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ROTOR PARAMETER IDENTIFICATION IN FIELD-ORIENTED INDUCTION MACHINE CONTROL BASED ON ELECTRICAL TORQUE ESTIMATION

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Abstract. In this paper, a novel approach to the on-line identification of the induction motor rotor time constant (T_r) is proposed, suitable for the use in conjunction with indirect field oriented (IFO) control of servo drives. Servo drives usually operate with closed speed or position loop and have a shaft sensor. Proposed mechanism is based on the torque, estimated from shaft sensor signals and it ensures robust T_r identification at zero speed as well. The slip calculator within the IFOC structure requires precise knowledge of the T_r, in order to provide decoupled flux and torque control. Variations of the T_r, caused mainly by the thermal drift of the rotor resistance, affect the amplitude and phase characteristics of the small signal torque transfer function. Additional information required for the adaptation process are the phase deviations which are sensed by correlating estimated and commanded torque. No additional sensors are needed and need for precise information of terminal voltages is also avoided. The usefulness of the new adaptation mechanism is validated by simulations.

Keywords. IFOC, Rotor time constant, Induction machine

INTRODUCTION

Specific advantages of induction machines over DC and DC-brushless motors lead to progressive use of IFO controlled induction motors in speed and position controlled servomechanisms. In these applications, the shaft sensor is always present for the purposes of closing the space loops. Inherently more robust at low speeds, in position-controlled electrical drives the IFO controller is preferred rather than direct field orientation (DFO) controller. Since the feedforward slip calculation implies open-loop decoupling of the induction motor, the IFO controller is sensitive to plant parameters [1-9]. Hence, for the correct field orientation, the parameter T_r^*, used in the feedforward model, must fit the actual rotor time constant T_r of the motor. An inaccurate setting of that parameter results in an undesirable cross coupling and deterioration of the overall drive performance.

Fluctuations of T_r are caused mainly by the thermal drift of the rotor resistance (R_r) and by the change of the motor inductance's due to the nonlinearity of the main flux path magnetic circuit. While the effects of the magnetic nonlinearity might be predicted and included into the IFOC feed-forward slip-calculator [6], the thermal drift presents a serious problem since the rotor temperature cannot be easily measured. For this reason, it is essential that high performance servo with induction motor are equipped with the means for detection and on-line correction of any difference between the modeled and the actual value of the T_r.

Several authors discussed possibilities of adaptation of parameter T_r^*, and different ideas and solutions were suggested [2-5]. Most of the T_r adaptation structures used up to now are based on the use of the terminal voltages and currents as an additional information required for the adaptation process. Advantage of these approaches is the fact that the stator voltages and currents are already available within the drive controller, and hence, no additional sensors or measures are needed.

The information on motor internal variables is contained in the back electromotive force component of the terminal voltages. As the speed drops down and the BACK-EMF diminishes, the voltage drop across the stator resistance and the secondary effects prevail making the estimation inoperable. Moreover, the voltages are usually not measured but calculated from the PWM gating signals, introducing the error caused by the lockout time (dead time) and further deteriorating the estimator performance at low speeds.

Parameter analyses of voltage and current spectrum offers the possibility for advanced estimation of motor parameters and states. Though, in most of the cases preliminary information about motor is required while the signals are obtain with significant computation delay.

In this paper is proposed new solutions for the T_r adaptation with no additional sensors or measures are needed, but the use of the terminal voltages is also avoided. We suggest structure where the adaptation mechanism is driven by signal from shaft sensor. The electromagnetic torque is estimated from the shaft sensor signal through the speed and acceleration observer structure. Further analyze will show that phase difference between some spectral components of estimated and commanded torque contain information about error in R_r^*. The use of a correlation function between commanded and estimated torque indicates the changes in R_r that can be used in identification process.

PRINCIPLE OF IDENTIFICATION SYSTEM OPERATION

The adaptation mechanism under consideration is driven by the phase difference in estimated and commanded torque. The method is based on linearised transfer function between torque response and the torque command current given in [1] :

$$W_M(s) = \frac{\Delta M_{el}(s)}{\Delta i_{qs}(s)} = \frac{3}{2} p \frac{L_m}{L_r} \Psi_{dr0} \frac{s^2 + a_1 s + a_2}{s^2 + b_1 s + b_2} \tag{1}$$

It is obvious that transient response to a torque command exhibits second-order system response. Coefficients of that second-order system depends on ratio of steady-state commanded current (I_{qs0}/I_{ds0}) , steady-state dq components of rotor flux (Ψ_{dr0}, Ψ_{qr0}) and degree of R_r detuning ($\Delta R_r/R_r$). For drive system with constant flux command it can be shown that dq components of rotor flux also depends of I_{qs0}/I_{ds0} and $\Delta R_r/R_r$:

$$\Psi_{dr0} = L_m I_{ds0} \left(1 - \frac{x(1+x)y^2}{1+(1+x)^2 y^2}\right),$$

$$\Psi_{qr0} = -L_m I_{ds0} \frac{xy}{1+(1+x)^2 y^2}, \tag{2}$$

where: $x = \frac{\Delta R_r}{R_r}$ $y = \frac{I_{qs0}}{I_{ds0}}$.

This leads to second-order system whose phase response depends of two parameters: I_{qs0}/I_{ds0} and $\Delta R_r/R_r$.

In order to discover the connection between the commanded and actual torque phase delay and $\Delta R_r/R_r$, dependence's of linearised transfer function coefficients on I_{qs0}/I_{ds0} and $\Delta R_r/R_r$ are found. The coefficients are:

$$b_1 = \frac{2}{T_r}, \qquad b_2 = \frac{1}{T_r^2} + \omega_{k0}^2, \tag{3}$$

$$a_1 = b_1 + \frac{1}{T_r} x \frac{1-(1+x)y^2}{1+(1+x)y^2},$$

$$a_2 = b_2 + \frac{1}{T_r^2} x \frac{1-(1+x)(3+x)y^2}{1+(1+x)y^2}. \tag{4}$$

Expression (3) shows a pair of complex poles with real part equal to $-1/T_r$ and imaginary part equal to commanded slip frequency. Expression (4) shows two zeros that in well tuned drive cancel the system poles. Found dependence leads to possibility of R_r estimation based on phase difference between actual and commanded torque. The main problem is coefficients dependence on commanded torque which, in case of the constant detuning level (constant $\Delta R_r/R_r$), causes the significant difference in phase characteristics of examined system.

Figures 1 and 2 contains phase characteristic of linearised transfer function of detuned system with commanded torque current as the parameter I_{qs0}, [0,1,4I_{qsn}]. Simulations were performed in case of standard 1hp induction motor. Similar results are obtained in case of 100hp motor.

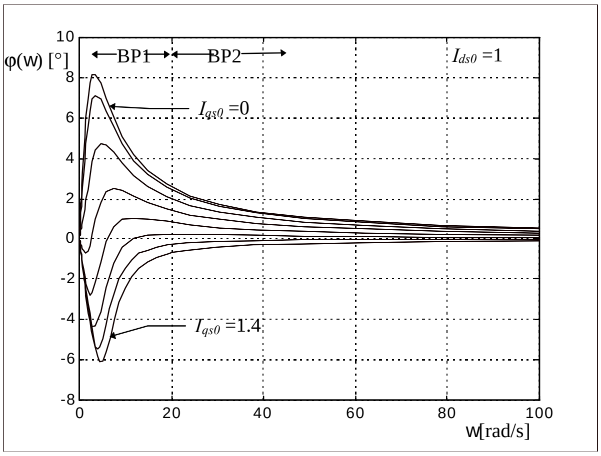

Figure 1 - Phase plots with $\Delta R_r/R_r$ = - 25 % .

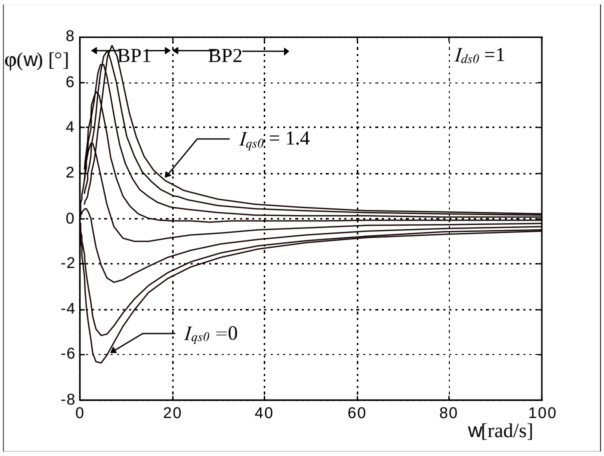

Figure 2 - Phase plots with $\Delta R_r/R_r$ *= +25 % .*

Two significant frequency bands are distinctive. First one (BP1) is in the vicinity of slip frequency. This band contains the most information about $\Delta R_r/R_r$, but it also suffers from large scale of phase change with change of I_{qs0}/I_{ds0}. Figures 1 and 2 shows that for the same level of $\Delta R_r/R_r$ change in I_{qs0}/I_{ds0} leads even to a change of phase sign. This problem can be solved by introducing the multiplier (K_1) dependent on torque and flux current command. Extraction of these frequencies is performed by the use of band-pass filters with variable central frequency. Central frequency is calculated from the slip frequency for I_{qs0}/I_{ds0} in which vicinity the actual linearisation is performed. The second band (BP2) is in the range of frequencies whose center is moved to higher values than the slip frequency. This band exhibits the consistency of phase plots, but the information contained is much smaller than in BP1 band. The change of phase sign caused by the change of I_{qs0}/I_{ds0} still exists, but for larger torque commands than in BP1. That problem is solved by the use of multiplier K_2.

LOAD AND FREQUENCY DEPENDENT GAINS

Multiplier's K_1 and K_2 are considered with special attention, because their dependence on commanded current ensures the proper operation of the suggested R_r automatic compensation structure. The frequency range and operating regime might change even a sign of phase deviations. Therefore it is inevitable to adapt identifier gains according to operation conditions.

Sensitivity of the transfer function phase to $\Delta R_r/R_r$ depends upon I_{qs0}/I_{ds0} and frequency range.

Therefore phase shift for spectral components in range BP1 is mostly determined by fluctuation of a_2 and b_2 while the phase difference in BP2 strongly depends on variations of a_1 and b_1.

To properly define the value of K_1 and K_2 it is necessary to find the limit torque current command after which the phase changes its sign. Equations 3,4 are used for this purpose.

The difference of coefficient's a_2 and b_2 is changing sign for rate of stator currents equal to:

$$\left(\frac{I_{qs0}}{I_{ds0}}\right)_1 = \frac{1}{\sqrt{(1+\Delta R_r / R_r)(3+\Delta R_r / R_r)}} \qquad (5)$$

For a_1 and b_1 the critical value of I_{qs0}/I_{ds0} *is*:

$$\left(\frac{I_{qs0}}{I_{ds0}}\right)_2 = \frac{1}{\sqrt{1+\Delta R_r / R_r}} \qquad (6)$$

For both selected frequency bands phase sign can be changed for different values of I_{qs0}/I_{ds0}. For $\Delta R_r/R_r \in [-0.25, 0.25]$ critical I_{qs0}/I_{ds0} is in two different bands:

$[(I_{qs0}/I_{ds0})_{1x}, (I_{qs0}/I_{ds0})_{1y}]=[0.5,0.75]$,
$[(I_{qs0}/I_{ds0})_{2x}, (I_{qs0}/I_{ds0})_{2y}]=[0.89,1.15]$. (7)

In manner to provide convergence of adaptation mechanism for all possible I_{qs0}/I_{ds0}, multipliers K_1 and K_2 are been defined as function of I_{qs0}/I_{ds0}:

$I_{qs0}/I_{ds0} < (I_{qs0}/I_{ds0})_{1x}$ => $K_1=1$
$I_{qs0}/I_{ds0} > (I_{qs0}/I_{ds0})_{1y}$ => $K_1= -1$
$(I_{qs0}/I_{ds0})_{1x} < I_{qs0}/I_{ds0} < (I_{qs0}/I_{ds0})_{1y}$ => $K_1=0$ (8)

$I_{qs0}/I_{ds0} < (I_{qs0}/I_{ds0})_{2x}$ => $K_2=1$
$I_{qs0}/I_{ds0} > (I_{qs0}/I_{ds0})_{2y}$ => $K_2= -1$
$(I_{qs0}/I_{ds0})_{2x} < I_{qs0}/I_{ds0} < (I_{qs0}/I_{ds0})_{2y}$ => $K_2=0$ (9)

STRUCTURE OF R_r IDENTIFIER

The authors suggest the following R_r correction structure (figures 3 and 4). Torque command is derived from closed loop speed or position controller. The electromagnetic torque is estimated from the shaft sensor signal through the speed and acceleration observer structure. Proposed torque observer filters the shaft sensor signals and derives the speed and acceleration estimates. Assuming that the load torque is slowly varying, or, that it does not posses any of its spectral energy in the frequency range of interest, we use the acceleration as a measure of generated electromagnetic torque. Suggested structure is based in the idea to maximally use the information contained in commanded and estimated torque phase difference and, at the same time, not to make any errors in R_r change. Mechanism starts with appearance of some spectral components in one of the selected frequency bands. Those spectral components may be extracted from torque pulsation or noise. The mechanism is turned off in stationary state of the drive operation which avoids the numerical divergence.

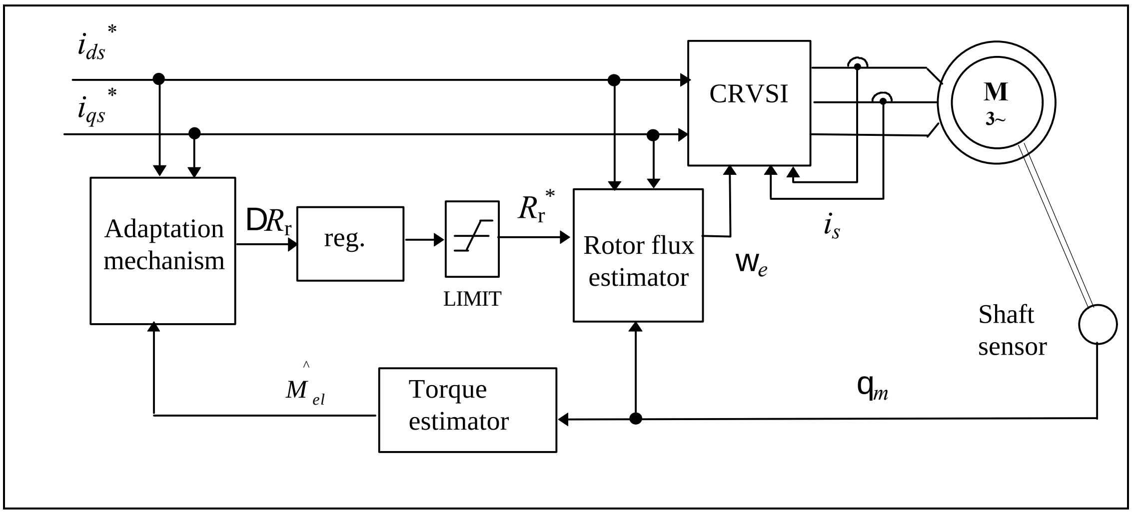

Figure 3 - IFO control of an induction machine with additional mechanism for R_r correction.

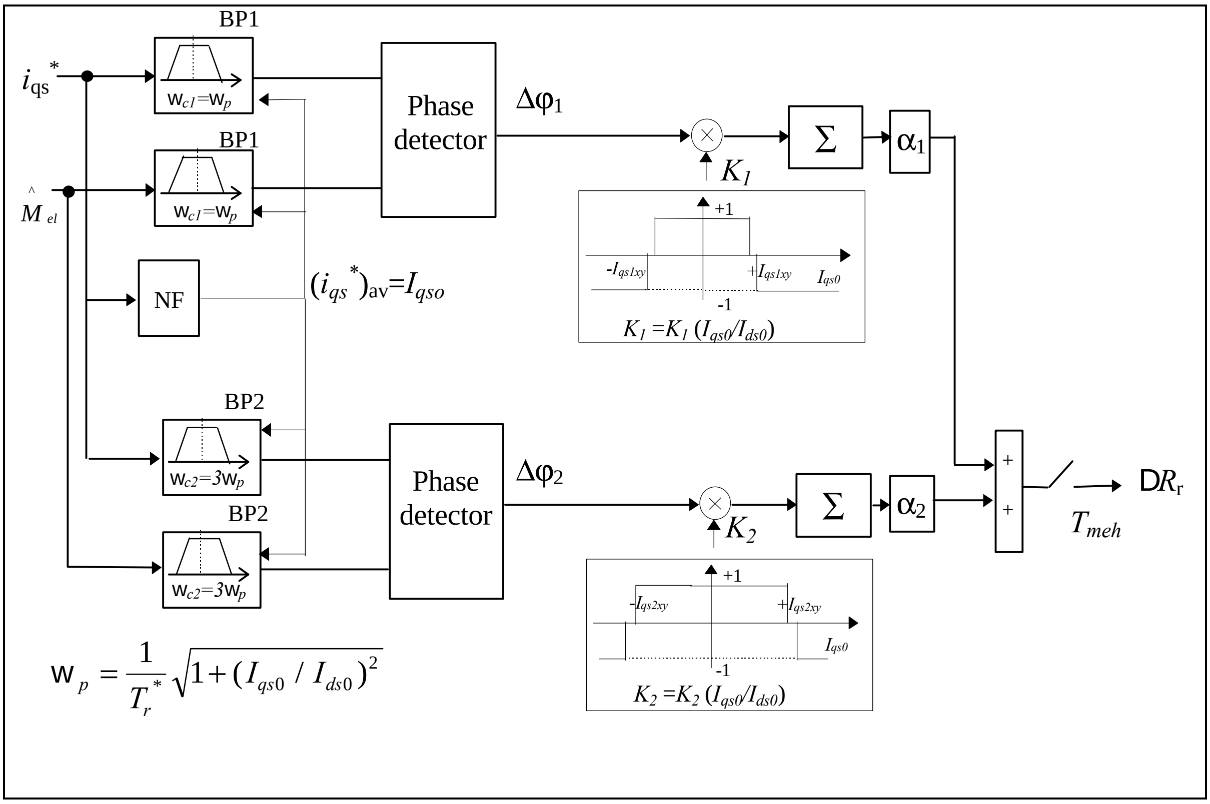

Figure 4 - Proposed adaptation mechanism for the correction of thermal drift in R_r.

RESULTS

Performance of the proposed mechanism is investigated by simulations. The whole drive is modeled in Matlab. Compensation of artificially introduced changes of R_r^* is simulated. Several simulations were performed, for both increase and decrease of R_r^* by 25%. Since the performance of the adaptation mechanism heavily depends on the load and flux level, simulations are performed for 3 values of I_{qs0}/I_{ds0}. In model is presumed that shaft sensor has resolution of $2\pi/2^{12}$ and that sampling rate of position signal is T=300μs. Figures 5-10 show output signal of detected error ERR and parameter R_r*.

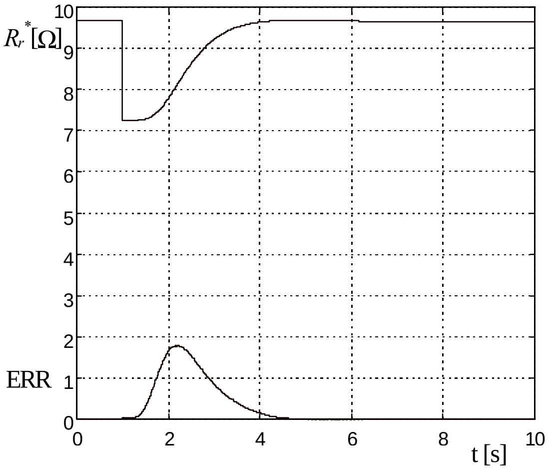

Figure 5 - $\Delta R_r/R_r$ = -25 %, $I_{qs0}/I_{ds0}=0.2$, $K_1=1$, $K_2=1$.

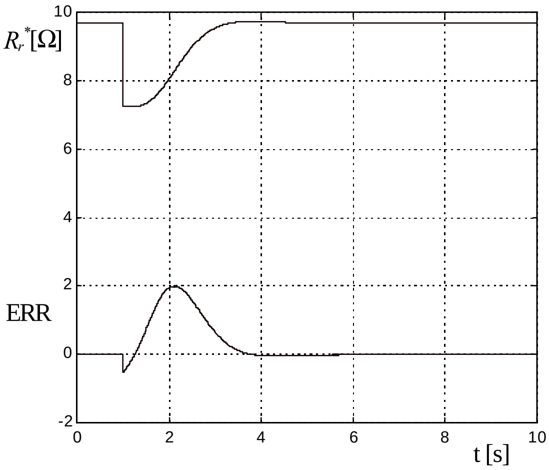

Figure 6 - $\Delta R_r/R_r$ = -25 %, $I_{qs0}/I_{ds0}=0.7$, $K_1=0$, $K_2=1$, $\alpha_2=10$.

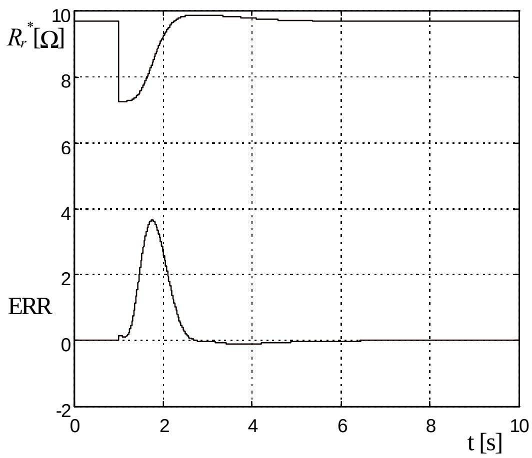

Figure 7 - $\Delta R_r/R_r$ = -25 %, $I_{qs0}/I_{ds0}=2$, $K_1=-1$, $K_2=-1$.

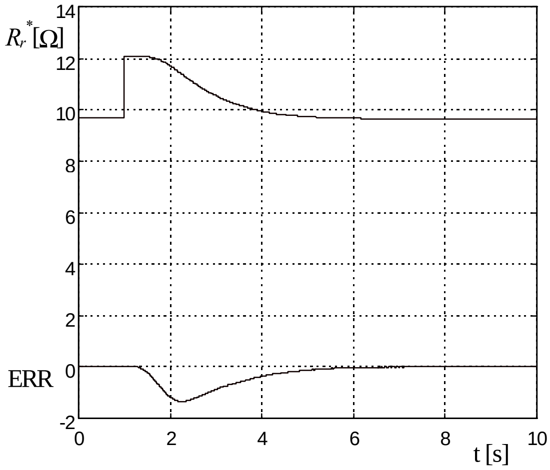

Figure 8 - $\Delta R_r/R_r$ = +25 %, $I_{qs0}/I_{ds0}=0.2$, $K_1=1$, $K_2=1$.

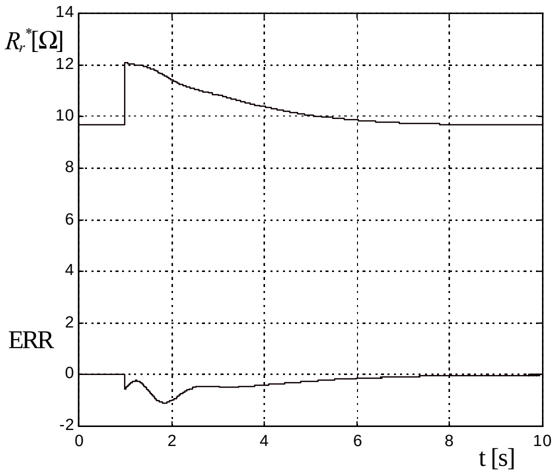

Figure 9 - $\Delta R_r/R_r$ = +25 %, $I_{qs0}/I_{ds0}=0.7$, $K_1=0$, $K_2=1$, $\alpha_2=10$.

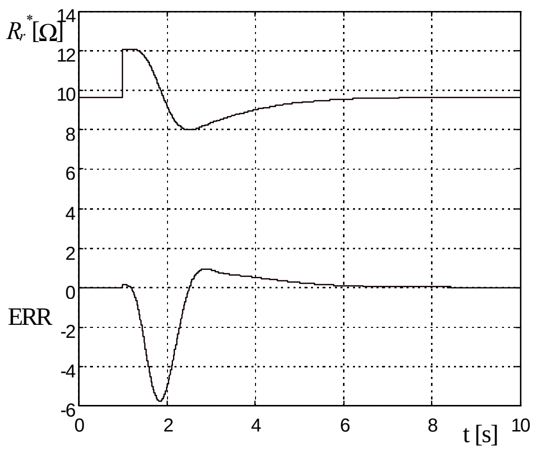

Figure 10 - $\Delta R_r/R_r$ = +25 %, $I_{qs0}/I_{ds0}=2$, $K_1=-1$, $K_2=-1$.

CONCLUSION

In this paper, a novel algorithm for rotor resistance identification is proposed. The paper gives analytical background for the design decisions made in the synthesis of the estimation and adaptation structures. The proposed algorithm is well suited for the applications in conjunction with high performance induction motor servo drives operating at zero speed at most of the time. Algorithm is robust against the lookout time induced errors and the stator resistance variations, due to fact that detuning detection doesn't rely upon the terminal voltages. Rather it uses the torque signal estimited from shaft sensor. Simulation's results of the adaptation mechanism for different loads, averaged speeds and changes in R_r are presented with good performance.

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