

THE IDENTIFICATION OF INDUCTION MOTOR INTERNAL QUANTITIES

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ABSTRACT

In the presented work a new identification method of difficult measured internal quantities of IM, such as components of magnetic flux vector and electromagnetic torque, is proposed. Commonly measurable quantities of IM like stator currents, stator voltage frequency and mechanical angular speed are used for identification to determine a feedback effect of the rotor flux vector on vector of stator currents of IM. Based on this feedback it is also possible to identify actual value of the rotor resistance, which can alter during IM operation. This has a significant impact on precision of identified quantities as well as on master control of IM. Stability of the identification structure is guaranteed by position of roots of characteristic equation of its linear transfer function. Results obtained from simulation measurements confirm quality, effectivity, feasibility, and robustness of the proposed identification method.

Keywords: induction motors, magnetic flux, motor torque, system identification, motion control, variable speed drives

1. INTRODUCTION

The use of induction motors (IMs) in electric drives introduces indisputable advantages consisting in their simple design, maintenance, operational reliability and efficiency. In industrial practice, IMs are used both for conventional and high-performance applications. From the control point of view, the control of IMs brings difficulties, because it requires more complicated actuators and generally more complex control algorithms like field orientation control (FOC) [1], direct torque control (DTC) [2], model predictive control (MPC) [3] and model reference adaptive control (MRAC) [4]. Nowadays, frequency converters with advanced control features present excellent actuators for induction motor drives. But for high quality control algorithms it is necessary to identify motor parameters and internal quantities that are changed during operation of the electric drive system, for example due to temperature fluctuations or magnetic flux saturation.

In the literature many approaches to determine basic stationary parameters of IMs are presented, such as winding resistances, main and leakage inductances and moment of inertia on the motor shaft, where their exact determination can significantly affect precision of the IM control. In [5] the finite element method is used to identify the parameters of the IM and its dynamic behavior. The literature [6] compares two methods of determining parameters of IM in steady state, while saturation of the magnetic circuit is also considered. In [7] identification of steady-state motor parameters based on integration (at standstill, using integral calculations) is shown. An overview of methods for identifying stator and rotor resistances in sensorless control of IM together with design of an observer is given in [8]. A review article on methods of on-line and off-line identification of IM parameters is given in [9].

For the high-quality dynamic control of IM, it is necessary to know the motor basic static parameters during its operation. Additionally, it is important to identify the basic internal quantities of the machine, such as the rotor magnetic fluxes and motor internal electrical torque on the rotor shaft. As the direct measurement of these quantities is

rather difficult and often impossible, the instantaneous values of these quantities can be obtained indirectly, using various more or less complex identification methods.

The traditional identification methods include methods based on a certain type of IM model (so-called model-based methods). These methods are generally very sensitive to the accuracy of the model parameters and the accuracy of the measurement of machine quantities [10]. The identification of the parameters, magnetic fluxes and torque of IM is often applied to a specific type of motor control in order to improve drive dynamics, or to eliminate the angular speed sensor. Improving the identification of IM magnetic fluxes based on a neural network, and thus improving the control at DTC (direct torque control), is described in [11]. Accurate identification of the IM parameters and magnetic fluxes for subsequent control by genetic algorithms using a reduced-order robust observer can be found in the [12].

This paper proposes a new high-quality dynamic identification structure for IM based on its mathematical model and allowing to identify rotor magnetic fluxes and IM electromagnetic torque simultaneously with an on-line adaptation of the rotor resistance. There is an identification method based on determining a feedback effect of the rotor flux vector on the vector of stator currents. The method requires only the knowledge of measurable quantities of IM, such as its stator currents and mechanical angular speed. The identification structure for identifying the rotor feedback influence on the stator of IM is simple and linear. Its stability is guaranteed by position of roots of the characteristic equation of its transfer function. It preserves the same properties within the whole range of angular of IM speeds. It also withstands any changes of rotor resistance. Achieved results confirming the efficiency and the quality of the proposed identification method were verified by the simulation measurements.

2. INDUCTION MOTOR MATHEMATICAL MODEL

Many different types of mathematical models of IM are described in the literature, depending on choice which

motor quantities are selected as state variables. Generally, an IM model consists of a system of five nonlinear first-order differential equations that cannot be solved analytically. When selecting the stator current and rotor flux for the model state variables one can describe the induction motor by the following equations [2]:

$$\begin{bmatrix} \frac{di_{1x}}{dt} \\ \frac{di_{1y}}{dt} \\ \frac{d\psi_{2x}}{dt} \\ \frac{d\psi_{2y}}{dt} \end{bmatrix} = \begin{bmatrix} -\omega_0 & \omega_1 & -K_{12}\omega_g & -K_{12}\omega_m n_p \\ -\omega_1 & \omega_0 & K_{12}\omega_m n_p & -K_{12}\omega_g \\ M\omega_g & 0 & -\omega_g & \omega_2 \\ 0 & M\omega_g & -\omega_2 & \omega_g \end{bmatrix} \begin{bmatrix} i_{1x} \\ i_{1y} \\ \psi_{2x} \\ \psi_{2y} \end{bmatrix} + \begin{bmatrix} K_{11} & 0 \\ 0 & K_{11} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_{1x} \\ u_{1y} \end{bmatrix} \quad (1)$$

$$n_p \frac{M}{L_2} (\psi_{2x} i_{1y} - \psi_{2y} i_{1x}) - T_{load} = J \frac{d\omega_m}{dt} \quad (2)$$

In this model, the particular motor quantities (the stator current vector \mathbf{i}_1 and the rotor flux vector $\boldsymbol{\psi}_2$) are expressed by their components in the reference frame x - y rotating synchronously with the stator field vector by the angular frequency ω_1 .

The notation of the IM parameters motor and their values used for simulation are given in the Table 1 in the Appendix. The parameters in (1) and (2) can be determined from the motor parameters by simple recalculation according to the following formulas:

$$K_{11} = \frac{3}{2} \left(L_{s1} + \frac{L_{s2} L_m}{L_{s2} + L_m} \right)^{-1} \quad (3)$$

$$K_{12} = -\frac{3}{2} \left(L_{s1} + L_{s2} + \frac{L_{s1} L_{s2}}{L_m} \right)^{-1} \quad (4)$$

$$\omega_0 = K_{11} \left[R_1 + \left(\frac{M}{L_2} \right)^2 R_2 \right] \quad (5)$$

$$M = \frac{2}{3} L_m \quad (6)$$

$$\omega_g = \frac{R_2}{L_2} \quad (7)$$

$$L_2 = \frac{2}{3} (L_{s2} + L_m) \quad (8)$$

The block diagram of the IM corresponding to equations (1) - (2) with the parameters adjusted according to the above equations (3) - (8) is shown in Fig. 1.

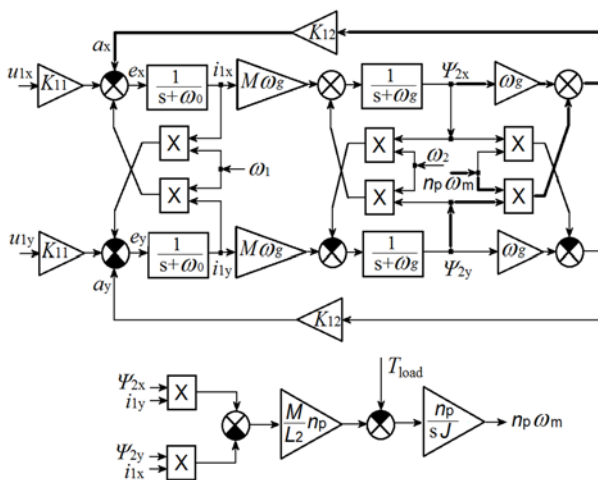


Fig. 1 Block diagram of IM in the x - y reference frame rotating synchronously with stator field vector

The dynamics of motor quantities (components of stator currents and rotor fluxes, and angular speed) after motor connection to the stator voltage $U_1 = 40$ V with the angular

frequency $\omega_1 = 28.03$ rad/s., obtained by digital simulation in MATLAB/Simulink program is shown in Fig. 2.

At verification of properties by numerical simulation it is assumed, that the IM operates under scalar control and for the supply voltage U_1 and frequency ω_1 the known ratio $U_1/\omega_1 = \text{const.}$ is kept. In this case, the x -component of the voltage u_{1x} can be considered identical to the magnitude of the stator voltage U_1 , i.e. $U_1 = u_{1x}$.

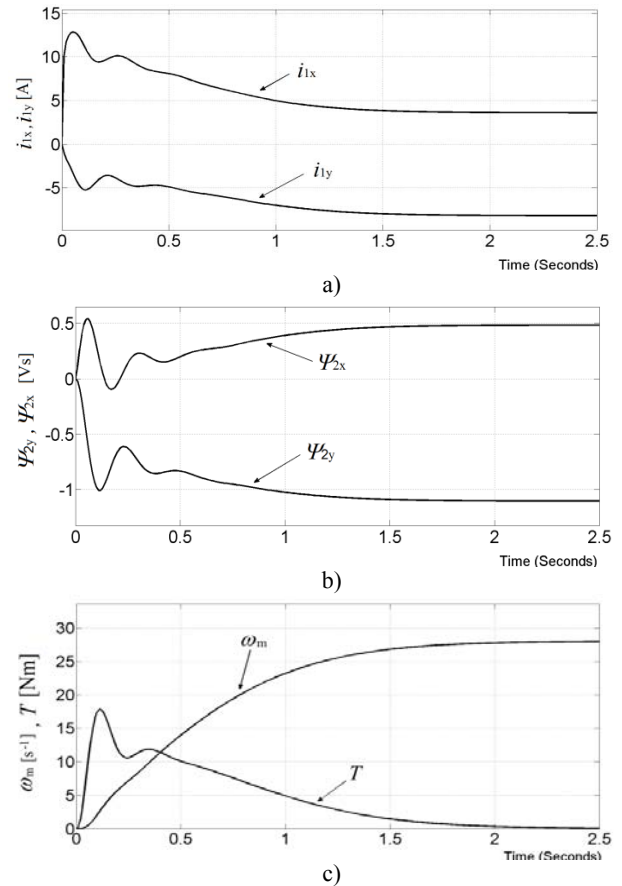


Fig. 2 Dynamic responses of the induction motor:

a) stator currents; b) rotor fluxes; c) mechanical angular speed and torque of the induction motor to step of input voltage and frequency

3. METHOD OF IDENTIFICATION STRUCTURE DESIGN

The purpose of the identification of the IM quantities is to determine their exact instantaneous values. The presented idea of the identification of hardly measurable internal quantities of the IM (the rotor flux vector components and electromagnetic torque) is based on the identification of the feedback effect of the rotor flux vector on the stator current vector. The identification of the feedback effect of the rotor flux is commonly completed based on the induced voltage, which is either equal to zero at zero speed or is insignificant at low speeds [10]. However, the considered feedback effect of the rotor flux also reflects itself on the stator current components equally within the entire speed range of IM. This fact was used in the design of the presented identification method. This influence upon the variable a_x is shown in the block diagram (Fig. 1), indicated by a thicker line starting from the quantities ψ_{2x} , ψ_{2y} and ω_m .

A similar path can be found for the variable a_y . For a clarity, the corresponding partial block diagrams are shown separately in Fig. 3.

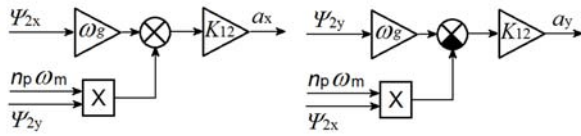


Fig. 3 Block diagrams for determining variables a_x and a_y

Let's suppose that for the induction motor with known instantaneous values of the stator input quantities U_1 a ω_1 , the stator current components i_{1x} , i_{1y} and the mechanical angular speed ω_m can be measured. The instantaneous feedback value of the stator current component i_{1x} from the first line of equation (1) is:

$$a_x = K_{12}(\omega_g \psi_{2x} + \omega_m n_p \psi_{2y}) \quad (9)$$

and similarly, for the stator current component i_{1y} it is:

$$a_y = K_{12}(\omega_g \psi_{2y} - \omega_m n_p \psi_{2x}) \quad (10)$$

For a high-quality dynamic identification of the variables a_x and a_y , the following identification structures have been designed (Fig. 4).

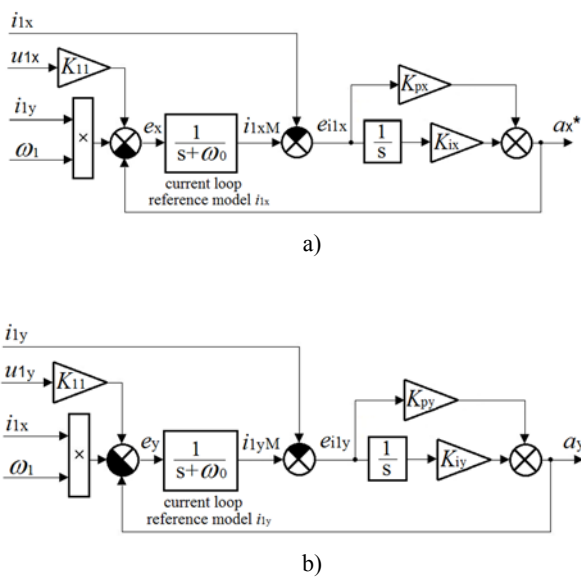


Fig. 4 The structures of identification of the rotor feedback influence on stator, for the variables: a) a_x^* ; b) a_y^*

Fig. 4a shows the identification structure of identification of the component a_x (where its identified value is denoted by an asterisk: a_x^*). It presents a structure with the reference model for the stator current RL circuit having the first order transfer function. The same input signals e_x and e_y , like the one affecting the stator current component i_{1x} (Fig. 1), are fed into this reference model. The feedback effect of the rotor flux on this stator current component is identified from the deviation of the measured current i_{1x} and its predicted value i_{1xM} obtained from the reference model. This deviation is processed by a PI (proportional-integral) controller, whose output a_x^* presents the identified value of a_x . The Laplace transfer function of the linear circuit is:

$$F(s) = \frac{a_x^*(s)}{i_{1x}(s)} = \frac{\frac{K_{px}s + K_{ix}}{s}}{1 + \frac{K_{px}s + K_{ix}}{s} \frac{1}{s + \omega_1}} = \frac{K_{px}s^2 + (K_{px}\omega_0 + K_{ix})s + K_{ix}\omega_0}{s^2 + (K_{px} + \omega_0)s + K_{ix}} \quad (11)$$

The circuit stability and its dynamics can be easily adjusted by a suitable choice of the proportional component gain and the integration component gain based on required position of poles of the transfer function (11). The identification structure in Fig. 4a is linear, and therefore its stability is guaranteed by negative real parts of the transfer function poles in the equation (11). This is obviously ensured, because all terms of the characteristic polynomial are positive.

Since the rotor time constant $1/\omega_g$ (for the considered IM it is about 35 ms) has the major influence on the dynamics of the feedback influence, the dynamics of the identification loop with the transfer function according to (11) was chosen. In this case, the two poles of the denominator are negative real and they are equal to -100. The substitute time constant according to the Shanon-Kotelnik theory will be approximately 5 times of the time constants corresponding to the poles, i.e., approx. 10 ms. Based on this, the calculated values of PI controllers in Fig. 4 are: $K_{px} = K_{py} = 10$ and $K_{ix} = K_{iy} = 11870$.

Analogically, according to the similar considerations and results like in the previous case, the identification structure of the identification of the component a_y (i.e., a_y^*) has also been designed (Fig. 4b). The properties of the designed identification structures have been verified by digital simulation (Fig. 5).

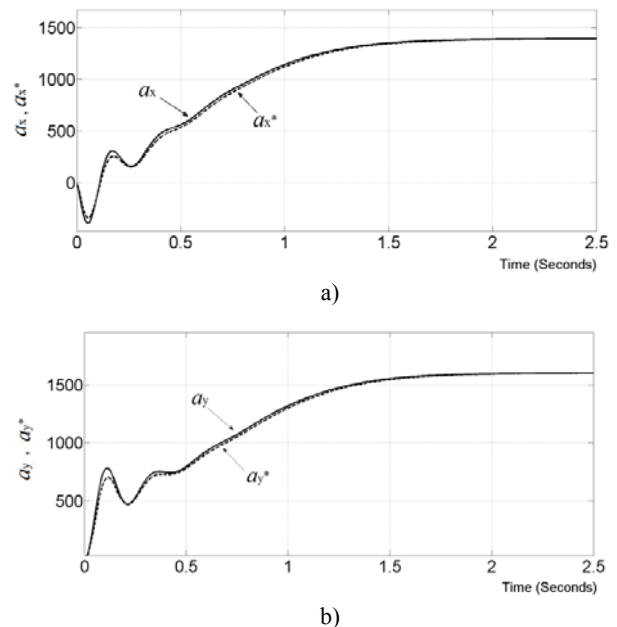


Fig. 5 Quality of identification of the variables: a) a_x^* ; b) a_y^*

Fig. 5 shows the time-waveforms of the actual internal variables a_x and a_y obtained from the IM model, as well as their identified time courses a_x^* and a_y^* . From them, it is clear that the proposed identification structures have excellent dynamic properties while being principally

stable. Due to accuracy of the sensed currents and voltages, which usually are sized within a range of a few percent, the deviations between the real and the identified values can be considered to be negligible, especially in dynamic states, because in the steady state these deviations ($a_x - a_x^*$ and $a_y - a_y^*$) are zero.

3.1. IDENTIFICATION OF ROTOR FLUXES AND TORQUE OF IM BASED ON THE VARIABLES a_x^* AND a_y^*

If the signals a_x^* and a_y^* at the output of the identification scheme in Fig. 4 are already known, then the rotor flux components can be estimated using the following equations:

$$\psi_{2x}^* = \frac{1}{K_{12}} \left(\frac{\omega_g a_x^* - \omega_m a_y^*}{\omega_g^2 + \omega_m^2} \right) \quad (12)$$

$$\psi_{2y}^* = \frac{1}{K_{12}} \left(\frac{\omega_g a_y^* + \omega_m a_x^*}{\omega_g^2 + \omega_m^2} \right) \quad (13)$$

The quality of the rotor flux components identification in comparison with their actual values obtained by simulation follows up from the time courses shown in Fig. 6.

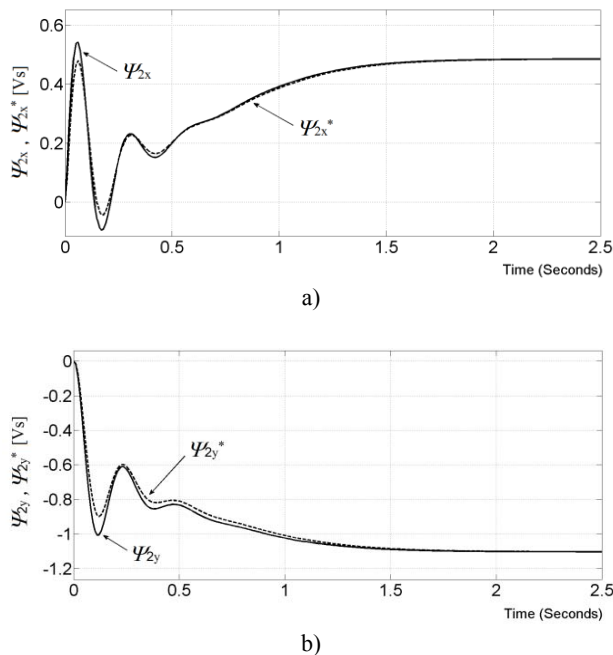


Fig. 6 Comparison of identified and actual components of IM rotor fluxes a) ψ_{2x} ; b) ψ_{2y}

From the figure it follows that the courses of the measured rotor flux vector components almost coincide with their identified time courses. The largest deviation in the dynamic state occurs approximately at time $t = 0.15$ s, and its value is less than 4%. This precision is fully satisfactory for use in any practical control application. In the steady state, the deviation between measured and identified components of the flux vector is zero, which corresponds to the zero identification deviation of the variables ($a_x - a_x^*$) and ($a_y - a_y^*$) in Fig. 5.

If the individual components of the rotor flux are identified, the motor electromagnetic torque can be determined on the basis of equation (2) as follows:

$$T^* = \frac{M n_p}{L_2} (\psi_{2x}^* i_{1y} - \psi_{2y}^* i_{1x}) \quad (14)$$

The identified electromagnetic torque waveform obtained by numerical simulation based on equation (14) is shown in Fig. 7. Its time course confirms the quality of identification both in steady and dynamic states. In the steady state, the identification deviation of the torque ($T - T^*$) is equal to zero again. The largest identification error in the dynamic state occurs in time $t = 0.15$ s and it represents approximately 3% of the maximum waveform range of the electromagnetic torque of IM. What concerns the maximal torque, three times nominal torque is considered here (equal to 60 Nm in the analyzed case).

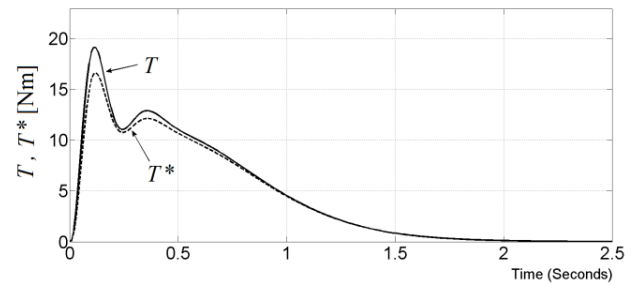


Fig. 7 Comparison of the identified electromagnetic torque T^* and the actual torque T of the induction motor

4. VERIFICATION RESULTS FOR VARIOUS OPERATING STATES

Subsequently, the properties of the rotor flux and torque identification method are verified by the simulation in various operating states.

Let's suppose that IM operating under scalar control is supplied by the voltage U_1 (where $U_1 = u_{1x}$) and is loaded gradually stepwise by the load torque T_{load} . For this reason random step changes of the input voltage U_1 applied to the stator of the motor and a step change of its load torque T_{load} were simulated, as illustrated in Fig. 8.

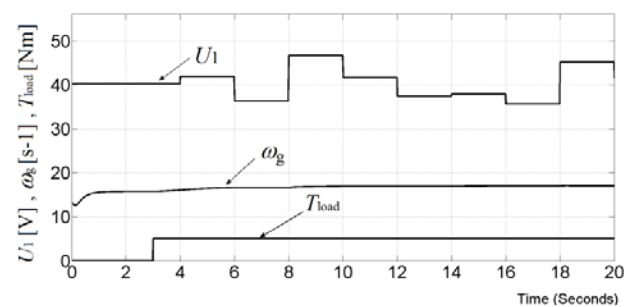


Fig. 8 Waveforms of the motor input quantities: voltage U_1 , and load torque T_{load} together with the course of parameter ω_g adaptation

At the time $t = 3$ s, a torque step of $T_{load} = 5$ Nm is applied to the motor. The stator voltage U_1 and the supply frequency jumps ω_1 are generated randomly in two-second time intervals, under maintaining the relationship $U_1/\omega_1 = const$. This operation can be considered as the worst case for the rotor resistance identification. In the praxis, this step change is not realistic.

In this case the rotor winding time constant ω_g was adapted from the initial value $\omega_{g0} = 13.18$ s⁻¹ to the value $\omega_g = 17.18$ s⁻¹ as shown in the Fig. 8.

Figure 8 shows the gradual improvement of the identification of the quality of the rotor flux components and motor electromagnetic torque identification, when taking into account the adaptation of the parameter ω_g (presenting the inverse value of the rotor resistance R_2).

The induction motor starts its operation from non-excited state and at starting, during the magnetic flux generation, the identification error lies at its maximum. After the motor has been excited, the error lies practically within the range $\pm 1\%$ of the actual value both in static and dynamic states of the identified quantities, like it follows from the time courses in the Fig. 9.

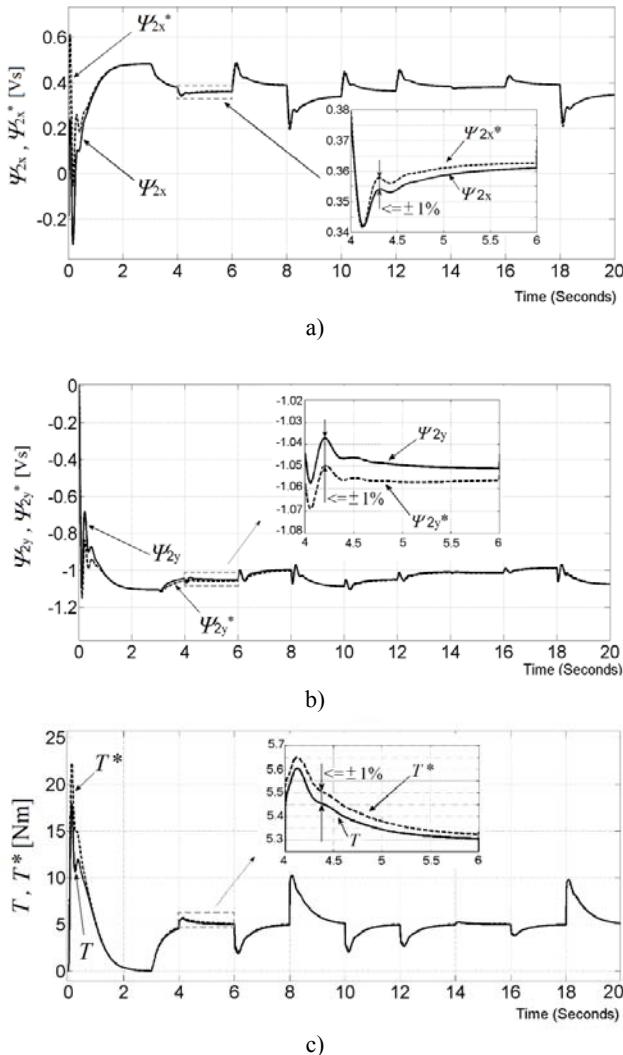


Fig. 9 Identification of the rotor flux vector components a) Ψ_{2x} ; b) Ψ_{2y} and c) motor torque T taking into account adaptation of the parameter ω_g

5. DISCUSSION AND CONCLUSIONS

In this paper, we have proposed an original method of a high quality identification of rotor fluxes and electromagnetic torque of induction motor (IM). It is based on identification of rotor feedback influence on stator currents with on-line adaptation of rotor resistance. For its operation the method utilizes commonly available measurable quantities of IM: stator currents and mechanical angular rotor speed. The identification structure for identifying the rotor feedback influence on the stator of IM is linear and its stability is guaranteed by

position of roots of the characteristic equation of its transfer function.

The proposed identification procedure can be divided into the following steps:

1. Identification of influence of the rotor feedback (more specifically: of the rotor flux) on the stator (more precisely: on the stator current), i.e. identification of introduced quantities a_x and a_y .
2. Calculation of rotor flux components from rotor mechanical angular speed and from identified values of the rotor feedback influence on stator – from the quantities a_x and a_y .
3. Calculation of the motor electromagnetic torque from measured stator currents and identified rotor flux vector components.

The quality and efficiency of the proposed identification method was verified by digital simulation in the MATLAB/Simulink program.

The results from numerical simulation (Fig. 5 – Fig. 7) show that the proposed method identifies at sufficient accuracy the feedback effect of the rotor flux vector on the stator current vector of the motor in steady and dynamic states. Based on these identified variables it is further possible to calculate components of internal rotor magnetic flux and electromagnetic torque. The accuracy of identification of these quantities depends on value of the IM rotor resistance expressed by the parameter ω_g , which is generally not known precisely and varies during operation (e.g. due to temperature change).

Experimental measurements performed on a laboratory model with IM for verification of the electromagnetic torque identification confirm that the proposed method of identification not only leads to a relatively easy-to-implement system but it is applicable at sufficiently fast sampling time of measured stator quantities of IM at standard accuracy of their measurement.

The identified internal quantities of the motor, such as the individual components of its rotor flux and the internal electromagnetic torque of the motor can be used for various commonly used methods of dynamic drive control like scalar control, different types of vector control and direct torque control of the induction motor.

APPENDIX

Table 1 Induction motor parameters and variables

Symbol	Quantity	Value
P_N	nominal power	3 kW
U_{1N}	nominal voltage	220 V
I_{1N}	nominal current	6.9 A
T_N	nominal torque	20 Nm
n_N	nominal revolution	1430 rev.min ⁻¹
n_p	number of poles	2
J	moment of inertia	0,1 kgm ²
L_2	inductance defined by equation (8)	0,14 H
R_1	stator phase resistance	1.8 Ω
R_2	rotor phase resistance	1.85 Ω
L_m	main inductance	0.202 H
M	mutual inductance defined by equation (6)	0.13 H
$L_{s1}=L_{s2}$	leakage inductance	0.0086 H

K_{11}	parameter defined by equation (3)	59.35 H ⁻¹
K_{12}	parameter defined by equation (4)	-56.93 H ⁻¹
ω_0	parameter defined by equation (5)	207,9 s ⁻¹
ω_g	rotor winding time constant – equation (7)	13.18 s ⁻¹
ω_1	angular frequency of stator voltage vector	[rad/s]
ω_m	rotor mechanical speed	[rad/s]
ω_2	angular slip frequency ($\omega_1 - \omega_m$)	[rad/s]
T	motor torque	[Nm]
T_{load}	load torque	[Nm]

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