МОНІТОРИНГ, ДІАГНОСТИКА ТА КЕРУВАННЯ ЕНЕРГЕТИЧНИМИ ПРОЦЕСАМИ ТА ОБЛАДНАННЯМ MONITORING, DIAGNOSTIC AND MANAGEMENT OF POWER PROCESSES AND EQUIPMENT

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EFFECTIVE CONTROL OF FIELD REGULATED RELUCTANCE MACHINE

The electrical drive based on field regulated reluctance machine is a good alternative to the induction drive because of various advantages related to energy efficiency. At the same time this type of drive is sensitive to coordinate and parametric disturbances which may affect energy efficiency and quality of control in various technological processes. This paper is to propose the method of development of control laws based on an idea of the reversibility of the Lyapunov direct method for the stability anal-ysis, and using the instantaneous value of energy as the predetermined Lyapunov function. This will ensure effective operation with a lesser sensitivity to variations of the motor's parameters, as well as the simplicity of realization of control system.

Key words: control, effective, field regulated reluctance machine.

Introduction. In many industries, the promising alternative to the most widely used induction electrical drive is one based on a field regulated reluctance machine (FRRM). Main advantages of this type of motors [2] are: high efficiency factor within a wide speed range; power factor is about 100%; a simple design and low production costs; high manufacturability and reliability; a wider speed control range in a zone of reduced magnetic flux; an easier heat removal. This study is dedicated to motor with independent electromagnetic excitation. It has a passive rotor with tooth structure and a stator with a classic distributed "star" 3-phase winding. Additionally, there is an excitation winding which is supplied from a direct current source. Miscalculations during identification of the parameters of the equivalent circuit of the FRRM can be caused by assumptions used in an applied methodology, as well as by the lack of basic information. During the motor operation, resistance of windings may be changed because of heating, and inertia moment may be deviated through changes of the kinematics. These parametric deviations resulted in differences between estimated and actual parameters of the electrical drive, which, in turn, leads to worsening of control performance. Naturally, the FRRM, as well as other types of alternating current motors, is an interrelated controlled object, substantially dependent on influence of inducted eddy currents. In this case, electrical drive control requires compensation of negative influence of these coordinate disturbances. Solution of the above mentioned problems by the classic methods of the automatic control theory, under the under conditions of uncertainties in a mathematical model, is rather complicated because requires additional algorithms of identification, adaptation or compensation. Analysis of methods for control law optimization showed [6] that solutions can be found based on a concept of reverse task of dynamics in combination with minimization of local functionals of instantaneous values of energies [3-5]. The reverse task of dynamics is to identify the control law which would ensure a given quality of control with desired static and dynamic performance of the system. The proposed method is based on an idea of the reversibility of the Lyapunov direct method for the stability analysis. This allows defining control laws which ensure that a closed loop has the predetermined Lyapunov function in form of the instantaneous value of energy. In this case, the specificity of optimization is not obtaining the absolute minimum of the quality functional, as usually used in traditional systems, but rather getting a certain minimal value which would assure a technically allowable dynamic error of the system.

This paper is aimed at the identification of respective control laws which would allow a lesser sensitivity to variations of the motor's parameters, as well as the simplicity of realization of the control system, and consequently ensure good control performance of electrical drive, required for most of industrial technologies.

Methodology of the study. A mathematical model of SIM IE in the coordinate system (d-q), oriented by the rotor magnetic axis, can be described by known non-liner equation system (1). It is shown from (1) that motor's coordinates are interrelated because of the existing nonlinearity caused by the operation of multiplication and

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coordinative disturbances. In classic control systems, compensation of the negative influence of coordinative disturbances is to be realized through setting specific feedbacks, the effectiveness of which depends on the accuracy of motor’s parameters. It is also possible to identify control laws based on the static decomposition of the controlled object (1) resulting in complication of the control system. In this study, solution is being found through the dynamic decomposition [1], using optimization method proposed in [3]. During the control system design, coordinate deviations $F_1 = L_m \frac{di_f}{dt} - \omega\psi_q$, $F_2 = \omega\psi_d$, and $F_3 = L_m \frac{di_d}{dt}$ are usually interpreted as indeterminate, but value limited $F_1 \le F_{1\max}$, $F_2 \le F_{2\max}$, $F_3 \le F_{3\max}$, while values of control signals u_d, u_q, u_f are sufficient for their compensation. In this case, a problem to control the interrelated controlled object comes to finding solution of local tasks to control four liner subsystems (1).

$$\begin{cases} L_s \frac{di_d}{dt} + R_s i_d = u_d + F_1; \\ L_s \frac{di_q}{dt} + R_s i_q = u_q + F_2; \\ L_f \frac{di_f}{dt} + R_f i_f = u_f + F_3; \\ J \frac{d\omega_r}{dt} = M - M_c; \\ \psi_d = L_s i_d + L_m i_f; \\ \psi_q = L_s i_q; \\ \psi_f = L_f i_f + L_m i_d; \\ M = \sqrt{3} Z_p \left[\psi_d i_q - \psi_q i_d \right], \end{cases} \qquad (1)$$

where i_d, i_q and u_d, u_q – d-axis and q-axis stator currents and voltages respectively; i_f and u_f – excitation current and voltage; $\omega = Z_p \omega_r$ and ω_r – electrical and angular rotor speed; Z_p – pole couple number; J – inertia moment; M, M_c – electromagnetic motor torque and load torque; ψ_d, ψ_q, ψ_f – d- and q-axis, as well as excitation winding fluxes; L_s, L_f, L_m – stator, excitation winding and mutual inductance; R_s, R_f – stator and excitation winding resistances.

The vector control system, according to first four differential equations of the system (1) consist of four control loops: for stator d-axis current i_d, q-axis current i_q, excitation current i_f, and motor speed ω_r. The speed loop is external to the internal loop of current i_q. This current defines a value of the electromagnetic torque of a motor. The excitation current i_f can be easily controlled within the range 1:8. This allows increasing a range of speed control with a constant power, in comparison with induction motor.

An object of the local control loop for the stator current i_d according to the 1st equation of the system (1)

$$L_s \frac{di_d}{dt} + R_s i_d = u_d + F_1 \qquad (2)$$

can be described by the first order linear differential equation with control signal u_d and disturbance F_1. A desired equation of the closed current loop, which defines expected control performance, can also be described by the first order differential equation [4,5]

$$\dot{z} + \alpha_{0i_d} z = \alpha_{0i_d} i_d^*, \qquad (3)$$

where i_d^* – referenced current. The equation (3) enables a type 1 astatic system for control variable, as well as smooth (with no overcontrol) current transients. Required transient time $t_n \approx 3/\alpha_{0i_d}$, is defined only by the coefficient α_{0i_d}.

The extent to which the real current control process is close to desirable one can be estimated through the functional, which depends on inductance-normalized instantaneous energy of the magnetic field by the 1st derivation of the current.

$$G(u_d) = \frac{1}{2}\left[\dot z(t) - \dot i_d(t)\right]^2. \qquad (4)$$

To minimize the functional, the gradient law of the 1st order can be used:

$$\frac{du_d(t)}{dt} = -\lambda_{i_d}\frac{dG(u_d)}{du_d}, \qquad (5)$$

where λ_{i_d} – a constant.

Substituting (2) and (4) into (5), the control law for the current i_d can be obtained

$$\dot u_d(t) = k_{i_d}(\dot z - \dot i_d), \qquad (6)$$

where $k_{i_d} = \lambda_{i_d} / L_s$ – the gain coefficient of the controller.

A variable $\dot z$ in the control law (6) plays a role of a necessary derivative on the current, which can be found in real time from the equation (3) through closing feedback on the current component $z = i_d$

$$\dot z = \alpha_{0i_d}(i_d^* - i_d). \qquad (7)$$

Integrating both parts of the equation (6) and taking into account (7), the control law for the current i_d can be finally obtained:

$$u_d(t) = k_{i_d}(z - i_d);$$
$$z = \alpha_{0i_d}\int_0^t (i_d^* - i_d)dt. \qquad (8)$$

Contrary to classic controllers, the designed one does not contain parameters of the controlled object (1), and has only the parameter α_{0i_d} which defines the desired equation of the closed-loop system performance (3).

The differential equation of closed control loop of the current i_d can be derived through substituting the control law (8) to (2):

$$\ddot i_d + (R_s / L_s + k_{i_d} / L_s)\dot i_d + (k_{i_d}\alpha_{0i_d} / L_s)i_d = (k_{i_d}\alpha_{0i_d} / L_s)i_d^* \qquad (9)$$

It demonstrates that control process is asymptotically stable. According to the Hurwitz criterion, coefficients of the equation (9) are positive $(k_{i_d}\alpha_{0i_d} / L_s) > 0$, $(R_s / L_s + k_{i_d} / L_s) > 0$. It is important that the stability of the control loop is maintained under unlimited increasing of the controller gain coefficient $k_{i_d} \to \infty$; and real (9) and designed (3) control processes are fully coincident. This is made obvious, if to divide all elements of the equation (9) by the coefficient k_{i_d} / L_s under condition $k_{i_d} \to \infty$

$$\frac{L_s}{k_{i_d}}\ddot i_d + \left(\frac{R_s}{k_{i_d}} + 1\right)\dot i_d + \alpha_{0i_d} i_d = \alpha_{0i_d} i_d^*. \qquad (10)$$

This specificity provides the dynamic decomposition of the system (1) and the robustness to parametric disturbances. During operation, the interrelated system is broke down into relatively independent local control loops, with their transients which run in accordance with the desired performance equation (3). Clearly, if the gain coefficient of the controller is technically limited, there is a dynamic error which is set through technical requirements to the quality of control.

During the development of the current control law, a small uncompensated time constant of the power frequency convertor T_μ, which is in the closed loop, was not taken into consideration. Assessment of its influence in form of the 1st order aperiodic unit can be carried out through the 3rd order differential equation of the closed loop system which is derived similarly to (9)

$$T_\mu \dddot i_d + (1 + T_\mu R_s / L_s)\ddot i_d + (R_s / L_s + k_{i_d} / L_s)\dot i_d + (k_{i_d}\alpha_{0i_d} / L_s)i_d = (k_{i_d}\alpha_{0i_d} / L_s)i_d^*. \qquad (11)$$

According to the Hurwitz criterion, the current loop stability can be achieved under the following condition:

$$(1 + T_\mu R_s / L_s)(R_s / L_s + k_{i_d} / L_s) > T_\mu k_{i_d}\alpha_{0i_d} / L_s. \qquad (12)$$

Assuming that $k_{i_d} \to \infty$, the stability condition can be finally presented as follows:

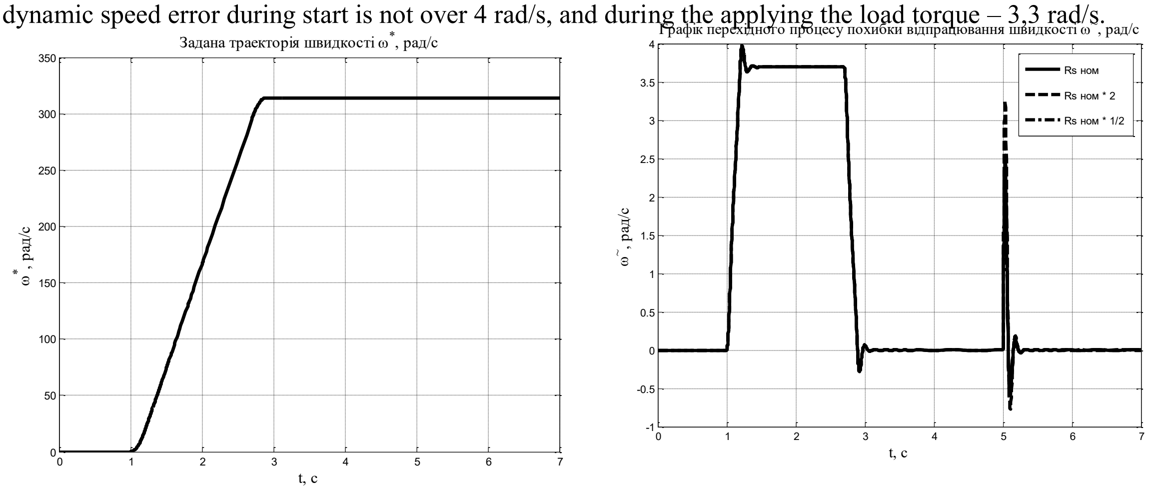
$$\alpha_{0i_d} < 1/T_\mu + R_s/L_s \qquad (13)$$

Thus, the time constant of the power frequency convertor T_μ limits a time response of the system, which is set by the coefficient a_{0d}.

The laws of regulation are developed similarly for other coordinates of the system.

The developed vector control system was investigated through modelling with the following parameters of the SIM IE: rated power $P_н$=208 кW; rated motor torque $M_н$=663 Nm; rated current $I_н$=458 A; rated speed $n_н$=3000 rpm. Controllers had parameters as follows: current controller I_D: α_{0id}=500, k_{id}=250; CURRENT CONTROLLER I_Q: α_{0iq}=500, k_{iq}=260; CURRENT CONTROLLER I_F: α_{0if}=50, k_{if}=250; SPEED CONTROLLER: $\alpha_{0\omega}$=150, k_ω=50.

Fig. 1a presents transients of referenced speed ω* during the electrical drive start period. Fig. 1b presents speed tracking error under variation of the stator resistance R_s: R_s = 0,0029 Ω (rated value), R_s = 0,00145 Ω (0.5 rated value) and R_s = 0,0058 Ω (2.0 rated value). As seen, this parametric disturbance does not affect the dynamic performance of the proposed system: three transients are identical, no recognizable differences. The maximal dynamic speed error during start is not over 4 rad/s, and during the applying the load torque – 3,3 rad/s.



a) b)

Figure 1 - Transients of referenced speed ω* during the electrical drive start period

The results of study presented above, clearly demonstrate that the electrical drive with FRRM, designed based on the proposed methodology, has good control performance, is simple for development, and allows required operation under the parametric disturbances.

Conclusions. Proposed electrical drive based on a field regulated reluctance machine (FRRM) can be designed based on the relatively simple methodology, applying a concept of reverse task of dynamics in combination with minimization of local functionals of instantaneous values of energies. This approach allows practical development of the controllers of the electro-mechanical system which would ensure a given quality of control and adequately simple practical realization under conditions of variation of the parameters of the controlled object and the uncertainties in a mathematical model. As a result, this type of electrical drive can be recommended for further development and promotion, to be used in technological processes and installations of various industries.

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УДК 621.3.076

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ЭФФЕКТИВНОЕ УПРАВЛЕНИЕ СИНХРОННОЙ РЕАКТИВНОЙ МАШИНОЙ С НЕЗАВИСИМЫМ ВОЗБУЖДЕНИЕМ

Электрический привод на основе на синхронной реактивной машины з независимым возбуждением является хорошей альтернативой асинхронному приводу из-за ряда преимуществ, связанных с энергоэффективностью. В то же время этот тип привода также чувствителен к координатным и параметрическим возмущениям, которые могут влиять на энергоэффективность и качество управления в различных технологических процессах. В работе предложен метод управления на основе идее обратимости прямого метода Ляпунова по исследованию устойчивости, в котором используется мгновенное значение энергии в качестве предопределенной функции Ляпунова. Это обеспечит эффективную работу с малой чувствительностью к изменениям параметров двигателя, а также простоту реализации системы управления.

Ключевые слова: управление, эффективность, синхронная реактивная машина

УДК 621.3.076

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ЕФЕКТИВНЕ КЕРУВАННЯ СИНХРОННОЮ РЕАКТИВНОЮ МАШИНОЮ З НЕЗАЛЕЖНИМ ЗБУДЖЕННЯМ

Електропривод на основі синхронної реактивної машини з незалежним збудженням є однією з альтернатив асинхронному електроприводу завдяки ряду переваг, пов'язаних з енергоефективністю. В той же час цей тип електропривода також чутливий до параметричних та координатних збурень, що негативно впливає на енергоефективність та якість керування в різних технологічних процесах. В роботі запропоновано метод керування на основі ідеї зворотності прямого методу Ляпунова по дослідженню стійкості, в якому використовується миттєве значення енергії в якості заданої функції Ляпунова. Це забезпечує ефективну роботу електропривода з малою чутливістю до зміни параметрів машини, а також просту реалізацію системи керування.

Ключові слова: керування, ефективність, синхронна реактивна машина

Надійшла 26.06.2017
Received 26.06.2017