Adaptive Observer for Field Oriented Control Systems of Induction Motors

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***Abstract*—In this paper an adaptive rotor flux observer is developed. This observer performs a real-time correction of the mutual inductance and rotor resistance of the motor using data from the DC-link voltage sensor, the inverter state and the phase current and position sensors. The observer compares the behavior of two independent observers (sensorless and sensored observers) in order to correct the parameters of the sensored observer. The adaptation algorithm corrects the mutual inductance, which can vary due to change of the magnetization current, and the rotor resistance, which can change due to variation of the rotor temperature. Computer simulation results are presented to validate the proposed method.**

***Index Terms*—Digital control, Induction motors, Microcontrollers, Motion control, Observers, Variable speed drives.**

I. INTRODUCTION

Flux vector control system provides most rapid and precise control of the motor torque for AC electric drives [1, 2]. They are implemented for various motors like induction motor, permanent magnet synchronous machine, synchronous reluctance machine, and other. The main principle of the flux vector or field oriented control regardless of the motor type is to find the flux position and control the quadrature current which usually is proportional to the produced torque. Thus, the flux is controlled by the D-axis current and the torque is controlled by the Q-axis current.

The position of the flux can be estimated by direct measurement of the field in the gap of the motor by means of Hall-sensors [3] or by indirect estimation by means of flux observers [2]. The direct measurement requires a special motor design, thus it is more expensive. Most of modern field oriented control systems use more cheap indirect flux estimation. There are various types of the flux observers based on different principles such as sliding mode observers (SMO), Kalman filters, model reference adaptive systems (MRAS) and others [4]. The main task of all these methods is to improve the accuracy of the rotor flux linkage estimation. But only very few of these methods adapt the parameters of the model to avoid estimation error [5, 6, 7], also the mathematical methods that they used are often too complex. This paper deals with a simple method for the rotor resistance and mutual inductance estimation.

The estimation of mutual inductance is needed if the drive operates in the field weakening mode or an energy saving control strategy using a decreased rotor flux. These operation modes vary flux linkage, thus the motor moves apart from saturation knee (see Fig. 1a), and the mutual inductance changes (see Fig. 1b). This change of the mutual inductance affects to the rotor inductance and consequently to the rotor time constant. The rotor resistance changes with the rotor temperature, also affecting to the rotor time constant.

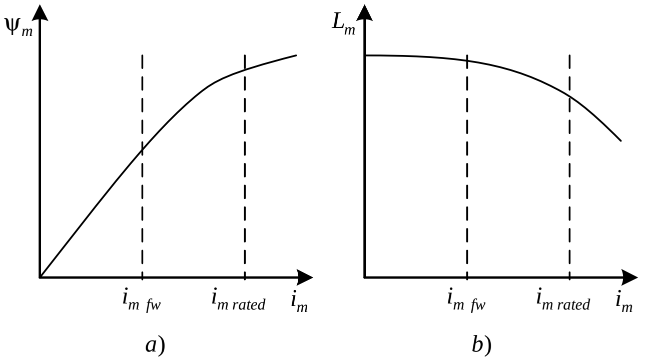
II. ROTOR FLUX LINKAGE OBSERVERS

A. *Sensored Observer*

The sensored observer is based on the rotor equations of the induction machine. The reference frames for the observer may vary depending on type of the sensor on the motor shaft. If it is incremental position encoder it is better to use rotor reference frames. If tachogenerator is used the stator reference frames are preferable. The rotor flux linkage reference frames can be used for both types of the sensor. The various structures of this observer for speed and position feedbacks are shown in Fig. 2. The rotor equations in the rotor flux linkage reference frame are

$$\left.\begin{aligned} 0 &= i_{rd} R_r + \frac{\mathrm{d}\psi_{rd}}{\mathrm{d}t} - \left(\omega_{\psi_r} - \omega\right)\psi_{rq};\\ 0 &= i_{rq} R_r + \frac{\mathrm{d}\psi_{rq}}{\mathrm{d}t} + \left(\omega_{\psi_r} - \omega\right)\psi_{rd}, \end{aligned}\right\} \tag{1}$$

where i_{rd} and i_{rq} are the rotor currents, ψ_{rd} and ψ_{rq} are the rotor flux linkage, ω is the rotor speed and ω_{ψ_r} is the speed of the rotor flux linkage. Assuming that in the rotor flux linkage reference frame the Q component of the rotor flux is equal to zero, equations (1) can be simplified to:



a)

b)

Fig. 1. Flux linkage (a) and inductance (b) vs. magnetization current

$$\left.\begin{aligned} 0 &= i_{rd}R_r + \frac{\mathrm{d}\psi_{rd}}{\mathrm{d}t};\\ 0 &= i_{rq}R_r + \left(\omega_{\psi_r} - \omega\right)\psi_{rd}.\end{aligned}\right\} \tag{2}$$

The rotor currents can be expressed from the stator currents and the rotor flux:

$$\left.\begin{aligned} \psi_{rd} &= L_m i_{sd} + L_r i_{rd}\\ \psi_{rq} &= L_m i_{sq} + L_r i_{rq}\end{aligned}\right\} \Rightarrow \left.\begin{aligned} i_{rd} &= \frac{\psi_{rd} - L_m i_{sd}}{L_r}\\ i_{rq} &= \frac{-L_m i_{sq}}{L_r}\end{aligned}\right\}. \tag{3}$$

And after substitution of (3) into (2) it gives:

$$\left.\begin{aligned} L_m i_{sd} &= \psi_{rd} + T_r\frac{\mathrm{d}\psi_{rd}}{\mathrm{d}t};\\ L_m i_{sq} &= \left(\omega_{\psi_r} - \omega\right)T_r\psi_{rd},\end{aligned}\right\} \tag{4}$$

and the structure depicted in Fig. 2.

This observer gives precise estimation of the rotor flux linkage and its angular position if all the observer parameters are equal to the actual motor parameters. It gives fast and accurate estimations independent of the operation speed. So, the accuracy of this observer mainly depends on the accuracy of the motor parameters. Unfortunately, these will change from motor to motor due to constructive tolerances, and during normal operation of the machine, e.g. due to desaturation of the machine in field weakening operation modes or to temperature variations.

B. *Sensorless observer*

The sensorless rotor flux linkage observer is shown in Fig. 3. It uses the stator voltage references and stator currents to estimate the rotor flux linkage. The stator equations of the induction motor in the stationary reference frame are:

$$\left.\begin{aligned} u_{s\alpha} &= i_{s\alpha}R_s + \frac{\mathrm{d}\psi_{s\alpha}}{\mathrm{d}t};\\ u_{s\beta} &= i_{s\beta}R_s + \frac{\mathrm{d}\psi_{s\beta}}{\mathrm{d}t}.\end{aligned}\right\} \tag{5}$$

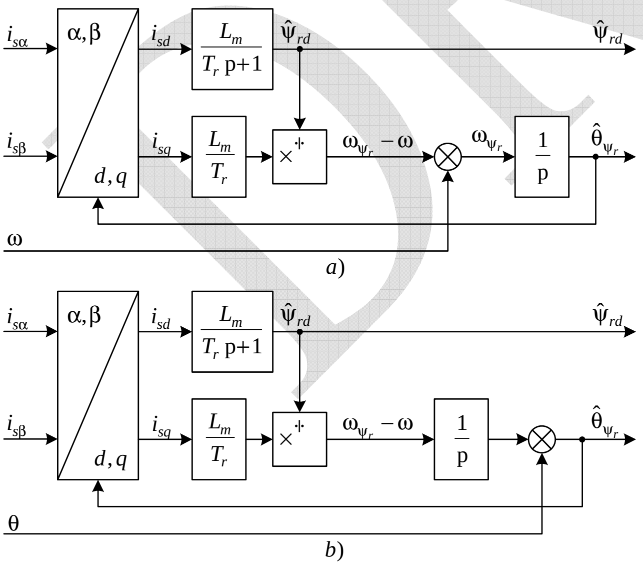


Fig. 2. Sensored rotor flux linkage observers: a – for speed feedback signal; b – for position feedback

The stator flux linkage can be expressed like:

$$\left.\begin{aligned} \psi_{s\alpha} &= L_s i_{s\alpha} + L_m i_{r\alpha};\\ \psi_{s\beta} &= L_s i_{s\beta} + L_m i_{r\beta},\end{aligned}\right\} \tag{6}$$

and the rotor current from:

$$\left.\begin{aligned} \psi_{r\alpha} &= L_m i_{s\alpha} + L_r i_{r\alpha}\\ \psi_{r\beta} &= L_m i_{s\beta} + L_r i_{r\beta}\end{aligned}\right\} \Rightarrow \left.\begin{aligned} i_{r\alpha} &= \frac{\psi_{r\alpha} - L_m i_{s\alpha}}{L_r}\\ i_{r\beta} &= \frac{\psi_{r\beta} - L_m i_{s\beta}}{L_r}\end{aligned}\right\}. \tag{7}$$

After substitution of (7) into (6) and (5) it gives the following equations for the rotor flux linkage observer:

$$\left.\begin{aligned} u_{s\alpha} &= i_{s\alpha}R_s + L_s\sigma\frac{\mathrm{d}i_{s\alpha}}{\mathrm{d}t} + \frac{L_m}{L_r}\frac{\mathrm{d}\psi_{r\alpha}}{\mathrm{d}t};\\ u_{s\beta} &= i_{s\beta}R_s + L_s\sigma\frac{\mathrm{d}i_{s\beta}}{\mathrm{d}t} + \frac{L_m}{L_r}\frac{\mathrm{d}\psi_{r\beta}}{\mathrm{d}t},\end{aligned}\right\} \tag{8}$$

where $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the global leakage coefficient of the motor.

The structure of the rotor flux linkage observer includes a sliding mode observer for terms in the right part of (8). The rotor flux linkage can be evaluated by integration of the sliding observer output. However, this requires a pure integration which results in drift problem. Thus, the pure integrator should be combined with the high-pass filter to supress the DC offset. The high-pass filter assembled with the integrator gives the first order link.

This observer cannot operate at low and zero speeds but it gives good accuracy on high speeds and is less dependent from the motor parameters than the sensored observer. Another problem is that it has some low frequency oscillations in its output values which results in torque ripples. Therefore, this observer is not desirable for control but it can be used for correction of the sensored observer parameters in real-time.

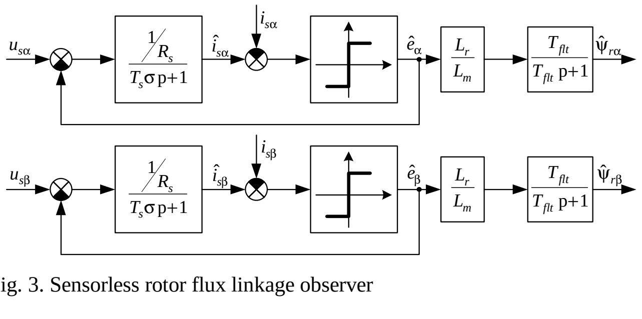


Fig. 3. Sensorless rotor flux linkage observer

III. ALGORITHM FOR CORRECTION OF THE OBSERVER PARAMETERS

The loci of the sensored and sensorless rotor flux linkage estimations are shown in Fig. 4. The amplitudes of the vectors are different, there is a phase shift, and the center of the locus for sensorless observer can be displaced form the point of origin during transients in torque and speed due to impact of the high-pass filter and integration errors.

The mutual inductance and rotor resistance affects the rotor time constant, while the amplitude of the flux linkage mainly depends on mutual inductance. Thus, the difference in amplitudes can be used to correct the value of the mutual inductance, and the difference in phase angles can be used to correct the value of the rotor resistance.

The adaptive observer structure is presented in Fig. 5. The sensored observer uses the measured currents and speed or rotor position to estimate the rotor flux linkage in stationary reference frame. The sensorless observer uses the voltage references and measured currents to estimate the rotor flux linkage in the rotor flux reference frame. To compare both estimations the sensored observer flux linkages pass through the coordinate transform block. The data from sensored observer are used in the field oriented control system. The difference between amplitudes and angles are the errors to the mutual inductance and rotor resistance controllers, which provide the estimations of these parameters. Finally, the estimated values are used to recalculate the parameters of the sensored and sensorless observers. The difference between both flux linkage estimations should be zero if the model and the actual motor parameters are equal.

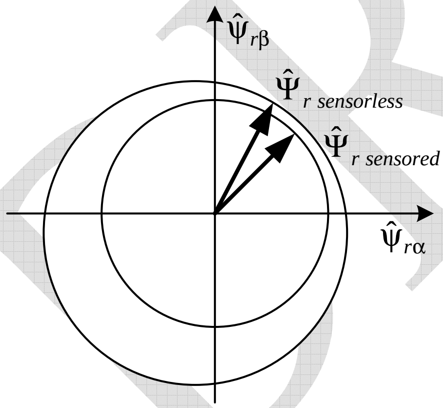


Fig. 4. Loci of the rotor flux linkage estimations

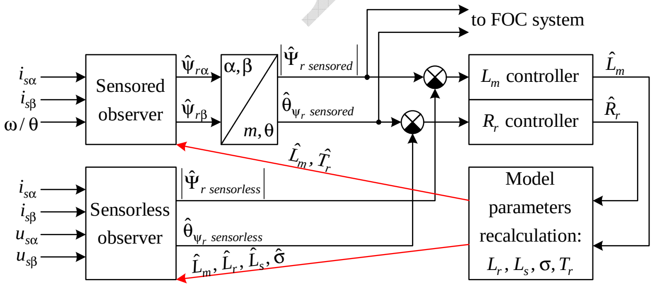


Fig. 5. Adaptive observer structure

IV. MODEL SIMULATION

An electric drive model was developed for simulation in MATLAB Simulink. The model includes inverter, induction motor, and control system. Inverter model includes dead-time and voltage drop in the switches and diodes. Induction motor model includes the magnetization curve which models the dependence between the mutual inductance and the magnetization current

$$i_m = \sqrt{\left(i_{s\alpha} + i_{r\alpha}\right)^2 + \left(i_{s\beta} + i_{r\beta}\right)^2}. \tag{9}$$

The electric drive model is written in C language to be compiled into MEX-file for Simulink. Integration step size is 1/150000000 s. This frequency corresponds to target microcontroller frequency 150 MHz. The motor and inverter models are calculated for each simulation step. Control system is performed at 16 kHz, which is equal to PWM frequency. ADC quantization (12 bits) and noise (1 LSB) are simulated. The inverter and motor models use double precision (64 bit) floating point and control system uses single precision (32 bit) arithmetic.

Fig. 6 shows the difference between the real motor flux linkage (thin blue line), the sensored observer estimation (purple dot-dashed line) and the sensorless observer estimation (green dashed line). Motor is running in v/f-constant mode at a speed of 3500 rad/s and with rated load. The upper plot shows the waveforms for incorrect values of L_m and R_r. The error between the real and model motor parameters is set to $\delta R_r = \delta L_m = 15\%$. The bottom plot shows waveforms for the case of correct model parameters.

It is seen from Fig. 6 that the sensorless observer is much more accurate than the sensored one, when running with incorrect parameters and it's possible to use its estimation as a reference for the sensored observer correction.

The adaptive observer was tested on a model. The drive was operated with field oriented control system. The model parameters were set with the errors $\delta L_m = 20\%$ and $\delta R_r = 10\%$. These values were corrected in a real-time. The motor reached the speed of 3500 rad/s with rated torque.

Fig. 7 and Fig. 8 show the result of the mutual inductance and the rotor resistance correction respectively. The blue dashed curve in Fig. 7 shows the real mutual inductance of the motor. It can be seen that the motor goes from saturation knee during acceleration when the field weakening region starts. The red curve is the model mutual inductance which tracks the change of the motor inductance. The lower plot with the pink curve shows the change of the error in % to the actual value. The same plots for the rotor resistance estimation process can be seen in Fig. 8. The tracking of the motor parameters is done with the error less than 4% for the mutual inductance and less than 2% for the rotor resistance.

The response and stability of this adaptive observer depends on the tuning of the L_m- and R_r-controllers. Both L_m and R_r outputs of the observer should be limited to reasonable range for the particular motor. In other way control system may failure at the overshoot moments as t = 0.7 s in Fig. 7 and Fig. 8.

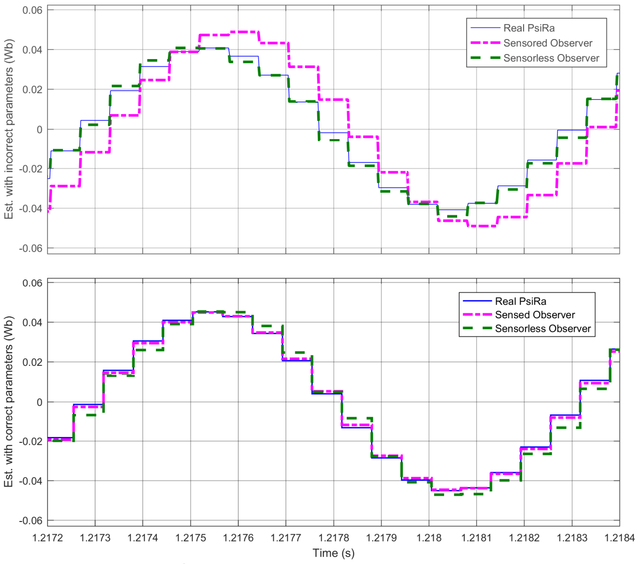


Fig. 6. Comparison of the estimations provided by the sensored and sensorless observers with incorrect and correct model parameters

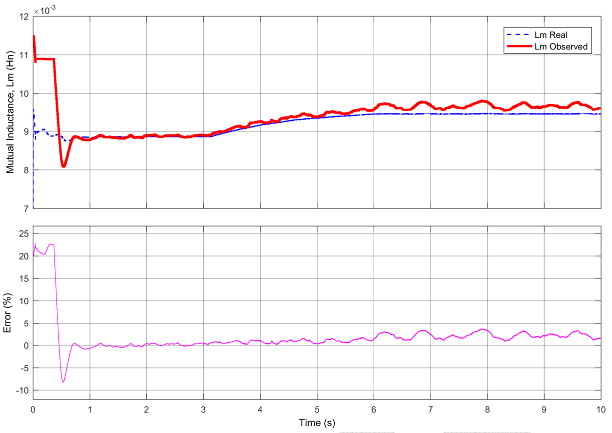


Fig. 7. Mutual inductance correction. Initial error is 20%. Correction starts at 0.4 s, when the magnetization of the motor is finished. The field weakening mode starts at 3.1 s.

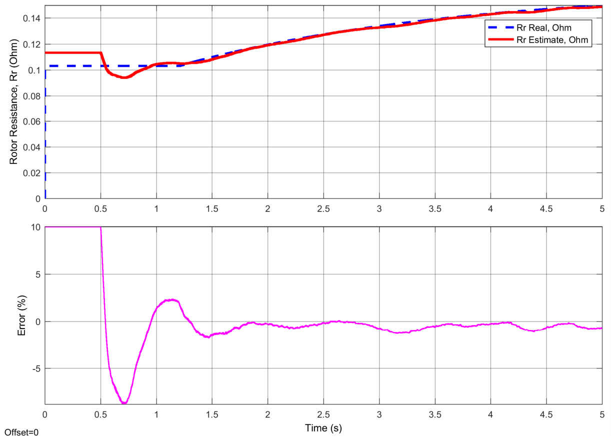


Fig. 8. Rotor resistance correction. Initial error is 10%. Correction starts at 0.5 s. The rotor heat-up process is simulated from 1.2 s.

V. CONCLUSIONS

An adaptive rotor flux linkage observer for induction motor drive control system has been proposed in this paper. It is applicable for the field oriented control systems using speed or position sensors, and provides accurate estimation of the rotor flux linkage for the whole speed range under reasonable deviation of the motor parameters due to saturation and/or temperature changes.

The considered observer can be implemented on modern DSP-microcontrollers like TMS320F28xxx family. Its current implementation is done in a single precision floating point. The sensorless part should be executed in ADC interrupt two or four times per PWM cycle and its sensored part should be executed in the same interrupt with the current controllers.

The tracked rotor resistance can be used not only for accurate estimation of the flux, but for indirect measurement of the rotor temperature. This can be used for thermal protection of the motor.

Experimental verification of the proposed methods is in progress.

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