Influence of parameters detuning on induction motor NFO shaft-sensorless scheme

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***Abstract*—In this paper, the parameter sensitivity analysis of shaft-sensorless induction motor drive with natural field orientation (NFO) scheme is performed. NFO scheme calculates rotor flux position using the rotor flux vector reference only, does not require significant processor power and therefore it is suitable for low cost shaft sensorless drives. This concept also eliminates the need for sensitive stator voltage vector integration and it is usable in low rotor speed range. However, low speeds are coupled with low stator voltage amplitudes, which inflate the NFO scheme sensitivity to an error in stator resistance parameter. Similar problems can also take place if mutual inductance parameter is detuned, but this time in whole speed range. This paper investigates the influence of each parameter error on the NFO control steady state characteristics and dynamic performance.**

***Index Terms*—AC motor drives, NFO, stator resistance**

I. INTRODUCTION

Vector control allows decoupled control of the flux and electrical torque of induction motor, which is the condition needed for high performance motor drive. The main problem for utilization of vector control concept is the need for shaft-sensor, which decreases the drives robustness and increases its price and production complexity. Above-mentioned is usually not acceptable for cost-sensitive drive applications. The attractive control solution for these applications is shaft-sensorless, providing it is robust to a motor parameter drift and measurement errors and offsets.

Different schemes for induction motor shaft speed and position estimation are proposed [1]. However, most of the proposed scheme are calculation intensive and memory demanding, and can't be implemented in a low cost drive. Low cost drive is usually based on a low cost digital signal processor having limited program and data memory and limited on-line signal processing capabilities [2]. The NFO concept uses minimum of processor time and memory recourses and can be very attractive control concept for these drives applications. NFO concept was first time patented in 1984 [3]. It uses simplified stator circuit model for rotor back-emf signal estimation, which is later used to generate the position of rotating coordinate system. The NFO concept is based on assumption that establish flux equals to its reference value, and that it is delayed for 90 degrees relatively to the vector of its back-emf. If this assumption is correct, the rotor back-emf is easily calculated, In addition, all the problems related to the stator back-emf integration are avoided. In original form, the NFO is stator flux vector based, but new published papers introduce the rotor flux vector based NFO scheme [4-6].

Main disadvantage of NFO scheme can be found in enclosed open loop back-emf vector estimator [7, 8]. This estimator is especially sensitive to an error in the stator resistance or mutual inductance parameters [9]. The stator resistance changes with the thermal drift and its parameter error can't be predicted [10, 11]. This mismatch becomes more serious in the low speed range mode of operations or during the start up procedure. The mutual inductance error influences the NFO control in whole speed range, but it is flux level dependent and can be predicted feed-forward.

This paper investigates the influence of error in both above-mentioned parameters on steady state characteristics and dynamic mode of drive operations. Different error levels are analyzed for each parameter individually, first in steady state condition. Steady state characteristics are displayed under the variety of operations conditions, for different steady state speeds and mechanical loads. Sensitivity level of steady state characteristics is presented by showing the steady state rotor speed error and achieved field orientation angle error. Secondly, the parameter sensitivity research was further expanded on dynamic regime of the detuned NFO scheme. The dynamic model simulation results, around different steady state points, were used to investigate the robustness and stability of the detuned NFO shaft-sensorless operation. Both models are developed in MATLAB, Simulink toolbox.

II. NFO CONCEPT

Main idea behind the NFO concept is usage of reference flux vector, rather than its estimated value. NFO concept can be explained using equivalent scheme of induction motor, given on figure 1.

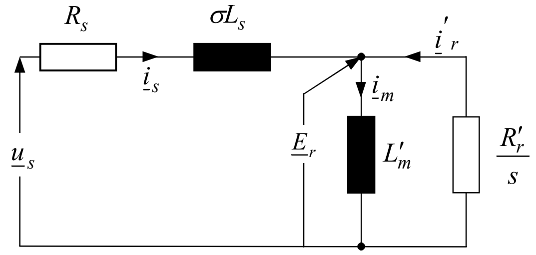

Fig. 1. Γ model of induction motor

This is Γ equivalent electrical model of induction motor, having: $L'_m = L_m^2/L_r$.

Electromotor force can be expressed, using Γ equivalent electrical model, in stator stationary reference frame:

$$\underline{E}_r^s = E_{\alpha r} + jE_{\beta r} = \frac{d\underline{\psi}_r^s}{dt} = L'_m \frac{d\underline{i}_m^s}{dt} . \quad (1)$$

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All the variables from (1) can be transformed in rotor flux reference frame:

$$\underline{E}_r^e = e^{-j\vartheta_{dq}}\,\underline{E}_r^s = E_{dr} + jE_{qr}\,. \qquad (2)$$

Based on (2), the rotor flux vector angle velocity can be calculated using q–axis back-emf component and d-axis stator current component ($i_{ds} = \underline{i}_m$):

$$E_{qr} = L'_m \omega_{dq} i_{ds} \Rightarrow \qquad \omega_{dq} = \frac{E_{qr}}{L'_m i_{ds}} \qquad (3)$$

Ones rotor flux vector angle velocity is known, rotor speed can be estimated using indirect field orientation control (IFOC) slip calculator. This is the expression for estimated rotor angular velocity:

$$\hat{\omega} = \omega_{dq} - \frac{1}{T_r}\frac{i_{qs}}{i_{ds}}\,, \qquad (4)$$

where, based on Γ equivalent scheme, $i_{ds} = i_m$.

First, vector of back-emf must be estimated. This can be done using stator circuit equations only, in the stationary reference frame:

$$\underline{E}_r^s = \underline{u}_s^s - R_s \underline{i}_s^s - \sigma L_s \frac{d\underline{i}_s^s}{dt}\,. \qquad (5)$$

Estimated back-emf, and as well all the variable used in (5), can be transformed from stator stationary coordinate system to the rotor flux rotational coordinate system:

$$\underline{E}_r^e = \underline{u}_s^e - R_s \underline{i}_s^e - \sigma L_s \frac{d\underline{i}_s^e}{dt} - j\omega_{dq}\sigma L_s \underline{i}_s^e \qquad (6)$$

Fig. 2. shows block diagram of NFO algorithm implemented in the rotor flux reference coordinate system. The diagram shows simple integration of estimated rotor vector velocity (ω_{dq}) used for rotor flux position calculation (ϑ_{dq}). Two coordinate transformations are used: one for current control in rotary coordinate system (the upper parts of the block diagram) and second, inverse transformation, used to transfer estimated rotor back-emf in presumed rotor flux coordinate system. The estimation of rotor back-emf vector is implemented using expression (5). Value of E_{dr} signal (6) should be zero, for ideally tuned system. This is the case for zero position error between the estimated and real rotor flux vector.

The scheme on Fig 2. includes the possibility of the stator resistance parameter error ($R_s^* = R_s$) and nominal mutual inductance parameter error ($L_m^* = L_m$). The flux reference is kept nominal, giving constant magnetic current amplitude ($i_m = i_{ds} =const$).

Different than classic indirect field orientation (IFO) vector control, NFO scheme does not use feed forward calculated slip angular frequency for vector orientation. Therefore, the NFO field orientation is insensitive to the rotor circuit parameter errors. However, the NFO estimation of rotor speed does rely on correct feed forward slip calculation. Although the orientation would be correct and stable, the archived speed would be different than referenced, if the rotor time constant parameter is not correct. The field orientation is also insensitive to the decrease of stator frequency value and also to a measurement offset errors, all due to the fact that integration is avoided.

This paper investigated the special type of NFO scheme, deployed in coordinate system connected to the rotor flux vector. This NFO scheme differs from traditional NFO oriented to the stator field (SFOC) and has some important advantages.

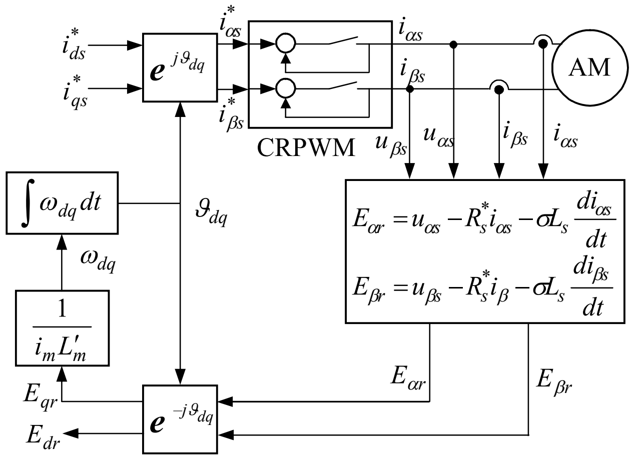

Fig. 2. Block diagram of NFO based shaft-sensorless drive in the rotor flux coordinates frame.

First of all, usage of rotor flux NFO leads to the same torque limits like in the IFOC case, SFOC torque limits are avoided. Secondly, the rotor flux orientation avoids cross-coupling blocks in the d and q current regulators. The only disadvantage is the usage of one extra parameter, namely the total stator inductance parameter σL_s, in addition to the parameters R_s* and L_m*. Fortunately, in most of the operational range, the σL_s parameter does not change and can be kept on constant, nominal value.

III. STEADY STATE MODEL OF NFO SCHEME IN ROTOR FLUX REFERENCE FRAME

In this chapter, the parameter sensitivity analysis of the rotor flux oriented NFO scheme is performed. In particular, the influence of the stator resistance and mutual inductance drifts on the steady state values of achieved rotor speed, angle orientation error and d-axis component of rotor back-emf is investigated.

Vector controlled drive uses current controlled voltage source inverter (CRVSI). Due to the current feedback one can presume that average values of injected d and q currents in motor windings are equal to their references. Having that in mind, the steady state mathematical model of induction motor can be expressed as:

$$0 = R_r i_{dr} - (\omega_{dq} - \omega)\cdot(L_r i_{qr} + L_m i_{qs}) \qquad (7)$$

$$0 = R_r i_{qr} + (\omega_{dq} - \omega)\cdot(L_r i_{dr} + L_m i_{ds}) \qquad (8)$$

$$T_L = \frac{3}{2} p L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \qquad (9)$$

Equations (7) – (9) are all in rotor flux reference frame. However, if the rotor speed and rotor flux controller are present, some of the variables in motor model equations are not independent anymore. Primary, the d current (i_{ds}) defines the rotor flux reference, and it is equal to its reference value. Secondly, due to the speed regulator, the steady state value of estimated rotor speed must be equal to the rotor speed reference value. If this is the case, equation (4) can be modified,

$$\omega^* = \hat{\omega} = \omega_{dq} - \frac{1}{T_r}\frac{i_{qs}}{i_{ds}}\,. \qquad (10)$$

Furthermore, the NFO control adds one more equation, the rotor back-emf equations (6):

$$E_{dr} = u_{ds} - R_s^* i_{ds} + \omega_{dq}\sigma L_s i_{qs} \quad (11)$$

$$E_{qr} = u_{qs} - R_s^* i_{qs} - \omega_{dq}\sigma L_s i_{ds} \quad (12)$$

All the expressions of the NFO steady state model (11)-(12) contain the R_s^* parameter. On the other hand, the motor stator resistance value is R_s, and it can be different from R_s^*. From the (3) i (12), we can shape the final form of NFO controller model:

$$L_m'^{*}\omega_{dq} i_{ds} = \left(R_s - R_s^*\right) i_{qs} + \omega_{dq}\left[(1-\sigma)L_s i_{ds} + L_m i_{dr}\right] \quad (13)$$

The NFO controller also operates with mutual inductance parameter, not necessary equal to the motor mutual inductance. Therefore, one can note that in models equation (13) the parameter $L'_m{}^*$ is used, instead of L'_m.

The independent variables (or inputs) of resulting NFO steady state model are: rotor speed reference – ω^*, d axis current reference – i_{ds}, (rotor flux) and load torque – T_L. The dependent variables (steady state model outputs) are the steady state values of one stator and two rotor currents – i_{qs}, i_{dr}, i_{qr}, rotor dq frame angular frequency – ω_{dq} and rotor angular frequency – ω. This model was calculated numerically in MATLAB, producing one output vector

$\mathbf{Y} = [i_{qs}, i_{qr}, i_{ds}, \omega_{dq}, \omega]^T$,

for each steady state input vector selected

$\mathbf{X} = [\omega^*, i_{ds}, T_L]^T$.

IV. NFO SCHEME SENSITIVITY TO THE PARAMETER DETUNING

4.1. NFO scheme sensitivity to the stator resistance parameter detuning

The NFO steady state model is used, with $R_s^* \neq R_s$ and $L_m^* = L_m$, to investigate the NFO scheme sensitivity to the stator resistance parameter error. The results for two different rotor speed references are displayed on the Fig.3 and Fig.4. Results are shown for rotor speed references 2,5Hz and 10Hz. Model assumes the correct value of all other NFO parameters.

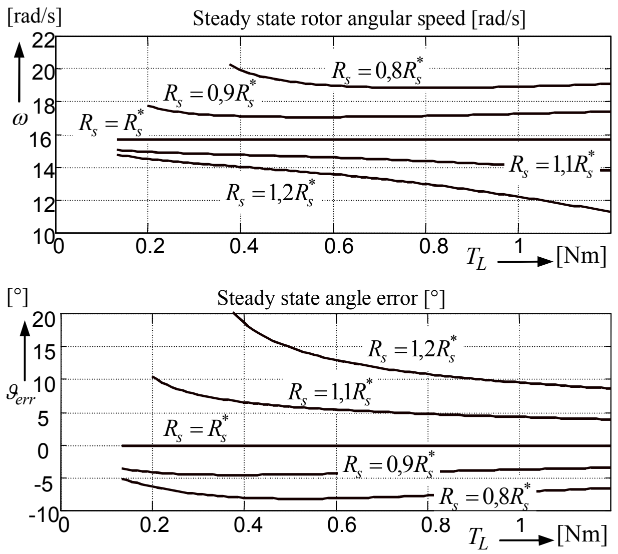

Fig. 3. The influence of mismatched stator resistance parameter: estimated speed error and field orientation. Results of steady state NFO model for 2,5 Hz rotor reference and load torque 0 – 1.2 Nm.

The figures show steady state values of achieved rotor speed and field orientation error (difference between the motor model and NFO estimated angle), for 2,5Hz and 10Hz rotor speed reference. The results are given for different load torques.

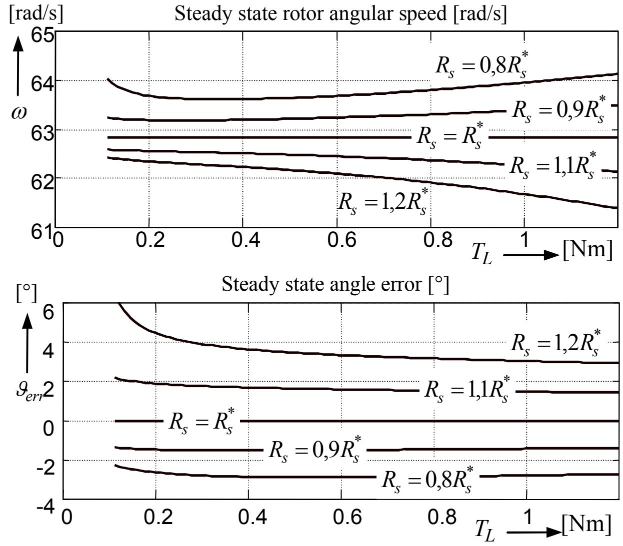

Fig. 4. The influence of mismatched stator resistance parameter: estimated speed error and field orientation. Results of steady state NFO model for 10 Hz rotor reference and load torque 0 – 1.2 Nm.

The steady state model results show significant detuning of NFO scheme, especially for low speeds range. The further investigation was performed using dynamic model of NFO estimator. The dynamic model results, for different R_s errors, are shown on Fig 5. Motor load of $T_L = 0{,}45$ Nm is simulated, reference speed was 2,5Hz. Stator resistance parameter was varied in steps. It can be noticed that the steady state error is similar to the one given on Fig 3, demonstrating agreement of two models.

Results show that R_s drift does not influence the steady state characteristics only, it can also lead to the unstable regime, as it is shown on the on Fig 5. Results show that critical situations can arise for R_s^* higher than R_s.

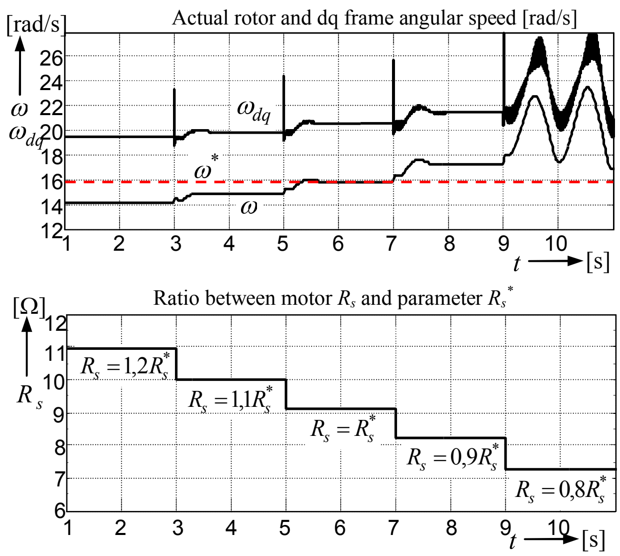

Fig. 5. Influence of R_s detuning on NFO structure. Dynamic model

4.2. NFO scheme sensitivity to the mutual inductance parameter detuning

The NFO steady state model, with $L_m^* \neq L_m$ and $R_s^* = R_s$, is used to investigate the NFO scheme sensitivity to the mutual inductance parameter error. The results for two different rotor speed references are displayed on the Fig.6 and Fig. 7. Results are shown for rotor speed references 2,5Hz and 10Hz, both for different load torques.

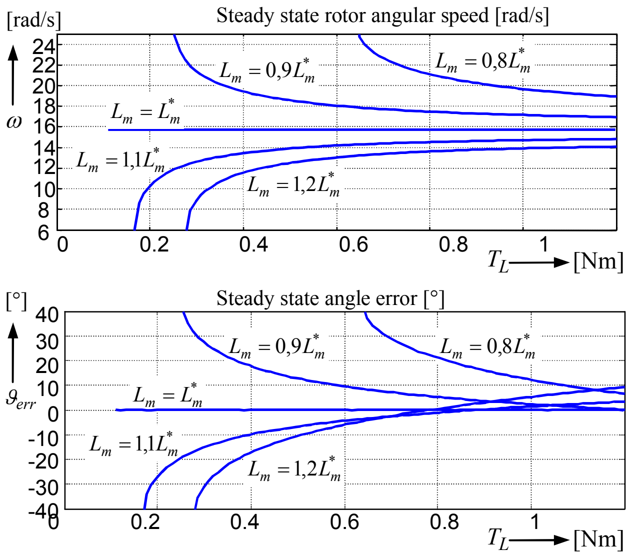

Fig. 6. The influence of mismatched mutual inductance parameter: estimated speed error and field orientation. Results of steady state NFO model. ω^* =2,5 Hz and torque 0 – 1.2 Nm.

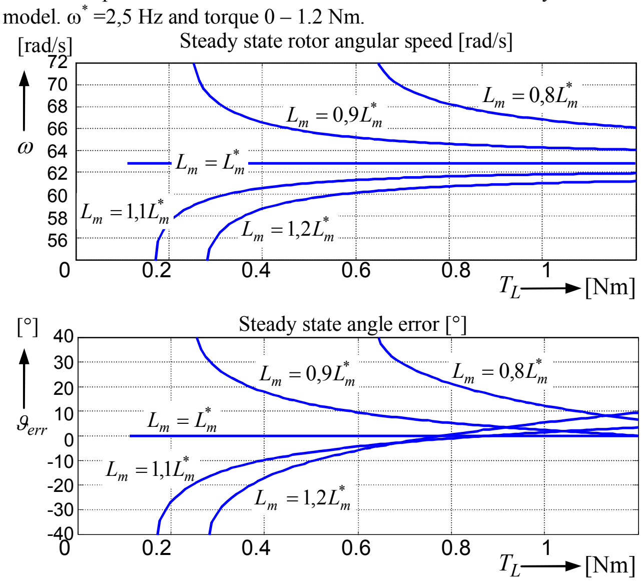

Fig. 7. The influence of mismatched mutual inductance parameter: estimated speed error and field orientation. Results of steady state NFO model, ω^* =10 Hz and torque 0 – 1.2 Nm.

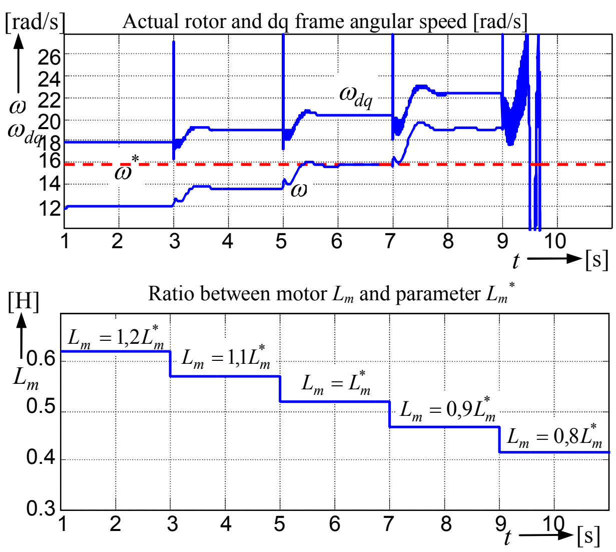

Fig. 8. Influence of L_m detuning on NFO structure. Dynamic model

The dynamic model results, for different L_m^* parameter errors are shown on Fig 8, with motor load T_L = 0,45 Nm and speed reference of 2,5Hz.

Results of the NFO steady state model show significant influence of both parameter errors to the NFO scheme performance. In addition, the dynamic model reviled inherent instability of NFO scheme taking place for certain error levels in both parameters. The stator resistance parameter error is more critical in low rotor speed range, and its influence almost completely disappears in the high speed range. On the other hand, the mutual inductance error affects the NFO control structure in whole rotor speed range.

V. CONCLUSION

The performance of NFO scheme under two critical parameters detuning conditions is analyzed in this paper. It is shown that an error in any of these two parameters, namely the stator resistance and mutual inductance parameter, directly leads to an error in achieved rotor speed and an error in the field orientation. Quality of detuned NFO controller also depends upon the load torque and the steady state rotor speed value. It was also shown that certain parameter error levels affect the stability and robustness of the NFO scheme. The overall results confirm parameter sensitivity of NFO shaft-sensorless scheme and show the necessity for a parallel, on-line parameter update.

APPENDIX

MOTOR PARAMETERS

700 W, 195 V, 2p=2, 4200 rpm, Δ

R_s = 9.1 Ω , R_r = 5.73 Ω , L_m = 0.585 H *, L_s = 0.615 H * ,
L_r = 0.615 H *, σL_s = 0.058 H * *nominal range

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