix} \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} \\
+ \begin{bmatrix} L_M p & 0 \\ 0 & L_M p \end{bmatrix} \begin{bmatrix} i_{\alpha r} \\ i_{\beta r} \end{bmatrix} 
\]

(11)

and using the 2-phase to 3-phase coordinate transformation, the three phase reference command voltage signal can finally be determined.

Thus, the final stator voltage, including frequency, phase and magnitude, can be directly derived from the motor dynamic equations according to the speed and flux requirements (reference). Voltage/current
sensors, signal feedback loops, and corresponding controllers are unnecessary. Moreover, this method requires neither complicated algorithm [7] nor time-consuming parameter online identification techniques [8]. So, the proposed control scheme can greatly simplify the system design and reduce overall cost.

3 Simulation Results

Digital numerical simulation is carried out to validate the proposed control method. Fig. 2 shows the system configuration of the vector control: a 2.2 kW induction motor is driven by a SPWM voltage-type inverter, and the three-phase voltage reference command applied to the inverter is derived from the flux and torque references. The simulation investigation is focused on the motor performance with decoupled torque and flux, a sensitivity study to evaluate parameter mismatch or deviation, and the tracking ability of the motor in detuned cases. The motor parameters are $R_S = 3 \Omega$, $R_r = 3.23 \Omega$, $L_M = 210mH$, $L_S = L_r = 223mH$, $P=2$. Figs. 3 and 4 show the torque and flux decoupled performance of the motor. In Fig. 3, the motor is running at a speed of 1000 rpm. It can be seen that as the load torque is suddenly changed from 5.5 Nm to 10.5 Nm (trace a), the rotor flux level hardly changes (trace b, c), although there is a small speed dip but then it is restored quickly (trace d). Fig. 4 shows a different case in that the flux level is suddenly changed at $t=5$ s by the manipulators (trace a, c), however the torque can be restored to its original level quickly (trace b).

Fig. 5 shows the tracking performance of the motor following a trapezoidal speed reference (trace a). Trace b is the speed error, and trace c is the rotor flux in the $\alpha$–axis. It can be seen that the flux level can be kept constant in different speed regions. The M-axis and the T-axis fluxes in trace d illustrate the effect of the rotor field-oriented control: $\lambda_{MT} = 0$, $\lambda_{MT} = const$. The speed tracking experiment is in a constant load condition (10Nm). This trapezoidal test can be used to evaluate the driver.
Fig. 5 Trapezoidal tracking running running in bi-direction operation, constant /variable speed and motoring/generative modes.

Fig. 6 Transient performance under step speed and load change responses (trace a). The load torque is
proportional to the rotor speed in this case. There are speed reference and load torque step changes at time $t=3$ s and at $t=3.5$ s (trace a, c) respectively. Trace d and b show the corresponding flux magnitude and $\alpha$ – axis flux.

Because there are no voltage/current feedbacks in this control method, parameter mismatching or detuned running is a major problem. The following tests are designed to evaluate this performance. In Fig.7, the DC link voltage, which is applied to the inverter, is set to have $\pm 20\%$ deviations from the rated voltages (the rated voltage is 500V) (trace a). It shows that the steady state torque is not changed (trace c), but the flux level is changed by as much as about 1200 rpm, traces a, b) and high-speed (1200 rpm, trace c, d). During $t=2s$ to 3s, $\hat{L}_{MSR} = L_{MSR}$. During $t=3s$ to 4s, $\hat{L}_{MSR} = 2L_{MSR}$. During $t=4s$ to 5s:

\[
\hat{L}_{MSR} = 0.5L_{MSR}, \quad \text{where} \quad L_{MSR} \text{ means the actual motor } L_{M}, L_{S}, L_{r} \text{ parameters, and } \hat{L}_{MSR} \text{ means the corresponding mismatched parameters used in the controller. These mismatching hardly affect the motor performance at high-speed and the influence is much more pronounced at low-speeds. The resistance mismatching influence is shown in Fig.9. It explains the flux level versus different stator and rotor resistances in low-speed (100rpm in trace a, b) and high-speed (1200rpm in trace d, c). During $t=2s$ to 3s, $\hat{R}_{sf} = R_{sf}$. During $t=3s$ to 4s, $\hat{R}_{sf} = 2R_{sf}$. During $t=4s$ to 5s, $\hat{R}_{sf} = 0.5R_{sf}$, \quad \text{where} \quad R_{sf} \text{ means the actual } R_{s}, R_{r} \text{ parameters, and } \hat{R}_{sf} \text{ means the mismatched } R_{s}, R_{r} \text{ parameters used in the controller. One can see that noticeable influence only appears in case of low speed running.}

For the proposed control method, it will have a general tolerance to operation with parameters mismatching to a certain extent. A transient performance with parameter mismatching is shown in Fig. 9. The mismatched parameters are: $\hat{R}_{sf} = 2 \hat{R}_{sf}$, $\hat{L}_{MSR} = 1.5 \hat{L}_{MSR}$. The load is set to be proportional to the rotor speed. One can see that although the transient time is increased a bit, the steady state flux and torque (speed) are still constant with very small ripples.

4 Conclusions

A vector control strategy for induction motor drives, which does not use voltage and current sensors, is proposed and tested. This scheme can reduce the system cost and simplify the control design. The current feedback loop and controller can be eliminated. It exhibits the decoupled effect between the flux and torque. Sensitivity to the parameter mismatching is evaluated by simulation, and it shows that the proposed algorithm works well over most speed ranges with the exception of low speeds. Moreover, the proposed system can operate stably with significant parameters mismatching as well.

References:


