Rotor Field Oriented Control with adaptive Iron Loss Compensation
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Rotor Field Oriented Control with adaptive Iron Loss Compensation

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Abstract—It is well known from the literature that iron losses in an induction motor implies field angle estimation errors and hence detuning problems. In this paper a new method for estimating the iron loss resistor in an induction motor is presented. The method is based on a traditional dynamic model of the motor referenced to the rotor magnetizing current, and with the extension of an iron loss resistor added in parallel to the magnetizing inductance. The estimator is based on the observation that the actual applied stator voltages deviates from the voltage estimated, when a motor is current controlled in a Field Oriented Control scheme. This deviation is used to force a MIT-rule based adaptive estimator. An adaptive compensator containing the developed estimator is introduced and verified by simulations and tested by real time experiments.

I. NOMENCLATURE

\[ i_{a,b,c} \]
\[ u_{a,b,c} \]
\[ i_d, i_q \]
\[ R_p, R_s \]
\[ L_d, L_q \]
\[ L_m \]
\[ T_r \]
\[ \alpha \]
\[ R_f \]
\[ L_f' \]
\[ L_m' \]
\[ Z_p \]
\[ \omega_{mech} \]
\[ \omega_{mR} \]
\[ i_m \]
\[ \rho \]
\[ \omega_{slip} \]
\[ w \]
\[ w_{slip} \]

II. MODEL OF THE INDUCTION MOTOR

In a reference frame fixed to the rotor magnetizing current and the q-axis the angular definitions given in fig. 1, we have the d-axis in the direction of the rotor magnetizing current \( i_{mR} \) and the q-axis orthogonal to the d-axis. Defining \( \omega_{mR} = \frac{\omega}{2} \) and the differential operator \( p \equiv \frac{d}{dt} \) the motor model is given by:

\[ u_{sd} = (R_s + pL'_s) i_{sd} - \omega_{mR} L'_s i_{sq} + pL'_m i_{mR} \]
\[ u_{sq} = (R_s + pL'_s) i_{sq} + \omega_{mR} L'_s i_{sd} + \omega_{mR} L'_m i_{mR} \]
\[ i_{mR} = \frac{1}{1 + \frac{T_r}{R_s} i_{sd}} \]
\[ \omega_{slip} = \frac{R_s i_{sq}}{L'_m i_{mR}} \]

with the developed electrical torque expressed by:

\[ m_e = \frac{3}{2} Z_p L'_m i_{mR} i_{sq} = \frac{3Z_p (L'_m i_{mR})^2}{2R_f} \omega_{slip} \]
The electrical equivalent diagram of (1) is shown in fig. 2. If a iron loss resistor is added to the space vector equivalent circuit as shown in fig. 3 the following equations are obtained in a rotor flux oriented coordinate system. The stator voltage equations are unchanged compared to the loss less case

\[
\begin{align*}
    u_{s_d} &= (R_s + pL'_s)i_{s_d} - \omega_m R'_s i_{s_q} + pL'_m i_{m_R} \\
    u_{s_q} &= (R_s + pL'_s)i_{s_q} + \omega_m R'_s i_{s_d} + \omega_m R L'_m i_{m_R}
\end{align*}
\]

but the currents have to be redefined as seen from fig. 3.

\[
\begin{align*}
    i_{r_e} &= (p + j\omega_m R'_s L'_m) i_{m_R} \\
    i'_r &= (p + j(\omega_m R'_s - \omega_r) L'_m) i_{m_R} \\
    i_s &= i_{m_R} + i_{r_e} + i'_r
\end{align*}
\]

The equation for \( i_s \) gives by elimination of \( i'_r \)

\[
    i_s = i_{m_R} + (p + j\omega_m R'_s) \frac{L'_m}{R'_r} i_{m_R} + (p + j\omega_{slip}) \frac{L'_m}{R'_r} i_{m_R}
\]

The imaginary part of this equation leads to

\[
i_{s_q} = (\omega_m R'_s L'_m \frac{R'_r}{R_{Fe}} + \omega_{slip} \frac{L'_m}{R'_r}) i_{m_R}
\]

From this expression \( \omega_{slip} \) becomes

\[
\omega_{slip} = \frac{R'_e i_{s_q}}{I_{m}^2 i_{m_R}} - \omega_m R'_s \frac{R'_e}{R_{Fe}}
\]

Compared with 1 the slip frequency is now reduced due to the introduction of the iron losses.

The real part of 3 gives

\[
i_{s_d} = i_{m_R} + p(\frac{L'_m}{R_{Fe}} + \frac{L'_m}{R'_r}) i_{m_R}
\]

Introduction of the time constant \( T_{Fe} = \frac{L'_m}{R_{Fe}} \) implies the following expression for \( i_{m_R} \)

\[
i_{m_R} = \frac{1}{1 + p(T_r + T_{Fe})} i_{s_d}
\]

The developed electrical torque is

\[
m_e = \frac{3Z_p (L'_m i_{m_R})^2}{2R'_r} \omega_{slip}
\]

The difference in formulas with and without iron loss modeling is shown in the table 1.

### III. Iron Loss Estimation

If the estimated value for the iron loss \( R_{Fe} \), deviates from the correct value \( R_{Fe} \) an error \( \varepsilon \) between the estimated and the correct value of the rotor field angle as shown in fig. 4 occurs. The slip frequency \( \omega_{slip} \) computed by the

<table>
<thead>
<tr>
<th>Without iron loss</th>
<th>With iron loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega_{slip} = \frac{R'<em>e i</em>{s_q}}{I_{m}^2 i_{m_R}} )</td>
<td>( \omega_{slip} = \frac{R'<em>e i</em>{s_q}}{I_{m}^2 i_{m_R}} - \omega_m R'_s \frac{R'<em>e}{R</em>{Fe}} )</td>
</tr>
<tr>
<td>( i_{m_R} = \frac{1}{1 + p(T_r + T_{Fe})} i_{s_d} )</td>
<td>( i_{m_R} = \frac{1}{1 + p(T_r + T_{Fe})} i_{s_d} )</td>
</tr>
<tr>
<td>( m_e = \frac{3Z_p (L'<em>m i</em>{m_R})^2}{2R'<em>r} \omega</em>{slip} )</td>
<td>( m_e = \frac{3Z_p (L'<em>m i</em>{m_R})^2}{2R'<em>r} \omega</em>{slip} )</td>
</tr>
</tbody>
</table>
field oriented controller based on estimated parameters is given as
\[
\dot{\omega}_{slp} = \frac{R_L i_q}{L_m i_m R} - \frac{\omega_m R}{R_F} \frac{L_m}{R_F}
\]

For the real field we have
\[
\omega_{slp} = \frac{R_L i_q}{L_m i_m R} - \frac{\omega_m R}{R_F} \frac{L_m}{R_F}
\]

Using the quasi stationary assumptions \( \dot{\omega}_{slp} = \omega_{slp} \) and \( \omega_m R = \omega_m R \) the following equation is obtained
\[
\frac{i_s}{i_m R} = \omega_m R \left( \frac{L_m}{R_m} - \frac{L_m}{R_F} \right)
\]

Introduction of \( T_{Fe} = L'_m \frac{R'_L}{R_F} \) and \( \dot{T}_{Fe} = L'_m \frac{R'_L}{R_F} \) leads to
\[
\frac{i_s}{i_m R} = \omega_m R (\dot{T}_{Fe} - T_{Fc})
\]

From fig. 4 we then get
\[
tg(\phi - \epsilon) - tg(\phi) = \omega_m R (\dot{T}_{Fe} - T_{Fc})
\]

For \(|\epsilon| << 1 \) and \(|\phi| < \pi/2\) we then have
\[
\frac{2}{1 + \cos(2\phi)} \epsilon = -\omega_m R (\dot{T}_{Fe} - T_{Fc})
\]

and
\[
i_m R = (1 - j\epsilon) i_m R
\]

Fig. 3 then leads to
\[
\ddot{u}_{sd} = \left( R_E + pL'_E \right) i_s d - \omega_m R L'_E i_q - \frac{R'_L R_F}{R'_E + R_F} (i_s d - i_m R)
\]

Due to the mentioned quasi stationary conditions \( pL'_E i_{sd} \) can be neglected. The error between the measured stator voltage \( u_{sd} \) and the value predicted using measured currents is \( \ddot{u}_{sd} \) given by
\[
\ddot{u}_{sd} = \ddot{u}_{sd} - R_E i_s d + \omega_m R L'_E i_q - \frac{R'_L R_F}{R'_E + R_F} (i_s d - i_m R)
\]

Equation 5 and 6 then gives
\[
\ddot{u}_{sd} = \omega_m R L'_E i_m R \epsilon
\]

elimination of \( \epsilon \) using 4 leads to the following linear relation between the estimation error \( \dot{T}_{Fe} - T_{Fc} \) and a measured error \( \ddot{u}_{sd} \)
\[
\ddot{u}_{sd} = -\phi_d (\dot{T}_{Fe} - T_{Fc})
\]

with \( \phi_d \) defined by
\[
\phi_d = 0.5(1 + \cos(2\phi)) \omega_m^2 R'_L L'_E i_m R
\]

For this kind of problem a modified MIT-rule can be applied in order to adapt the iron loss time constant \( T_{Fe} \)
\[
\frac{dT_{Fe}}{dt} = \gamma \frac{\phi_d}{c_0 + \phi_d^2} \ddot{u}_{sd}
\]

If the estimated \( \dot{T}_{Fe} = L'_m \frac{R'_L}{R_F} \) is used in the calculation of \( \omega_{slp} \) as expressed in equation 1, the Field Oriented Controller shown in fig. 11 may easily be modified to include iron losses.

**IV. Simulations**

All simulations are based on the rotor field oriented control scheme shown in fig. 11. The parameters used for simulation are \( L_m = 0.37 H, R_L = 3.5 \Omega, R_E = 5.0 \Omega, L'_E = 0.022 H \) and \( Z_p = 2 \). Fig. 5 shows the rotor speed used as test sequence both for simulations and experiments on the motor test bench. Because the nominal speed for the motor is 1420 rpm the effect of field weakening is also included. The iron loss resistor used for
v.u_e = \frac{1}{2800}\left(1 + 200/10\right) for |\omega|_mR > 10
\left(1 + 200/10\right) else
and the resulting iron loss resistance for the test sequence is shown in fig. 6. The error \( \hat{u}_d \) in 7 is shown in fig. 7. The steady state value different from zero is due to the fact that no iron loss compensation is performed in this experiment. Fig. 8 and 9 shows the result of an simulation with estimation of the iron loss resistor \( R_{Fe} \) and compensation using table 1. For comparison fig. 8 show the correct value of the iron loss resistor too.

V. Experiments

For the practical experiments an 1.5kW 2-pole motor is used. The control scheme for traditional field oriented control is shown in fig. 11, but an extension to the scheme compensating for iron losses is straight forward using table 1. The speed reference signal for the real system is equal to the reference signal used for simulation and as it is seen from fig. 10 compared to fig. 5 the resulting rotor speed and simulated speed are nearly equal. Fig. 12 shows the adapted iron loss resistor. In the figure the situation with fast adaptation is shown, which results in a oscillating estimate. This can be eliminated by a reduction of the adaptation gain \( \gamma \). It is a trade off between stability and adaptation speed. Fig. 13 shows the error signal with and without iron loss compensation as expressed in 7.

VI. Conclusions

A iron loss resistor has been introduced in the traditional scheme for rotor flux oriented control, and an estimator for estimating this resistor has been developed based on a parameter linear description between the parameter error and the calculated error between the measured stator
voltage and the estimated one. The reformulation process is essential in order to get a simple adaptive scheme. A MIT-rule has been chosen for simplicity, but other methods like RLS and Kalman Filter approaches can be used as well due to the parameter linear formulation. Simulations have shown the validity of the method, it is able to estimated the iron loss resistance correctly and for the chosen parameters in the estimator rather fast, but it is a balance between adaptation speed and the fulfillment of the quasi stationary assumption. Practical experiments show that the method via the compensation strategy is able to improve the detuning problems observed in practice when motors contain iron loses.

Fig. 11 - Field Oriented Control

Fig. 12 - Estimated iron loss resistor

Fig. 13 - Estimation error $\tilde{u}_{ed}$ with and without compensation for iron losses

**References**


