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A METHOD OF MINIMISING THE POWER LOSSES IN AN INDUCTION MOTOR WITH A SQUIRREL-CAGE ROTOR WITH VECTOR CONTROL*

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An approach to optimizing the flux linkage of the rotor of an induction motor is considered when the motor operates in a vector control mode with indirect orientation in the direction of the field. In this system, the expression for the frequency of the rotor e.m.f. contains the rotor winding impedance; this impedance must therefore be precisely estimated in real time. It is proposed that this should be done using a fuzzy-logic adaptation mechanism. The results of using such a mechanism in a physical model confirm its effectiveness.

Key words: induction motor, rotor, vector control, fuzzy logic.

THE LOSSES in electrical machines depend on the level of the magnetic flux, the power, higher harmonics, the load etc. [1]. Moreover, an electrical machine is usually designed so that its efficiency is a maximum on full load, close to the rated operating conditions [2], and the magnetic flux in this case is maintained at the nominal level. If the load is reduced while the flux level remains the same, the relative iron losses increase. Hence, to retain the efficiency of the magnetic circuit, the flux level must be reduced [3, 4]. The question then is what value of the flux ensures the optimal functioning of the magnetic system?

There have been numerous attempts to answer this question. Among the best known methods the method of «search control» should be mentioned, which has been applied to both vector and scalar control [1, 2, 5]. In this method the output power is maintained constant while the input power is minimized by reducing the magnetic flux. The disadvantage of this method is the long time needed to establish the flux.

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A fuzzy-logic method was used in [6] to reduce the control current i_{ds} in order to obtain minimum input power. This method is quite attractive since it is independent of the parameters of the machine and the speed of rotation. However, the problem of «separation» and of taking into account the change in the rotor time constant was not solved.

The problem of optimizing the vector control taking iron losses into account was also considered in [4, 7], but neglecting the change in the rotor resistance due to heating. An approach to optimization based on monitoring the rotor flux as a function of the motor torque was proposed in [8], but the iron losses were not taken into account, which caused undesirable deflections from the optimum operating conditions.

In this paper we consider a method of optimization which enables the rotor magnetic flux to be determined as a function of the specified torque, taking into account the iron losses. The aim of the method is to minimize the total losses of the electrical machine and does not require additional sensors and regulators. As was shown in [6] and [9], this method is characterized by the fact that the direct-axis and quadrature-axis currents are equal. The change in the rotor resistance is estimated and taken into account using fuzzy logic.

One of the advantages of the method is its adaptation to the change in the impedance when the rotor flux changes [10], which, on the one hand, enables the efficiency to be maintained at the same level when the rotor resistance changes and, on the other, enables the approximate value of this resistance to be determined, which is then used to minimize the total losses.

The change in the rotor resistance. The principle of indirect vector control is based on a calculation of the slip frequency ω_{sl} needed to orient the direct axis along the direction of the rotor field. An accurate calculation of the slip frequency enables optimal decomposition of the vector of the stator current into two components to be ensured. One of these components, the quadrature component, enables the electromagnetic torque to be monitored, and the second component enables the rotor flux to be monitored. If the frequency of the control signal ω_{sl} is determined with an error (because of the change in the rotor resistance), the rotor current also differs from its accurate value. Hence, the current of the stator winding increases and the ratio of the motor torque to the stator current decreases, which is equivalent to a reduction in the motor efficiency due to an increasing in the resistive losses.

The mismatch problem mentioned above can be solved if instead of the conventional method the slip is found using a fuzzy-corrector, which determines the correction factor k_r [12].

In this system, to improve the «decomposition» caused by the change in the rotor resistance, the slip calculator [12] is replaced by a fuzzy adaptation mechanism, which generates the factor k_r and brings the rate of the slip change to real time. The adaptation is based on an analysis of the errors for both axes of the rotating field. To solve the adaptation problem, which is based on an estimation of the

stator flux components, a mechanism of estimating the rotor flux components is needed. Expressions for the rotor fluxes were obtained for the running operating conditions, and, thus, a fuzzy-logic corrector was developed with deviations e_1 and e_2 for d - and q -axis as inputs (see expression (9)). On the other hand, five fuzzy sets were chosen for each variable (the number «five» was chosen as a compromise between the data-processing time and the accuracy of the results). This corresponds to «5×5» rules of the «IF — THEN» type in the final unit. All membership functions have a triangle symmetrical uniform form. For the fuzzy sets PG and NG of the input variables a trapezoidal form was chosen. An increase for both axes is interpreted as a negative error, and in this case the fuzzy-corrector increases the rate of change of the slip. Otherwise, a decrease in the fluxes along both axes is interpreted as a positive error, obliging the corrector to reduce the rate of increase of the slip. If the signs of the deviations are different, the corrector does not act and hence the increment remains equal to zero. If the deviation is zero along the quadrature axis but not along the direct axis, the corrector does not react, since the motor operates under optimization operating conditions.

In addition, the «max-min» method was used for defuzzification of the output variable [12].

The corrected value of the slip is obtained by multiplying the conventionally calculated slip by a correction factor k_r .

As a result, we find:
a fuzzy-regulator is more reliable than the conventional one as regards the change of the electric drive and the load parameters;

optimal decomposition is carried out due to the adaptation mechanism, which is based on an estimation of the components of the rotor flux by the fuzzy-controller;

adaptation of the rotor time constant ensures operation with maximum torque-to-current ratio;

a comparison of our results with the results of earlier publications shows that under steady operating conditions the control system developed ensures the same characteristics as the conventional ones, but with the advantage of operating with a variable flux. This enables one to combine the adaptation method with the method of optimizing the motor control system.

The optimization algorithm. The total losses of the motor under steady operating conditions can be estimated using the equivalent circuit referred to the stator (Fig. 1).

$$\begin{aligned}\Delta P_s &= R_1 (i_{ds}^2 + i_{qs}^2); \\ \Delta P_r &= R_2 (i_{dr}^2 + i_{qr}^2); \\ \Delta P_c &= R_c I_c^2 = R_c \left(\frac{L_m \omega_s}{R_c} I_m \right)^2.\end{aligned}\quad (1)$$

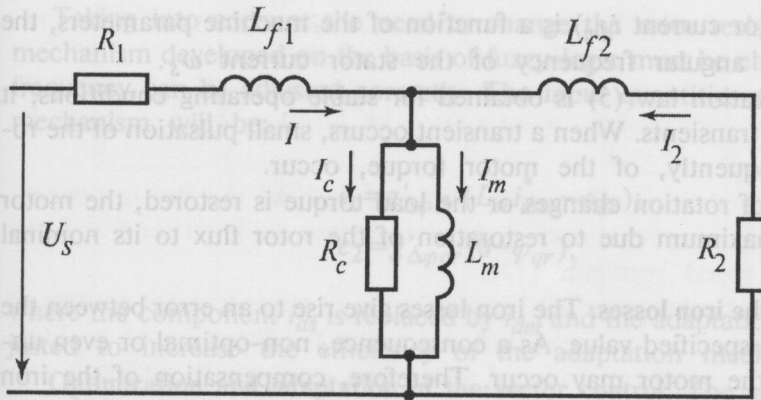


FIG. 1. Equivalent circuit of the electrical machine

In the steady state, if the flux is maintained constant by the fuzzy-corrector, we have

$$R_2 i_{dr} = 0 \Rightarrow i_{dr} = 0; \tag{2}$$

$$i_{qr} = \frac{-L_m}{L_{f2}} i_{qm}. \tag{3}$$

Substituting (2) and (3) into (1), after some reduction we obtain [17]:

$$\Delta P = a\varphi_r^2 + bM + c\left(\frac{M}{\varphi_r}\right)^2, \tag{4}$$

where

$$a = \left(\frac{R_1}{L_m^2} + (R_1 + R_c) \frac{\omega_s^2}{R_c^2} \right);$$

$$b = 2R_1 \frac{\omega_s}{R_c};$$

$$c = \frac{R_1 L_2^2}{p^2 L_m^2} + \frac{R_2}{p^2} + \frac{\omega_s^2 L_{f2}^2}{R_c^2} \left(\frac{R_1 + R_c}{p^2} \right).$$

The objective function (4) enables the optimum value of the rotor flux, corresponding to zero derivative, to be found

$$\varphi_r = \lambda \sqrt{M}, \tag{5}$$

where

$$\lambda = \sqrt{\frac{c}{a}}.$$

Here the rotor flux (or current i_{dm}) is a function of the machine parameters, the torque M^* and the angular frequency of the stator current ω_s .

Since the optimization law (5) is obtained for stable operating conditions, it cannot be applied to transients. When a transient occurs, small pulsation of the rotor flux and, consequently, of the motor torque, occur.

When the speed of rotation changes or the load torque is restored, the motor torque becomes a maximum due to restoration of the rotor flux to its nominal value.

Compensation of the iron losses. The iron losses give rise to an error between the motor torque and its specified value. As a consequence, non-optimal or even unstable operation of the motor may occur. Therefore, compensation of the iron losses is necessary in order to optimize the various operating conditions of the motor [14].

In the case of vector control with oriented rotor flux one of the main goals is to align the direct axis of the rotating system of co-ordinates with the axis of the rotor flux; hence, we must consider the equation for the rotor flux in a rotating system of coordinates [15, 16].

$$T_{fr} \frac{d\varphi_r}{dt} + j(\omega_s - p\omega_r)\varphi_r + \varphi_r = \varphi_m, \quad (6)$$

where

$$T_{fr} = L_{f2} / R_2.$$

Using the conventional approach to decomposition of the rotor flux, we obtain

$$\begin{aligned} i_{ds} &= \frac{1}{R_i} \frac{d\varphi_{dm}}{dt} - \frac{\varphi_r}{L_{f2}} + \frac{\varphi_{dm}}{L_{f2}} + \frac{\varphi_{dm}}{L_m} - \frac{\omega_s}{R_c} \varphi_{qm}; \\ i_{qs} &= \frac{1}{R_i} \frac{d\varphi_{qm}}{dt} + \frac{\varphi_{qm}}{L_{f2}} + \frac{\varphi_{qm}}{L_m} + \frac{\omega_s}{R_i} \varphi_{dm}. \end{aligned} \quad (7)$$

For the steady state, taking into account the ratio φ_r / L_m and I_{qm} , we have

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} \frac{1}{L_m} & -\frac{\omega_s}{R_{fe}} L_m \\ \frac{\omega_s}{R_i} & \frac{L_2}{L_{f2}} \end{bmatrix} \times \begin{bmatrix} \varphi_r \\ i_{qm} \end{bmatrix}. \quad (8)$$

Equations (8) contain a term related to the equivalent iron-loss resistance; therefore, a relation exists between the two axes of the control system. Equations (8) enable the decomposition unit to be changed so that the iron losses are taken into account.

Experiments. To check the theoretical states, a laboratory model was constructed. The parameters of the motor used are as follows:

$R_1=4.85$ Ohm; $R_2=3.805$ Ohm; $R_f=500$ Ohm; $L_{f2}=0.016$ H; $L_m=0.258$ H; $J_m=0.031$ kg·m²; $U_n=220/380$ V; $P_n=1.5$ kW; $M_n=10$ N·m²; $L_{f1}=0.016$ H; $\mu=0.008$; $\omega_r=1440$ rpm.

The motor is supplied from a frequency converter, whose inverter is current-controlled by two bang-bang regulators. A fuzzy-regulator designed for five fuzzy sets was used as a speed regulator [12].

The control system. In the proposed system for the corrected vector control of an induction motor the decomposition unit, known in the literature as an FOC unit, is replaced by the compensation and adaptation unit, which performs two functions. First, this unit takes the iron losses into account and, second, the change in the parameters of the motor, in particular, the rotor resistance, is taken into account.

The value of the rotor resistance, which largely depends on the motor temperature, is used to calculate the slip in the units for decomposing the magnetic flux and the torque.

The adaptation unit has two inputs and one output. The calculated values of the rotor flux deviations $\Delta\varphi_{dr}$ and $\Delta\varphi_{qr}$, which are equal to the differences between the components of the oriented flux of the rotor and the estimated components (based on the stator currents and voltages after they are transformed into rotating co-ordinates $\Delta\varphi_{dr}$ and $\Delta\varphi_{qr}$) are applied to its input.

At the output of the adaptation unit, a signal is generated, proportional to the rotor resistance, the constant of proportionality being also used to optimize the rotor flux by establishing the value of the torque, which is generated by the speed regulator (the phase regulator using five fuzzy sets of fuzzy logic [12]).

In addition, the function Θ is calculated, which together with the specified value of the torque, is used in the optimization unit to calculate the optimum value of the motor flux, which depends on the angular frequency of the stator current ω_s and the rotor resistance $R_2=k_r R_2^*$.

Control without optimization. Curves for vector control without optimization are shown in Fig. 3. The decomposition is implemented by orientating the flux along the (d, q) axis and maintaining it at the nominal level of 1 Wb (Fig. 3b). Hence, the direct-axis component of the stator current i_{ds} is equal to 3.867 A. At the instant $t=2$ s the load torque is reduced to 35% of its nominal value. After this the quadrature-axis current i_{qs} falls to 0.823 A, and, since i_{ds} is maintained constant (see Fig. 3c), the stator current becomes $I_s=3.956$ A. The operation under low load (overexcitation) is clearly illustrated by the difference between the curves of the stator current components.

Control with optimization. The introduction of the adaptation mechanism enabled the efficiency of the system to be improved, particularly under low load operating conditions. This is due to the fact that the reduction in the load torque is ac-

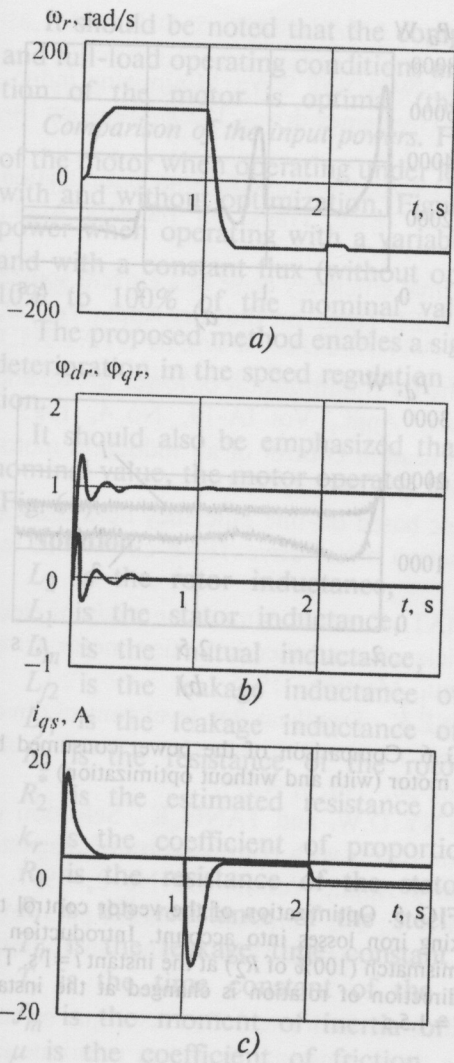


FIG. 3. Non-optimized vector control under low-load operating conditions taking the iron losses into account (without mismatch). The direction of rotation is changed at the instant $t = 1$ s

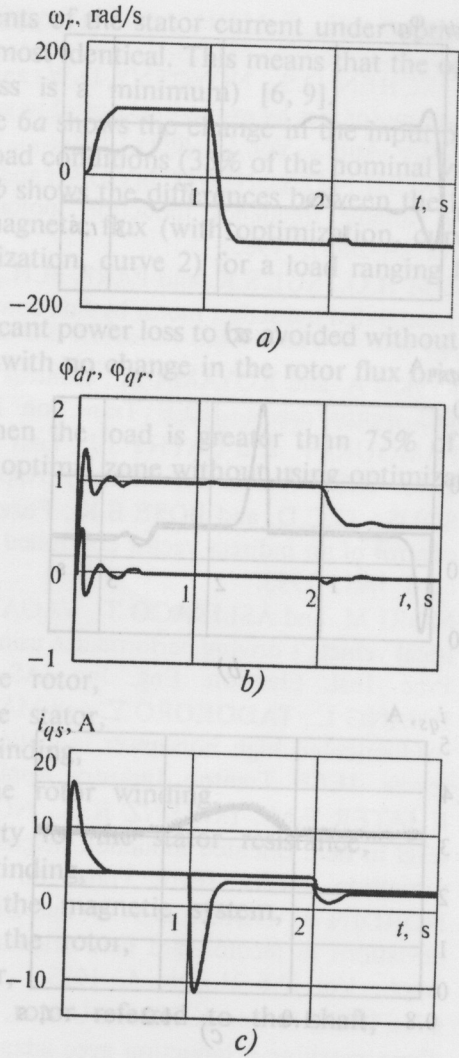
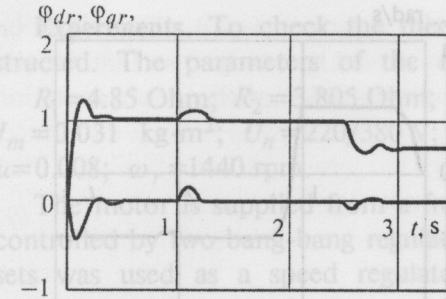
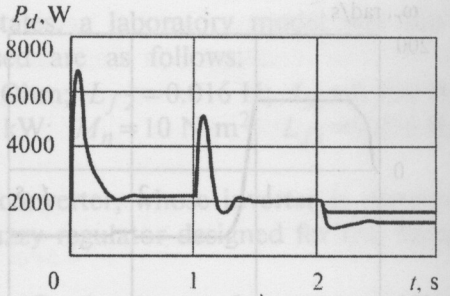


FIG. 4. Optimized vector control taking the iron losses into account (without mismatch). The direction of rotation is changed at the instant $t = 1$ s

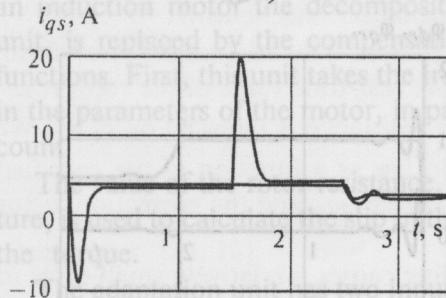
companied by a reduction in the rotor flux (Fig. 4b) without disturbing its orientation. Indeed, the direct-axis current falls to $i_{ds} = 2.321$ A and the quadrature-axis current increases to $i_{qs} = 2.02$ A (Fig. 4c) to compensate for the reduction in the torque (6). As a consequence, the absolute value of the stator current is reduced to $I_s = 3.077$ A, which is less than the value corresponding to control without optimization ($I_s = 3.157$ A). Note that the effectiveness of the speed regulation in this case is hardly affected (Fig. 4a).



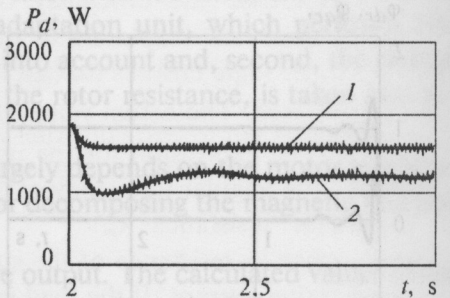
a)



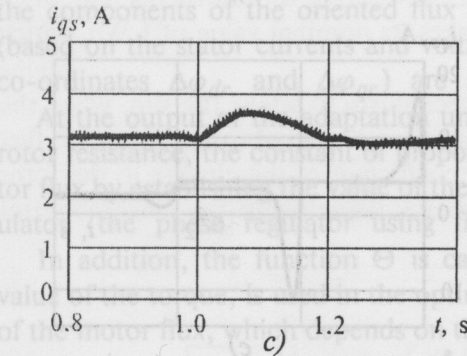
a)



b)



b)



c)

FIG. 6. Comparison of the power consumed by the motor (with and without optimization)

FIG. 5. Optimization of the vector control taking iron losses into account. Introduction of mismatch (100% of R_2) at the instant $t=1$ s. The direction of rotation is changed at the instant $t=1.5$ s

Control with adaptation and optimization. The combined use of adaptation and optimization units improves the efficiency of the system if there is a difference between the actual and calculated values of the time constant. This is illustrated in Fig. 5. During vector control uncorrected deviation causes, on the one hand, a loss of decomposition and, on the other, an increase in the stator current for the same load torque. As a consequence, the static and dynamic characteristics of the electric drive and the power efficiency of the system deteriorate. The problem was solved using fuzzy-adaptation (Fig. 5a and c). Under low-load operating conditions the use of the adaptation unit enables the direct-axis current to be reduced to 2.462 A (Fig. 5b and c) and the quadrature-axis current was equal to 2.180 A.

It should be noted that the components of the stator current under optimized and full-load operating conditions are almost identical. This means that the operation of the motor is optimal (the loss is a minimum) [6, 9].

Comparison of the input powers. Figure 6a shows the change in the input power of the motor when operating under low load conditions (35% of the nominal value) with and without optimization. Figure 6b shows the differences between the input power when operating with a variable magnetic flux (with optimization, curve 1) and with a constant flux (without optimization, curve 2) for a load ranging from 10% to 100% of the nominal value.

The proposed method enables a significant power loss to be avoided without any deterioration in the speed regulation and with no change in the rotor flux orientation.

It should also be emphasized that when the load is greater than 75% of the nominal value, the motor operates in the optimal zone without using optimization (Fig. 6b).

Notation.

- L_2 is the rotor inductance,
- L_1 is the stator inductance,
- L_m is the mutual inductance,
- L_{f2} is the leakage inductance of the rotor,
- L_{f1} is the leakage inductance of the stator,
- R_2 is the resistance of the rotor winding,
- R_2^* is the estimated resistance of the rotor winding,
- k_r is the coefficient of proportionality for the stator resistance,
- R_1 is the resistance of the stator winding,
- R_i is the resistance of the steel of the magnetic system,
- T_{fr} is the leakage time constant of the rotor,
- T_r is the time constant of the rotor,
- J_m is the moment of inertia of the rotor referred to the shaft,
- μ is the coefficient of friction,
- p is the number of pole pairs,
- ω_s and ω_r are the angular frequencies of the stator and rotor respectively,
- ω_{sl} is the slip angular frequency,
- M , M^* and M_r are the motor torque, specified torque and load torque respectively,
- i_{ds} and i_{qs} are the d - and q -components of the stator current respectively,
- i_{dr} and i_{qr} are the d - and q -components of the rotor current respectively,
- i_{dm} and i_{qm} are the d - and q -components of the magnetizing current respectively,
- φ_{dr} and φ_{qr} are the d - and q -components of the rotor flux respectively,
- Δp and Δp_i total losses and iron losses respectively,
- Δp_s and Δp_r are the stator and rotor losses respectively.

REFERENCES

1. KIRCHEN D.S., NOVOTNY D.W. and WANWISOOT S.W., Minimizing induction motor loss by excitation control in variable frequency drives. *IEEE Trans. on Industry Appl.*, Vol. IA-20(1), 1984.
2. KIRCHEN D.S., NOVOTNY D.W. and LIPO T.A., On-line efficiency optimization of variable frequency induction motor drives. *IEEE Trans. on Industry Appl.*, Vol. IA-20(1), 1985.
3. KIM H.G., SUL S.K. and PARK M.H., Optimal efficiency drive of a current source inverter-fed induction motor by flux control. *IEEE Trans. on Industry Appl.*, Vol. 20, No. 6.
4. KISKO A. and KOYAMA M., Control means for minimization of losses in AC and DC motor drives. *IEEE Trans. on Industry Appl.*, Vol. IA-19, No. 4, 1983.
5. FAMOURI P. and CATHY J.J., Loss minimization control of an induction motor drive. *IEEE Trans. on Industry Appl.*, Vol. 27, No. 1, 1991.
6. SOUSA G.C.D. and BOSE B.K., Fuzzy logic based on-line efficiency optimization control of an indirect vector controlled induction motor drive. *IEEE conference record IAS*, 1993.
7. MORI M. and ASLIKAGO T., VAGAYAMATI K. et al., Simulation study of electrical vehicle's driving performance using efficiency controlled induction motor drive. *Proc. Inst. Electron. Eng. Jpn.-IAS. Annu. Meeting*, 1995.
8. HUANG L., TADOKORO Y. and MATSUSE K., Deadbeat flux level control direct field oriented high horsepower induction servo motor using adaptive rotor flux observer. *IEEE Trenton Industry Appl.*, Vol. 30, No. 4, 1994.
9. KHATER F.M., LORENZ R.D., NOVOTNY D.W. and TANG K., Selection of level in field oriented induction machine controllers with consideration of magnetic saturation effects. *IEEE Trans. on Industry Appl.*, Vol. IA-23, No. 2, 1987.
10. NORDIN B., DONALD W.N. and ZINGER S., The influence of motor parameter deviations in feedforward field orientation drive systems. *IEEE Trans. on Industry Appl.*, Vol. IAS-21, No. 4, 1985.
11. CHETATE B. and KHELDOUN A., Commande indirecte à flux rotorique orienté d'une machine à induction avec adaptation de la constante de temps rotorique par logique floue. *First International Conference on Electrical Engineering, ICEE'2000*, November, 2000, Boumerdès (Algeria).
12. CHETATE B. and KHELDOUN A., Adaptive control of induction motor by fuzzy logic. *Review of Sciences and Technology of Hydrocarbons*, No. 3, 2003.
13. ABRAHAMASEN F., BLAABJERG A., PEDERSON J.K., et al., On the energy optimized control of standard and high efficiency induction motors on CT and HVAC applications. *IEEE Trans. on Industry Appl.*, Vol. 34, No. 24, 1998.
14. MATSUSE K., YOSHIZUMI T., KATSUTA S., and TANIGUSHI S., High-response flux control of direct field oriented induction motor with high efficiency taking core loss into account. *IEEE Trans. on Industry Appl.*, Vol. 35, No. 1, 1999.
15. LEVIE E., SOKOLA M., BOGLIETTI A. and PASTROLI M., Iron loss in rotor flux oriented induction machines: identification, assessment of detaining and compensation. *IEEE Trans. on Power Electronics*, Vol. 11, No. 5, 1996.

16. MIZLING T., TAKAYAMA J., ICHIOKA T., TERASHIMA T., Decoupling control methods of induction motors taking stator core losses into consideration. Conference Record IEEE IAS 1990 Annual Meeting, 1990.
17. CHETATE B. and KHELDOUN A., Model based minimization of power loss in vector control. Proceedings of the 2nd International Symposium on Electrical, Electronic and Computer Engineering, 11–13 March 2004, Nicosia.

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Key words: pulsed converter, dynamic operating conditions, bipolar reversible, pulse-width modulation, local stability.

Abstract: The development of closed-loop automatic control systems (ACS) in which switched converters are used involves correctly choosing the parameters of the regulation loops for which stable operation of the system is ensured over the entire range of control and perturbing actions. This is due, first of all, to the progress which has been made by leading electronics companies in perfecting power semiconductor devices with field control (MOSFET and IGBT transistors and GTO thyristors), which enable relatively cheap and reliable converters of electricity with the simplest structure of the power circuit to be constructed. This is due, first of all, to the progress which has been made by leading electronics devices, and in systems for supplying power to technological processes [1–3].

Introduction: Frequency electric drives, reversible and nonreversible d.c. electric drives, static frequency power compensators, stabilized power supplies for domestic and radioelectric devices, and in systems for supplying power to technological processes [1–3].

1. Introduction: The development of closed-loop automatic control systems (ACS) in which switched converters are used involves correctly choosing the parameters of the regulation loops for which stable operation of the system is ensured over the entire range of control and perturbing actions. This is due, first of all, to the progress which has been made by leading electronics companies in perfecting power semiconductor devices with field control (MOSFET and IGBT transistors and GTO thyristors), which enable relatively cheap and reliable converters of electricity with the simplest structure of the power circuit to be constructed. This is due, first of all, to the progress which has been made by leading electronics devices, and in systems for supplying power to technological processes [1–3].

2. Dynamic operating conditions of pulsed voltage converters: based on different kinds of pulse-width modulation and whose behaviour is described by piecewise-smooth differential equations are investigated. Features specific to the evolution of the quality of the output signal in the space of parameters of the automatic control system are considered. The limits of stable operation of the system as a function of the system parameters are obtained.

3. Bipolar reversible: dynamic operating conditions, pulse-width modulation, local stability.

4. Pulse-width modulation: dynamic operating conditions, pulse-width modulation, local stability.

5. Bipolar reversible: dynamic operating conditions, pulse-width modulation, local stability.

References: 1. MIZLING T., TAKAYAMA J., ICHIOKA T., TERASHIMA T., Decoupling control methods of induction motors taking stator core losses into consideration. Conference Record IEEE IAS 1990 Annual Meeting, 1990. 2. CHETATE B. and KHELDOUN A., Model based minimization of power loss in vector control. Proceedings of the 2nd International Symposium on Electrical, Electronic and Computer Engineering, 11–13 March 2004, Nicosia.

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