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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 loses 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 resistor 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.**

NOMENCLATURE

$i_{sA,B,C}$	stator phase currents A,B and C
$u_{sA,B,C}$	stator phase voltages A,B and C
$\overline{i}_s$	stator current complex space vector
$\overline{u}_s$	stator voltages complex space vector
R_s, R_r	resistances of a stator and rotor phase winding
L_s, L_r	self inductance of the stator and the rotor
L_m	magnetizing inductance
T_r	rotor time constant ($T_r = L_r/R_r$)
σ	leakage factor ($1 - L_m^2/(L_sL_r)$)
R'_r	referred rotor resistance ($R'_r = (L_m/L_r)^2R_r$)
L'_s	referred stator inductance ($L'_s = \sigma L_s$)
L'_m	referred magnetizing inductance ($L'_m = (1-\sigma)L_s$)
Z_p	number of pole pairs
ω_{mech}	angular speed of the rotor
ω_{mR}	angular speed of the rotor flux
i_{mR}	rotor magnetizing current
ρ	rotor flux angle
w_r	electrical rotor speed($w_r = Z_p w_{mech}$)
w_{slip}	speed slip ($w_{slip} = w_{mR} - w_r$)

I. Introduction

Field Oriented Control is a well established discipline. The relevance is witnessed by a large numbers of investigations carried out both from a theoretical and a practical point of view [5]. The theory are based on the general theory of electrical machines neglecting iron losses. The dominating part of the iron losses in an induction machine caused by the stator may be modeled with a pair of equivalent d-q axis windings [4]. This is equivalent to adding a resistor and an inductance in parallel to the magnetizing inductance in the space vector dynamic equivalent circuit. The equivalent iron loss inductance is a fictitious parameter modeling the eddy-current losses during transients and the iron loss resistor models the power dissipation in the stator core. In [4] the iron loss inductance is neglected because it is claimed to have no impact in steady state, but the resistor is estimated and used in a iron loss compensating scheme [1], to eliminate one of the sources for detuned operation of the field oriented controller.

In [2] and [3] it is shown how the iron loss leads to a considerable error in the field angle estimated without iron loss compensation. It is shown that both stator, air-gab and rotor flux show very similar impact to omission of the iron loss resistor in the control scheme. Because rotor flux oriented control leads to a simple scheme for compensation and is far the most popular for vector control, the analysis in this paper is restricted to this scheme.

In the present paper a new method is introduced in order to cope with the well known detuning problems caused by the omission of iron loss compensation. The innovation in the scheme used compared to traditional schemes is that the iron loss resistor is continuously adapted and used for compensation. The performance of the method is verified both by simulations and by practical experiments.

II. Model of the induction motor

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

$$\begin{aligned}
u_{sd} &= (R_s + pL'_s)i_{sd} - \omega_{mR}L'_si_{sq} + pL'_mi_{mR}\\
u_{sq} &= (R_s + pL'_s)i_{sq} + \omega_{mR}L'_si_{sd} + \omega_{mR}L'_mi_{mR}\\
i_{mR} &= \frac{1}{1+T_rp}i_{sd}\\
\omega_{slip} &= \frac{R'_ri_{sq}}{L'_mi_{mR}}
\end{aligned} \tag{1}$$

with the developed electrical torque expressed by:

$$m_e = \frac{3}{2}Z_pL'_mi_{mR}i_{sq} = \frac{3Z_p(L'_mi_{mR})^2}{2R'_r}\omega_{slip}$$

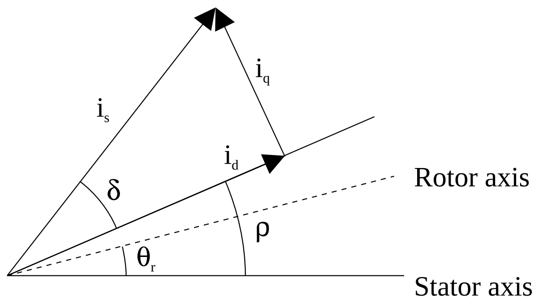

Fig. 1 – Rotor field angle definition

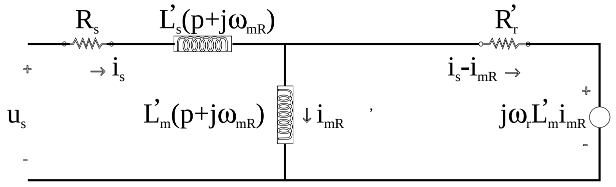

Fig. 2 – Space vector equivalent circuit in a rotor flux oriented reference frame

The electrical equivalent diagram of (1) is shown in fig. 2.

If an 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

$$\begin{aligned} u_{sd} &= (R_s + pL'_s)i_{sd} - \omega_{mR}L'_s i_{sq} + pL'_m i_{mR} \\ u_{sq} &= (R_s + pL'_s)i_{sq} + \omega_{mR}L'_s i_{sd} + \omega_{mR}L'_m i_{mR} \end{aligned} \tag{2}$$

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

$$\begin{aligned} i_{Fe} &= (p + j\omega_{mR})\tfrac{L'_m}{R_{Fe}} i_{mR} \\ i'_r &= (p + j(\omega_{mR} - \omega_r))\tfrac{L'_m}{R'_r} i_{mR} \\ i_s &= i_{mR} + i_{Fe} + i'_r \end{aligned} \tag{3}$$

The equation for i_s gives by elimination of i'_r

$$i_s = i_{mR} + (p + j\omega_{mR})\frac{L'_m}{R_{Fe}} i_{mR} + (p + j\omega_{slip})\frac{L'_m}{R'_r} i_{mR}$$

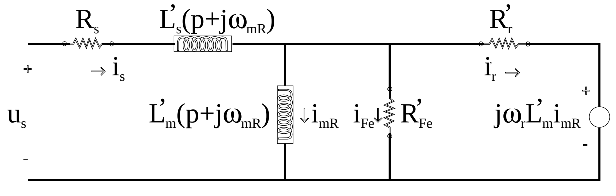

Fig. 3 – Space vector equivalent circuit in a rotor flux oriented reference frame including transferred resistor

TABLE 1. Comparison of equations used for field oriented control with and without modeling iron losses

	Without iron loss	With iron loss
$\omega_{slip} =$	$\dfrac{R'_r i_{sq}}{L'_m i_{mR}}$	$\dfrac{R'_r i_{sq}}{L'_m i_{mR}} - \omega_{mR}\dfrac{R'_r}{R_{Fe}}$
$i_{mR} =$	$\dfrac{1}{1 + pT_r} i_{sd}$	$\dfrac{1}{1 + p(T_r + T_{Fe})} i_{sd}$
$m_e =$	$\dfrac{3Z_p(L'_m i_{mR})^2}{2R'_r}\omega_{slip}$	$\dfrac{3Z_p(L'_m i_{mR})^2}{2R'_r}\omega_{slip}$

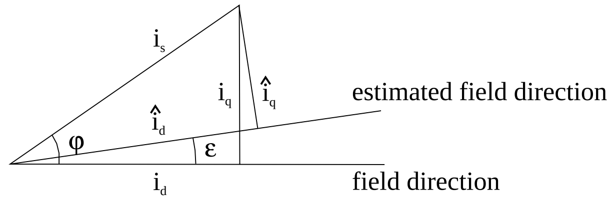

Fig. 4 – Estimated and real rotor field coordinates

The imaginary part of this equation leads to

$$i_{sq} = (\omega_{mR}\frac{R'_r}{R_{Fe}} + \omega_{slip})\frac{L'_m}{R'_r} i_{mR}$$

From this expression ω_{slip} becomes

$$\omega_{slip} = \frac{R'_r i_{sq}}{L'_m i_{mR}} - \omega_{mR}\frac{R'_r}{R_{Fe}}$$

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

The real part of 3 gives

$$i_{sd} = i_{mR} + p(\frac{L'_m}{R_{Fe}} + \frac{L'_m}{R'_r}) i_{mR}$$

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

$$i_{mR} = \frac{1}{1 + p(T_r + T_{Fe})} i_{sd}$$

The developed electrical torque is

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

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 $\hat{R}_{Fe}$ deviates from the correct value R_{Fe} an error ε between the estimated and the correct value of the rotor field angle as shown in fig. 4 occurs. The slip frequency $\hat{\omega}_{slip}$ computed by the field oriented controller based on estimated parameters is given as

$$\hat{\omega}_{slip} = \frac{R'_r \hat{\imath}_{sq}}{L'_m \hat{\imath}_{mR}} - \hat{\omega}_{mR} \frac{R'_r}{\hat{R}_{Fe}}$$

For the real field we have

$$\omega_{slip} = \frac{R'_r i_{sq}}{L'_m i_{mR}} - \omega_{mR} \frac{R'_r}{R_{Fe}}$$

Using the quasi stationary assumptions $\hat{\omega}_{slip} = \omega_{slip}$ and $\hat{\omega}_{mR} = \omega_{mR}$ the following equation is obtained

$$\frac{\hat{\imath}_{sq}}{\hat{\imath}_{mR}} - \frac{i_{sq}}{i_{mR}} = \omega_{mR}(\frac{L'_m}{\hat{R}_{Fe}} - \frac{L'_m}{R_{Fe}})$$

Introduction of $T_{Fe} = \frac{L'_m}{R_{Fe}}$ and $\hat{T}_{Fe} = \frac{L'_m}{\hat{R}_{Fe}}$ leads to

$$\frac{\hat{\imath}_{sq}}{\hat{\imath}_{mR}} - \frac{i_{sq}}{i_{mR}} = \omega_{mR}(\hat{T}_{Fe} - T_{Fe})$$

From fig. 4 we then get

$$tg(\varphi - \varepsilon) - tg(\varphi) = \omega_{mR}(\hat{T}_{Fe} - T_{Fe})$$

For $|\varepsilon| << 1$ and $|\varphi| < \pi/2$ we then have

$$\frac{2}{1+\cos(2\varphi)}\varepsilon = -\omega_{mR}(\hat{T}_{Fe} - T_{Fe}) \qquad (4)$$

and

$$i_{mR} = (1 - j\varepsilon)\hat{\imath}_{mR}$$

Fig. 3 then leads to

$$\begin{aligned} \hat{u}_{sd} = \; & (R_s + pL'_s)\hat{\imath}_{sd} - \omega_{mR} L'_s \hat{\imath}_{sq} + \frac{R'_r R_{Fe}}{R'_r + R_{Fe}}(i_{sd} - \hat{\imath}_{mR}) \\ & + \omega_{mR} L'_m \hat{\imath}_{mR} \varepsilon \end{aligned} \qquad (5)$$

Due to the mentioned quasi stationary conditions $pL'_s\hat{\imath}_{sd}$ can be neglected. The error between the measured stator voltage $\hat{u}_{sd}$ and the value predicted using measured currents is $\tilde{u}_{sd}$ given by

$$\tilde{u}_{sd} = \hat{u}_{sd} - R_s \hat{\imath}_{sd} + \omega_{mR} L'_s \hat{\imath}_{sq} - \frac{R'_r R_{Fe}}{R'_r + R_{Fe}}(i_{sd} - \hat{\imath}_{mR}) \qquad (6)$$

Equation 5 and 6 then gives

$$\tilde{u}_{sd} = \omega_{mR} L'_m \hat{\imath}_{mR} \varepsilon$$

elimination of ε using 4 leads to the following linear relation between the estimation error $\hat{T}_{Fe} - T_{Fe}$ and a measured error $\tilde{u}_d$

$$\tilde{u}_{sd} = -\phi_d(\hat{T}_{Fe} - T_{Fe}) \qquad (7)$$

with ϕ_d defined by

$$\phi_d = 0.5(1 + \cos(2\varphi))\omega_{mR}^2 L'_m \hat{\imath}_{mR}$$

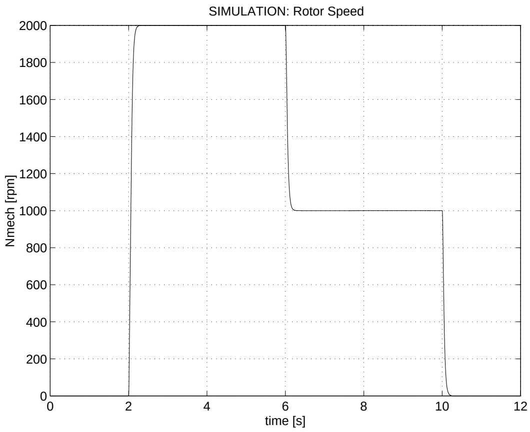

Fig. 5 – Standard speed sequense

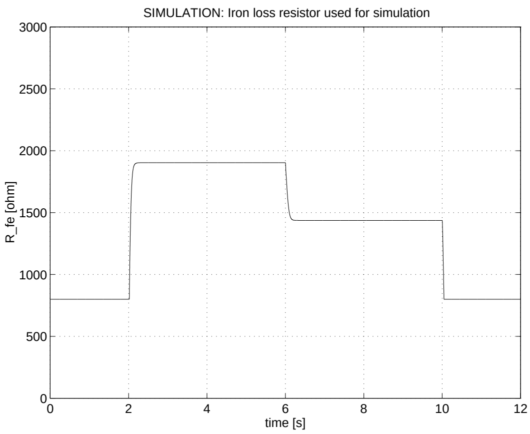

Fig. 6 – Iron loss resistor used for simulation

For this kind of problem a modified MIT-rule can be applied in order to adapt the iron loss time constant $\hat{T}_{Fe}$

$$\frac{d\hat{T}_{Fe}}{dt} = \gamma \frac{\phi_d}{c_0 + \phi_d^2} \tilde{u}_{sd}$$

If the estimated $\hat{R}_{Fe} = \frac{L'_m}{\hat{T}_{Fe}}$ is used in the calculation of ω_{slip} as expressed in table 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 $L'_m = 0.37H$, $R'_r = 3.5\Omega$, $R_s = 5.0\Omega$, $L'_s = 0.022H$ 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 $1420rpm$ the effect of field weakening is also included. The iron loss resistor used for

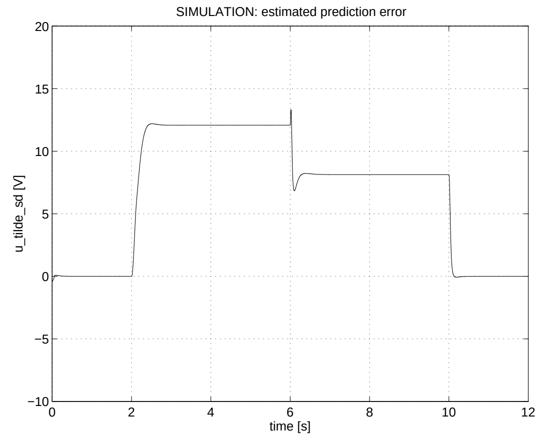

Fig. 7 – $\tilde{u}_{sd}$ without iron loss compensation

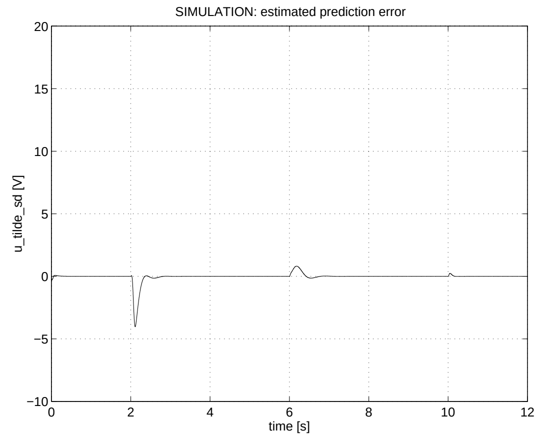

Fig. 9 – $\tilde{u}_{sd}$ with compensation using estimated iron loss resistor

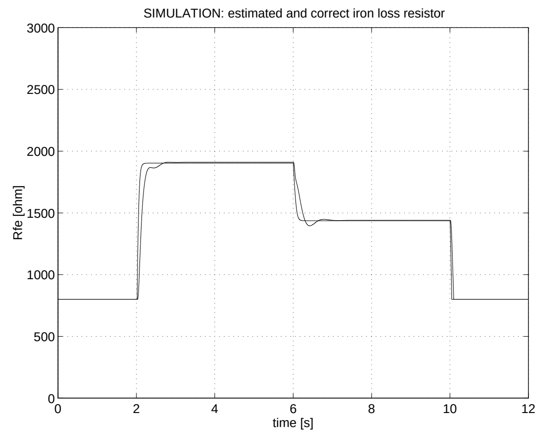

Fig. 8 – estimated and real iron loss resistor

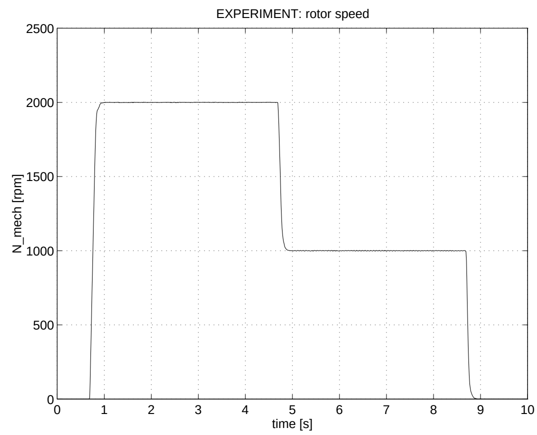

Fig. 10 – Rotor speed

simulation is simulated as

$$R_{Fe}^{-1} = \begin{cases} \dfrac{1}{2800}(1 + 200|\omega|_{mR}^{-1}) & \text{for } |\omega|_{mR} > 10 \\ \dfrac{1}{2800}(1 + 200/10) & \text{else} \end{cases}$$

and the resulting iron loss resistance for the test sequence is shown in fig. 6. The error $\tilde{u}_d$ 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 ba a reduction of the adaptation gain γ. 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

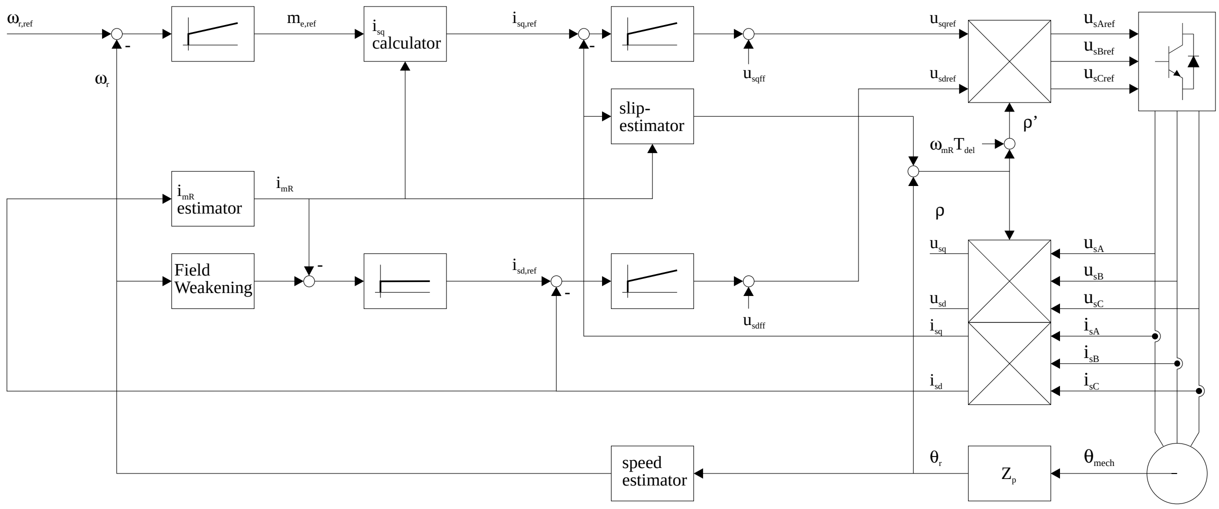

Fig. 11 – Field Oriented Control

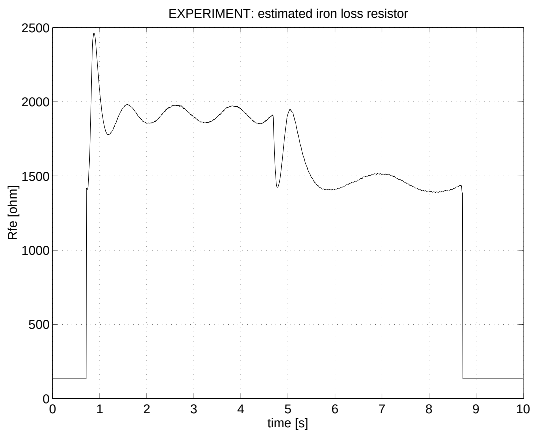

Fig. 12 – Estimated iron loss resistor

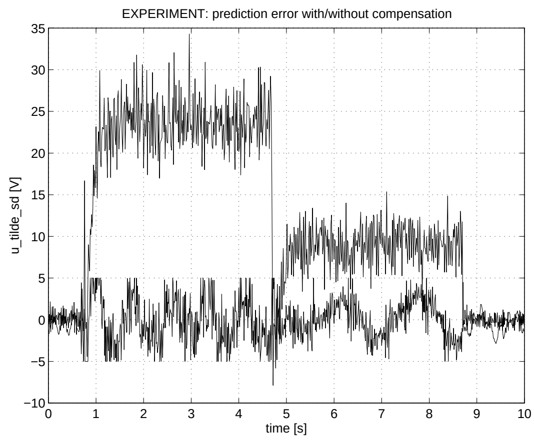

Fig. 13 – Estimation error $\tilde{u}_{sd}$ with and without compensation for iron losses

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.

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