Adaptation of the Rotor Time Constant for Variations in the Rotor Resistance of an Induction Motor

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Abstract - An induction motor with indirect field oriented control has a very good dynamic behaviour and as a consequence is well suited for high performance applications. But, the indirect field oriented controller is very sensitive to variations in the rotor time constant. Therefore, an adaptation algorithm has to be used to track the variations of the rotor time constant on-line. In this paper, we present a scheme for estimating the rotor time constant from the motor terminal measurements alone. The technique is based on estimation of the magnitude of the actual rotor flux space phasor when the motor drive torque is constant. This in turn is used for rotor time constant adaptation. A novel point in this approach is that the rotor time constant adaptation can be performed even at zero rotor speed and also at low loads. Further, the adaptation algorithm involves no derivative terms. The entire system has been simulated and the results presented validates the above concept.

1. Introduction

Field oriented control of induction motor decouples the flux and torque producing components of the stator currents and hence allows for their independent control. To achieve field orientation, knowledge of the instantaneous flux position in the induction motor is essential. This is done by using flux sensors (direct field oriented control) or by means of flux estimation algorithms from the measurement of terminal variables (indirect field oriented control). In the direct field oriented control, flux sensors like search coils or Hall effect devices are required which have to be built into the induction motor. This calls for modifications in the machine design and therefore is not suitable for general induction machines. They are also unable to measure the fluxes at very low frequencies. Further, these sensors are inherently less rugged than the motors themselves and therefore the reliability of the system is considerably reduced. In order to make the field oriented control more generally applicable, the indirect field oriented control is used. Here the flux space vector is estimated using the motor model. Either the rotor flux, stator flux or the airgap flux can be estimated and correspondingly one can have a rotor field oriented control, a stator field oriented control or an airgap field oriented control. In this paper, we focus our attention only on rotor field oriented control of induction motors. The rotor flux space vector is estimated from the motor model. But, the estimate depends on the rotor time constant which varies with saturation of the magnetising inductance and variations in rotor resistance due to temperature. While the problem of saturation effect of the magnetising inductance can be accounted for by modelling the nonlinearity of the magnetics involved, the rotor resistance changes cannot be predicted easily. Therefore, an algorithm for on-line adaptation of the rotor time constant has to be used.

Many strategies have evolved over the years for solving the problem of tracking the rotor time constant. One of the schemes is to derive a function F which is a function of variables that can be measured at the terminals of the motor. Then a reference function F* is chosen from the motor model such that the difference F*-F is a measure of the error in the rotor time constant estimate. In [1] a modified reactive power function which relates the stator voltages, stator currents, the derivatives of the stator currents and the machine inductive parameters is used to track the rotor time constant. In [2], model reference adaptive controllers are discussed where the reference models are based on motor torque, d and q-axes voltages and the reactive power. Then an improved scheme is presented where the magnitude of the stator voltage is used as a reference model to perform on-line tuning of the rotor time constant. In [3], a predetermined negative sequence current perturbation is injected into the motor. The corresponding negative sequence voltages are sensed and decomposed into the d-axis and q-axis components. By injecting the signals at two different frequencies where one is dc, the rotor resistance was uniquely determined. But there is some difficulty in implementation as the negative sequence voltage components, especially the dc components will be small compared to the stator voltages and hence would demand very high resolution sensing and proper noise rejection hardware. Extended Kalman filter scheme has also been proposed by many authors as in [4] where the Kalman gains are a function of the rotor speed. Here, the choice of the process and sensor noise co-variances is by trial and error approach.

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In this paper, we present a scheme where a factor called the field disorientation factor, F_d is determined. This factor has to be zero for perfect field orientation. If the field is not oriented, then a non-zero value of F_d results and this in turn is used to tune the rotor time constant. F_d is determinable from the rotor flux, which is estimated when the motor drive torque is constant. The advantages in this scheme are (i) only the terminal variables are used (ii) no derivatives of the currents are used (thereby avoiding the associated numerical instability) and (iii) the rotor time constant tracking is possible at zero rotor speed and low loads.

In the topics to follow, we shall discuss briefly the induction motor flux model in the rotor flux reference frame in section 2. Then we shall present the concept of the field disorientation factor using two approaches in section 3. This is followed by a discussion on the scheme used for adaptation in section 4. Section 5 discusses some implementational aspects which is followed by presentation of the simulation results in section 6.

2. Flux Model

Using the d-q axis theory [5], the rotor flux model of the induction motor in the rotor flux reference frame is

$$\tau_r \frac{di_{mr}}{dt} + i_{mr} = i_{sd} \qquad \text{...(1)}$$

$$\omega_s = \frac{d\rho}{dt} = \omega_m + \frac{i_{sq}}{i_{mr} \cdot \tau_r} \qquad \text{...(2)}$$

where

τ_r = rotor time constant = L_{rr}/R_r
and $L_{rr} = L_{\sigma r} + M$;$L_{\sigma r}$ is the rotor leakage inductance and M is the magnetising inductance. R_r is the rotor resistance.
i_{mr}= the equivalent rotor magnetising current which is given by Ψ_r/M where Ψ_r is the rotor flux space phasor magnitude.
ρ= the spatial position of the rotor flux space phasor
i_{sd}= the component of the stator current along the rotor flux
i_{sq}= the component of the stator current that is in quadrature with the rotor flux
ω_s= synchronous frequency ie. the frequency at which the rotor flux rotates
ω_m= is the electrical frequency of the rotor

From the above equations it becomes evident that the direct component of the stator current, i_{sd}, can be used for

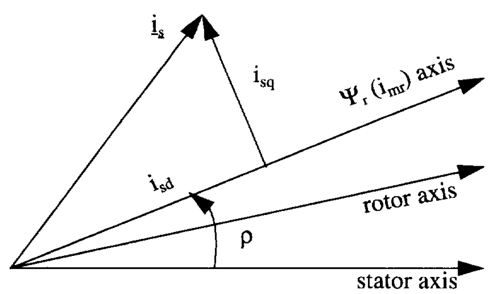

Fig.1 Space phasor diagram for the induction motor

controlling the rotor flux magnitude,i_{mr} which has a spatial position as given by the integral of eqn.(2).

It is evident from figure 1 that for a decoupled control of the rotor flux and the machine torque, the spatial position of the rotor flux, ρ, should be accurately estimated. The rotor flux position that is obtained using eqn.(2) is dependent on the rotor time constant, τ_r, which varies with changes in rotor resistance and saturation of magnetising inductance. Hence it is necessary to perform an on-line adaptation of the rotor time constant to obtain good dynamic performance from the induction motor.

3. Field Disorientation Factor, F_d

Basically in this adaptation scheme, a factor called the field disorientation factor, F_d is determined, which is a measure of the detuning in the rotor time constant. This field disorientation factor is then used to tune the model rotor time constant in such a manner so as to achieve zero value of F_d.The field disorientation factor shall be discussed using two approaches both of which lead to identical conclusions. The first approach is a geometric one which uses the space phasor diagram of the stator currents and the second approach uses the flux model of the induction machine as stated in eqns.(1) and (2).

3.1. Geometric Approach:

Referring to the space phasor diagram of the stator currents in figure 2, the variables with the * represent the actual values of the variables in the motor and those without the * represent the estimated values which are used for control. When there exists a mismatch between the machine variables and the estimated model variables, then the model rotor flux axis differs in spatial position from the actual rotor flux axis by $\Delta\delta$. Figure 2 shows the space phasor diagram of the stator currents and the rotor flux when the rotor flux has reached the steady state. In this operating condition, from eqn.(1) it is evident that $i_{mr}=i_{sd}$.

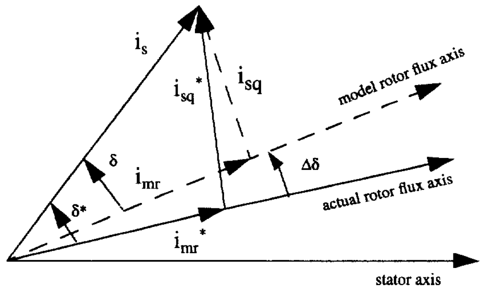

Fig.2 Actual and model space phasors

From figure 2, it is evident that

$$i_{mr} = i_s \cdot \cos\delta \qquad ...(3)$$

$$i_{sq} = i_s \cdot \sin\delta \qquad ...(4)$$

$$i^*_{mr} = i_s \cdot \cos\delta^* \qquad ...(5)$$

$$i^*_{sq} = i_s \cdot \sin\delta^* \qquad ...(6)$$

From eqns.(3) to (6) it can be shown that

$$\sin(\delta^* - \delta) = \frac{(i^*_{sq} \cdot i_{mr} - i_{sq} \cdot i^*_{mr})}{i^2_s} \qquad ...(7)$$

The field disorientation factor, F_d is defined as

$$F_d \equiv (i^*_{sq} \cdot i_{mr} - i_{sq} \cdot i^*_{mr}) \qquad ...(7a)$$

From eqn.(7), as i^2_s is non-zero, F_d must be zero if $\Delta\delta$ is to be zero. In other words, if there occurs a detuning in the value of the rotor time constant, then this would result in a non-zero value of F_d which in turn would mean that the model rotor flux axis is displaced from the actual rotor flux axis by an angle $\Delta\delta$. If $\Delta\delta$ has to be brought back to zero, then F_d must be forced to zero. Hence the problem of adaptation of the rotor time constant reduces to forcing F_d to zero.

3.2. Flux Model Approach:

This approach makes use of the flux model ie. eqns.(1) and (2). Again if the variables with * indicate the actual machine values, then

$$\omega^*_s = \frac{d}{dt}\rho^* = \omega^*_m + \frac{i^*_{sq}}{i^*_{mr} \cdot \tau^*_r} \qquad ...(8)$$

One of the control inputs to the induction motor is the frequency of the stator currents and hence $\omega_s = \omega^*_s$. Also as the rotor speed is directly measured, $\omega_m = \omega^*_m$.

Applying the above constraints to eqns.(2) and (8), the mismatch in the rotor time constant $\Delta\tau_r = (\tau^*_r - \tau_r)$ is given by

$$\Delta\tau_r = \tau^*_r - \tau_r = \tau^*_r \cdot \left(\frac{i^*_{sq} \cdot i_{mr} - i_{sq} \cdot i^*_{mr}}{i^*_{sq} \cdot i_{mr}}\right) \qquad ...(9)$$

Using the definition given in eqn.(7a) for the field disorientation factor, F_d, eqn.(9) reduces to

$$\Delta\tau_r = \tau^*_r \cdot \left(\frac{F_d}{i^*_{sq} \cdot i_{mr}}\right) \qquad ...(10)$$

Again from eqn.(10) it is evident that when there is a mismatch between the model and the machine rotor time constants, F_d becomes non-zero. Thus the field disorientation factor, F_d, can be used to tune the rotor time constant in such a manner as to make F_d equal to zero or in other words achieve field orientation.

4. Adaptation Algorithm

The adaptation algorithm involves the determination of the field disorientation factor, F_d which is passed through a controller, the output of which is used to tune the rotor time constant as shown in figure 3. The controller used in the adaptation loop is a simple proportional-integral controller with a large time constant of the order of a few seconds. As the time constant for the rotor resistance variation with temperature is large compared with the rotor time constant itself, F_d can be evaluated when the motor drive torque has achieved constancy. The advantage in determining F_d when the motor drive torque is constant is that the stator and the rotor currents are sinusoidal under such an operating condition. It will be shown that when the currents are sinusoidal, the actual rotor flux i_{mr}^* (which is used in F_d evaluation) is an algebraic function of the stator voltages and currents; and further it is also independent of the motor resistances.

Referring to figure 3, the F_d evaluator should have as its inputs i_{mr}, i_{sq}, i^*_{mr} and i^*_{sq}. The values of i_{mr} and i_{sq} can be directly obtained from the model and i^*_{mr} and i^*_{sq} are evaluated using the measured values of stator voltages and currents. The approach for evaluating i^*_{mr} and i^*_{sq} is now discussed.

4.1. i^*_{mr} determination:

The equivalent rotor magnetising current is determined using the model of the induction motor in the stator (ie. α–β) reference frame. In [6] the airgap flux is determined using only the measured stator voltages and currents which is also independent of the motor resistances. The rotor flux is determined using a similar approach. The stator and the rotor equations for the induction motor in the stator reference frame are

$$V_{s\alpha} = R_s \cdot i_{s\alpha} + L_{ss} \cdot \frac{di_{s\alpha}}{dt} + M \cdot \frac{di_{r\alpha}}{dt} \qquad ...(11)$$

$$V_{s\beta} = R_s \cdot i_{s\beta} + L_{ss} \cdot \frac{di_{s\beta}}{dt} + M \cdot \frac{di_{r\beta}}{dt} \qquad ...(12)$$

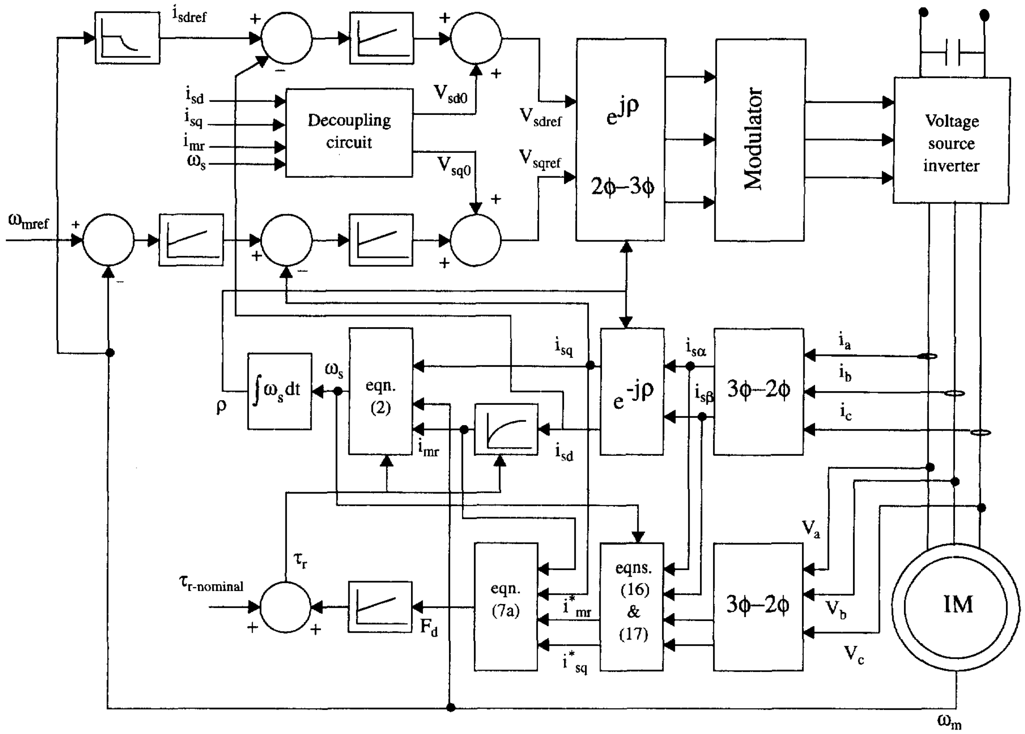

Fig.3. Rotor flux oriented speed control of induction motor with τ_r adaptation

$$0 = R_r \cdot i_{r\alpha} + L_{rr} \cdot \frac{di_{r\alpha}}{dt} + M \cdot \frac{di_{s\alpha}}{dt} + \omega_m \cdot (M \cdot i_{s\beta} + L_{rr} \cdot i_{r\beta}) \quad (13)$$

$$0 = R_r \cdot i_{r\beta} + L_{rr} \cdot \frac{di_{r\beta}}{dt} + M \cdot \frac{di_{s\beta}}{dt} - \omega_m \cdot (M \cdot i_{s\alpha} + L_{rr} \cdot i_{r\alpha}) \quad (14)$$

where

R_s is the stator resistance. $i_{s\alpha}$ and $i_{s\beta}$ are the α and β axes stator currents in the stator reference frame and $i_{r\alpha}$ and $i_{r\beta}$ are the corresponding rotor currents. $V_{s\alpha}$ and $V_{s\beta}$ are the stator voltages in the stator reference frame. $L_{ss}=L_{\sigma s}+M$ and $L_{\sigma s}$ is the stator leakage inductance. All other variables are as defined in section 2.

The dynamics of the rotor flux is very slow compared to the dynamics of the stator currents which are generally 10 to 20 times faster and further the variations in the rotor time constant with temperature is an order of magnitude slower than the dynamics of the rotor flux. Hence, sinusoidal constraints can be applied on the stator and rotor currents to evaluate the magnitude of the rotor flux, Ψ_r. Applying the sinusoidal constraints

$$i_{s\alpha} = I_{sm} \cdot \sin(\omega_s t)$$

$$i_{s\beta} = I_{sm} \cdot \sin\left(\omega_s t - \frac{\pi}{2}\right)$$

$$i_{r\alpha} = I_{rm} \cdot \sin(\omega_s t - \theta_{sr})$$

$$i_{r\alpha} = I_{rm} \cdot \sin\left(\omega_s t - \theta_{sr} - \frac{\pi}{2}\right)$$

where θ_{sr} is the phase difference between the stator and the rotor currents.

in the motor model eqns.(11) to (14) and solving for the rotor flux magnitude results in

$$\psi_r = \sqrt{\frac{L_{rr}}{\omega_s}(V_{s\beta} \cdot i_{s\alpha} - V_{s\alpha} \cdot i_{s\beta}) - \left(L_{rr} \cdot L_{ss} - M^2\right) I^2_{sm}} \quad (15)$$

and

$$i^*_{mr} = \frac{\Psi_r}{M} \quad ...(16)$$

From eqns.(15) and (16), it is evident that the actual value of the rotor flux is an algebraic function of the synchronous frequency,ω_s and the measured values of the stator voltages and the currents. Further, eqns.(15) and (16) are independent of the stator and the rotor resistances of the motor.

4.2. i^*_{sq} determination: The q-axis component of the stator current in the rotor flux reference frame can be determined from the stator current space phasor, i_s that can be measured and i^*_{mr}. From figure 2 it is evident that

$$i^*_{sq} = \sqrt{i^2_s - i^{*2}_{mr}} \quad ...(17)$$

where

$$i^2_s = i^2_{s\alpha} + i^2_{s\beta} = I^2_{sm} \quad ...(18)$$

5. Implementation Scheme

The block diagram for the rotor flux oriented speed control of induction motor with rotor time constant adaptation is shown in figure 3. The scheme consists of the current control loop nested in the speed control loop. Individual controllers for the d-axis and the q-axis currents are used in the synchronous frame. To avoid cross coupling between the d and the q-axis voltages, voltage decoupling equations are to be used to obtain good current control action [7]. The d-axis and the q-axis reference voltages, V_{sdref} and V_{sqref}, are transformed to the stationary ie. the stator reference frame, by performing an axis rotation through ρ. The two phase voltage references in the stator reference frame are then transformed to three phase stator reference voltages. The three phase stator reference voltages are fed to the modulator which is generally based on a pulse width modulation scheme like the sine-triangle comparison or the space vector modulation strategy. The modulator output drives the switches of the voltage source inverter.

The stator currents are measured and transformed to the synchronous reference frame as shown in figure 3. The d-axis and q-axis currents are used as feedback signals for the current control loop. i_{sd} is passed through a low pass filter with time constant τ_r to obtain the equivalent rotor magnetising current, i_{mr}. The rotor speed, w_m, i_{sq}, i_{mr} and the rotor time constant, τ_r are used to determine the rotor flux position, ρ. The ρ thus evaluated is used for $e^{-j\rho}$ and $e^{j\rho}$ transformations.

The stator voltages and currents that are transformed to two phase signals are used to evaluate i^*_{mr} and i^*_{sq}. These variables along with i_{mr} and i_{sq} are used to evaluate the field disorientation factor, F_d. F_d is then passed through a proportional-integral controller, the output of which is summed with the nominal value of the rotor time constant to obtain the tuned value of the rotor time constant. This tuned value of the rotor time constant is used in the flux model to determine the flux amplitude and position. As a proportional-integral controller is used to adapt τ_r, the

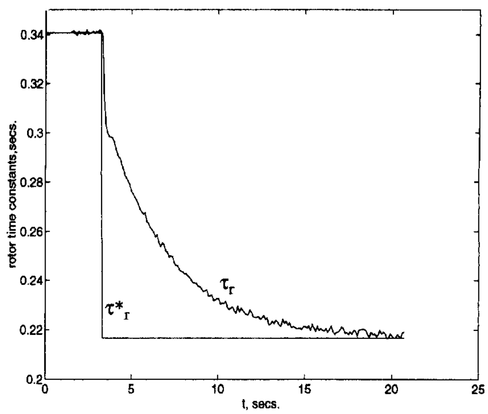

Fig.4 τ_r adaptation at w_m=25rad/s & 50% load

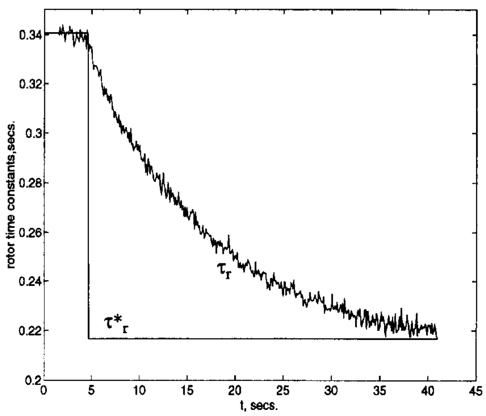

Fig.5 τ_r adaptation at w_m=25rad/s & 10% load

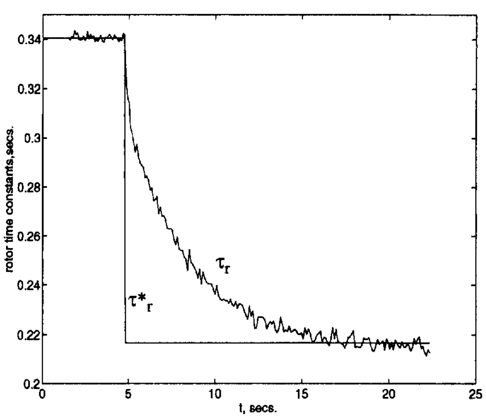

Fig.6 τ_r adaptation at w_m=0rad/s & 50% load field disorientation factor, F_d is forced to zero thereby ensuring proper field orientation and rotor time constant.

6. Simulation Results

The block schematic shown in figure 3 was simulated using SIMULINK. The motor used in the simulation has the following specifications

3 Phase, 400 Vac, 3000rpm, 2 pole
Rs=3.471 ohms
Rr=1.2727 ohms
$L\sigma s$=14.71 mH
$L\sigma r$=14.71 mH
M=418.8 mH

The simulation results are shown in figures 4,5 & 6. Figure 4 shows the adaptation of the rotor time constant to a step change in the actual rotor time constant at half the full load torque. Figure 5 shows the rotor time constant adaptation at 10% of the full load torque. Figure 6 shows the rotor time constant adaptation at zero rotor speed.

One should note that as the load torque becomes smaller, i^*_{sq} becomes smaller which results in a smaller value of the field disorientation factor, F_d. Therefore for lower loads at a given rotor speed the adaptation is slower as is evident from the figures 4 &5.

A point to note in the evaluation of i^*_{mr} and i^*_{sq}, is that they involve evaluation of square roots. As the field oriented control is usually performed by digital processors, implementation of the square root is generally not a problem. Also as the adaptation loop is a much slower loop compared to the current and the speed control loops, the time overhead in calculating square roots will not be high. Another point to be noted during evaluation of i^*_{mr} is that a low pass filter has to be used to filter out the switching harmonics in the stator voltages as the stator voltages are pulse width modulated switching waveforms.

There is yet another point that one should note during implementation. The evaluation of the field disorientation factor is done under sinusoidal stator current constraints. Hence, during transients the adaptation process should be disabled. Either the i_{sq} component of the stator current space phasor or an estimate of the drive torque provides the necessary information regarding the transients during which time the rotor time constant adaptation process is disabled.

7. Conclusions

In this paper, the problem in field orientation due to rotor time constant variation is discussed. The use of field disorientation factor as a measure of detuning in the rotor time constant has been elucidated. The adaptation algorithm which uses the field disorientation factor to tune the rotor time constant against changes in the rotor resistance has also been discussed. In this scheme, only the stator terminal variables are used and no derivative terms are required. Further the adaptation is possible at zero rotor speed and low loads.

8. References

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