Influence of Rotor Time Constant error on IFOC Control Structure

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***Abstract*—This paper describes the influence of detuned value of induction motor rotor time constant parameter on overall performance of indirect field oriented control (IFOC) algorithm. The rotor time constant detuning sensitivity of IFOC drive is investigated in this paper. Presented computer simulation and experimental results show significant influence of parameter mismatch on IFOC structure, especially for high load values. Therefore, if significant rotor time constant drift is expected, an on-line estimation mechanism is required.**

***Index Terms*—rotor time constant, induction motor, indirect field oriented control.**

I. INTRODUCTION

SPECIFIC advantages of induction motor over DC and DC-brushless motors lead to its progressive use in the speed and position controlled servomechanisms. In these motor drive applications, the shaft sensor is always present for the purposes of closing the space loops. Therefore, inherently more robust at low speeds, the indirect field orientation (IFO) controller is preferred choice for the drive with the position sensor [1]. However, since the feed forward slip calculation implies open-loop decoupling of the induction motor, the IFO controller is more sensitive to the plant parameters variation [2]. Hence, for the correct field orientation, the rotor time constant parameter (Tr*), used in the feed forward model, must fit the actual rotor time constant (Tr) of the motor. An inaccurate setting of that parameter results in an undesirable cross coupling and deterioration of the overall drive performance.

In this paper the initial rotor parameter is tuned based on equivalent machine model [3] and off –line tests like no load and load test. However, fluctuations of Tr are further caused by the thermal drift of the rotor resistance (Rr) and by the change of the motor inductances due to the nonlinearity of the main flux path magnetic circuit. While the effects of the magnetic nonlinearity may be predicted and included into the IFOC feed-forward slip-calculator [4], the thermal drift presents a serious problem since the rotor temperature cannot be easily measured. For this reason, it is essential to investigate the influence of rotor time constant parameter mismatch on IFOC structure.

II. INDUCTION MOTOR MODEL WITH TWO STATE VARIABLES

Three phase induction motor has simple construction but unfortunate highly complex model and consequently complex control structure. The induction motor model can be build based on different state vectors. In this paper the model based on stator current and rotor flux state vectors is used. This model with stator current as state vector is suitable for most vector drives which already contain current regulated voltage source inverter –CRVSI.

Stator circuit voltage equilibrium equations, together with flux equations [5] make electrical part of induction motor model :

$$\begin{aligned}\vec{\mathbf{u}}_s &= R_s\vec{\mathbf{i}}_s + \frac{d\vec{\psi}_s}{dt} + j\omega_{dq}\vec{\psi}_s \\ 0 &= R_r\vec{\mathbf{i}}_r + \frac{d\vec{\psi}_r}{dt} + j(\omega_{dq}-\omega_r)\vec{\psi}_r\end{aligned} \tag{1}$$

$$\begin{aligned}\vec{\psi}_s &= L_s\vec{i}_s + L_m\vec{i}_r \\ \vec{\psi}_r &= L_m\vec{i}_s + L_r\vec{i}_r\end{aligned} \tag{2}$$

where:

$$\vec{\mathbf{u}}_s = \begin{bmatrix} u_{ds} \\ u_{qs} \end{bmatrix},\ \vec{\mathbf{i}}_s = \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix}\ \text{i}\ \vec{\psi}_r = \begin{bmatrix} \Psi_{dr} \\ \Psi_{qr} \end{bmatrix}$$

are voltage, stator current and rotor flux vectors, but all ones in ***dq*** coordinate system, which rotates sinchronosly with field (speed $\boldsymbol{\omega_{dq}}$). Differential equation of rotor flux is:

$$\frac{d\vec{\psi}_r}{dt} = -R_r\vec{i}_r - j(\omega_{dq}-\omega_r)\vec{\psi}_r \tag{3}$$

Complex machine equations are:

- *Stator equation of model:*

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$$T_\sigma \frac{d\vec{\boldsymbol{i}}_s}{dt} + \vec{\boldsymbol{i}}_s = -j\omega_{dq} T_\sigma \vec{\boldsymbol{i}}_s + \frac{k_r}{R_\sigma T_r}(1 - j\omega_r T_r)\vec{\psi}_r + \frac{1}{R_\sigma}\vec{\boldsymbol{u}}_s \qquad (4)$$

- *Rotor equation of model:*

$$T_r \frac{d\vec{\psi}_r}{dt} + \vec{\psi}_r = -j(\omega_{dq} - \omega_r)T_r \vec{\psi}_r + L_m \vec{\boldsymbol{i}}_s \qquad (5)$$

where are:

$$T_\sigma = \frac{L_\sigma}{R_\sigma}, L_\sigma = L_s\left(1 - \frac{L_s L_r}{{L_m}^2}\right),$$

$$R_\sigma = R_s + R_r {k_r}^2, \quad k_r = \frac{L_m}{L_r}, T_r = \frac{L_r}{R_\mathrm{r}}$$

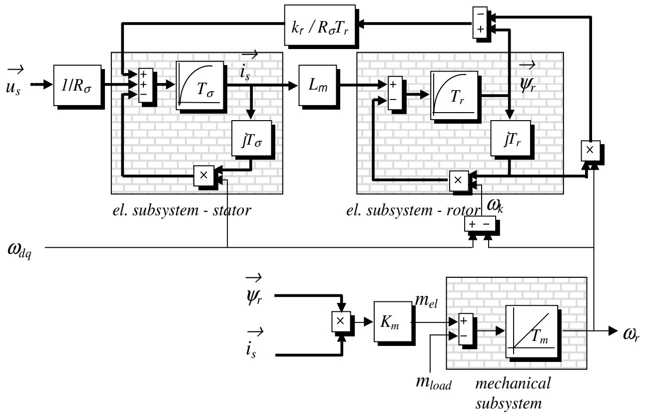


Fig. 1. Model machine in complex domain with stator current and rotor flux vectors as state variables

The equation of mechanical subsystem is:

$$T_m \frac{d\omega_r}{dt} = \frac{3}{2} p \frac{L_m}{L_r}(\vec{\psi}_r \times \vec{\mathbf{i}}_\mathbf{s}) - m_{opt} \qquad (6)$$

where electromagnetic torque is shown as vector product of rotor flux and stator current. Block diagram of complex signals of this model is shown on fig 1.

III. INDIRECT ROTOR FLUX ESTIMATION MODEL

Efficiently driving of asynchronous motor can be done by adjusting frequency and voltage RMS or current RMS. Additionally, choosing right phase attitude of control stator value, it is possible to achieve same effects as they exist at direct current motor with independent excitation.

In order to have optimal vector control of asynchronous motor, it is necessary to control flux and electromagnetic torque independently [1]. Control contour for this variables can be separated by regulation amplitude of stator magnetize excitation force and its relative position in respect of rotor flux vector. Magnetizing excitation stator force can be controlled by current regulated voltage inverter (CRVSI). By elimination of stator voltage equations, electrical subsystem model is simplified and it consists of only one vector equation (5).

In the case of ideal current regulation, in motor is imposed current vector which amplitude and phase attitude are the same as reference. In this way, it is possible to exclude electrical subsystem from analysis. But, in order to have independent control, it is still necessary to know rotor flux position.

Rotor flux position is calculated by algorithm of indirect vector control. In this algorithm, position estimation is done in current model of rotor, which on behalf of stator current vector and mechanical rotor position simulates rotor occurrences.

In a case of ideal current regulated voltage inverter, it can be considered that measured and referenced component stator currents are identical. Therefore, referenced stator component can be used as input in rotor electrical subsystem.

By setting adequate referenced values to current regulated voltage inverter, it is possible to achieve desired complex vector input stator current on desired frequency excitation field ***(ω_{dq}).***

As far as rotor frequency is known (it is provided by measure or estimation of that value), by control frequency of excitation field is practically controlled slip frequency $\boldsymbol{\omega_k}$.

The use of current regulated voltage inverter gives simplified machine model, still there is not provided independent flux and electromagnetic torque control. In that case, quadrature stator component change would induce rotor flux change, not only torque change. That torque change would not be linear with quadrature stator current increase.

Current regulated voltage inverter beside stator currents amplitude, control frequency of stator rotating filed $\boldsymbol{\omega_s}$.
In a case of known electrical rotor frequency $\boldsymbol{\omega_r}$, it is obviously possible to control slip frequency.

In the event that rotor flux vector is set exactly on ***d*** axis**,** it makes flux and torque control independent ($\boldsymbol{i_{qs}}$ value does not influence on rotor flux). It means that if $\boldsymbol{\psi_{qr}}$ is equalized with zero, it gives [1]:

$$\omega_k = \frac{L_m i_{qs}}{T_r \psi_{dr}} \qquad (7)$$

i.e. rotor q flux is zero (8).

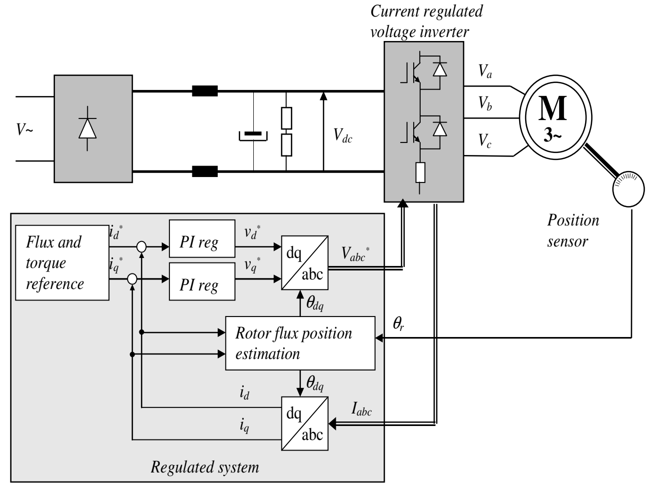


Fig. 2. Schematic of vector controlled motor with current regulated voltage inverter

$$T_r \frac{d\psi_{qr}}{dt} + \psi_{qr} = 0 \qquad (8)$$

Therefore, rotor vector flux on ***d*** axis is:

$$T_r \frac{d\psi_{dr}}{dt} + \psi_{dr} = L_m i_{ds} \tag{9}$$

In this way, it is possible to control amplitude rotor flux only by change of ***d*** component stator current, completely independent of ***q*** component.

Moreover, the expression for electromagnetic torque is simpler, for the same change of flux amplitude it is given linear torque change with change of stator ***q*** component [1]:

$$m_{el} = K_m \psi_{dr} i_{qs} \ , K_m = \frac{3}{2} p \frac{L_m}{L_r} \tag{10}$$

In this way, command flux and torque contour are independent, therefore it is possible to have optimal control of asynchronous motor.

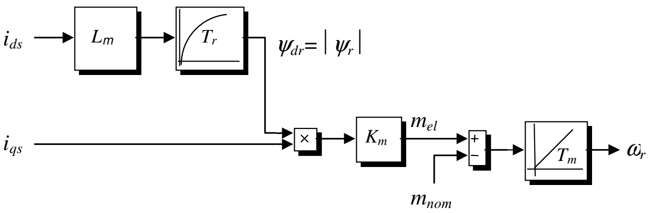


Fig. 3. Simplified model of asynchronous machine

IV. INFLUENCE OF ROTOR TIME CONSTANT ERROR ON IFOC CONTROL

One of the most important tasks of DSP is to calculate all relevant quantities from the model (Fig. 2) in a real time. If the calculations are done according to a real model and in a efficient time, orientation of rotor flux vector is correctly evaluated and independent motor flux and torque control is fulfilled.

Shown model use rotor electrical time constant T_r^* as a parameter, so the model is highly sensitive to its error. If the assumed value of the parameter T_r^* is not consistent with real value $T_r=L_r/R_r$, orientation of rotor flux vector is not correctly estimated. In that case, flux and torque control loops are not independent.

Based on mathematical model of vector controlled induction motor and with the drive simulation in *Matlab*, it could be seen how the potential source of error in T_r^* will affect IFOC drive. In a drive with position sensor, indirect determination of rotor flux vector is directly dependent on slip calculation. Direct component of flux vector in stationary state has a form [1]:

$$\psi_{dr} = L_m \cdot i_{ds} \tag{11}$$

so the slip could be calculated as:

$$\omega_k = \frac{1}{T_r} \cdot \frac{i_{qs}}{i_{ds}} \tag{12}$$

In Eq. (12) i_{qs} and i_{ds} are command input values for slip calculator.

In indirect vector control constant k_{Tr}=1/Tr is of interest, i.e. whole drive structure is dependent on accurate determination of parameter k_{Tr}.

Simulation with k_{Tr} parameter variation is considered on loaded motor with m=1.5[Nm]. Motor is started from zero speed and in a moment ***t=4s*** parameter k_{Tr} is increased for 20%, until moment ***t=8s*** when it is decreased for 20% regard to the accurate value. As could be seen from simulation results in Fig. 4, orientation of synchronous reference frame is lost with the change of parameter k_{Tr} . As an implication of that vector control is also lost which is occured with quadrature component in rotor flux vector ψ_{qr}.

With lose of vector control there is considerable change in stator current quadrature component, as an implication of changing parameter k_{Tr}. In the no-load case, change of parameter k_{Tr} will not affect motor flux and stator current quadrature component.

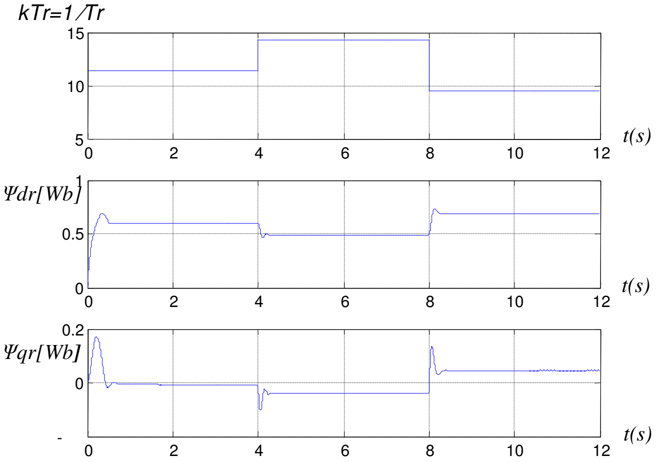


Fig.4. Simulation results – loaded (m = 1.5 [Nm]) motor flux variation with the change of parameter kTr (±20%).

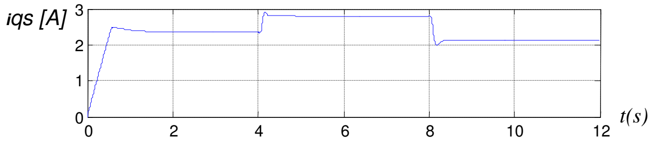


Fig.5. Simulation results – loaded (m = 1.5 [Nm]) motor current i_{qs} variation with the variation of parameter kTr (±20%).

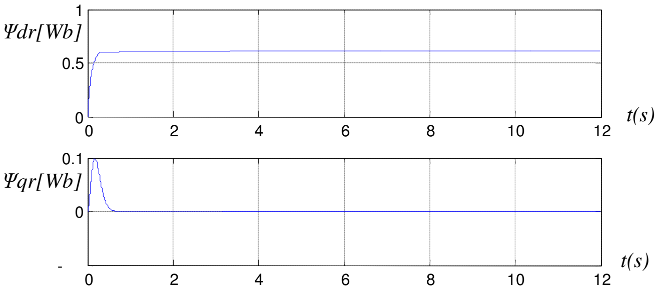


Fig.6. Simulation results – no-loaded motor flux variation with the variation of parameter kTr (±20%).

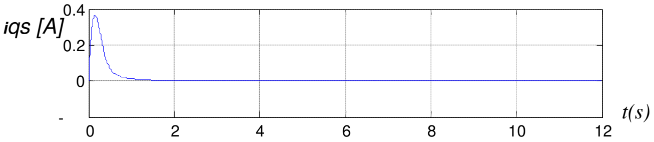
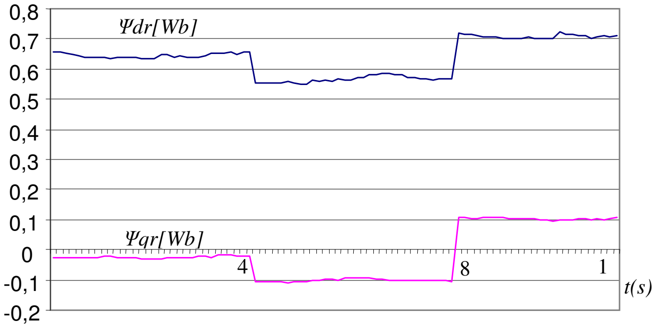


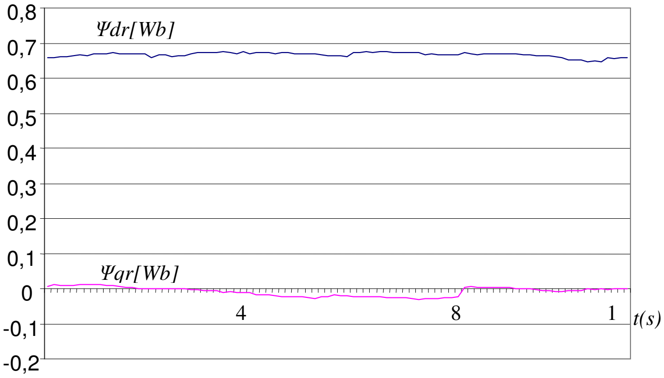
Fig.7. Simulation results – no-loaded motor current iqs variation with the variation of parameter kTr (±20%).

V. EXPERIMENTAL VERIFICATION

Experimental results are done with the motor whose data are used in mathematical model in *Matlab* simulation. With the Freescale DSP 56F8013 as a control unit, simulation results are practically confirmed. Experimental results are shown in Figs. 8 and 9.



Sl.8. Experimental results – loaded (m=1.5 [Nm]) motor flux variation with the variation of parameter kTr (±20%).



Sl.9. Experimental results – no-loaded motor flux variation with the variation of parameter kTr (±20%).

VI. CONCLUSION

This paper shows high sensibility of IFOC drive to incorrect value of rotor electrical time constant. Moreover, it is shown that sensibility is increased as a motor load is increased. So, rotor time constant must be tracked down during whole drive operation, since to magnetic field saturation level and also since to temperature change. According to unpredictable influence of other physical quantities, it is needed to incorporate on-line mechanism (during the drive operation) for rotor time constant identification.

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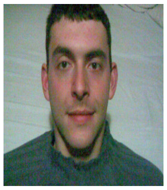

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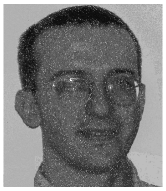

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