UDC 681.515 doi: 10.20998/2079-8024.2019.16.05

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ROBUST CONTROL THE ROTOR MECHANICAL ANGULAR SPEED OF SURFACE MOUNTED PERMANENT MAGNET SYNCHRONOUS MOTOR

There has been proposed robust control the rotor mechanical angular speed of a surface mounted permanent magnet synchronous machine under conditions of parametric uncertainty. The perturbations have been bound with incomplete information about the structure mathematical model and parameters of the control object. Consequently, a field oriented control system has the considerable degradation of transient processes of electrical and mechanic coordinates. The improve performance the quality of transition processes in system with cascade control decides by means of the application control algorithms based on the concept of inverse problems of dynamics combined with the minimization of the local instantaneous energy values functional.

Keywords: robust control, surface mounted permanent magnet synchronous machine, speed, control algorithms, parametric perturbations.

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РОБАСТНЕ КЕРУВАННЯ КУТОВОЮ ШВИДКІСТЮ РОТОРА СИНХРОННОГО ДВИГУНА З ПОСТІЙНИМИ МАГНІТАМИ

Запропоновано робастне регулювання кутової швидкості ротора синхронної машини з постійними магнітами в умовах параметричної невизначеності. Збурення пов'язані з неповною інформацією про структуру математичної моделі та з параметрами об'єкта керування. В наслідок чого у системі векторного керування спостерігається значна деградація перехідних процесів електричних і механічних координат. Покращення показників якості перехідних процесів у системі з каскадним керуванням вирішується за допомогою застосування алгоритмів керування, що засновані на концепції зворотних задач динаміки в поєднанні з мінімізацією функціональних локальних миттєвих значень енергії. Синтезовані алгоритми керування записуються безпосередньо з рівняння об'єкта та рівняння бажаної якості керування без розв'язання задачі оптимізації в традиційному сенсі та не містять операцій диференціювання, що спрощує їх реалізацію. Алгоритми керування надають замкнутій системі властивість стійкості в цілому, що дозволяє вирішувати задачі керування взаємопов'язаних та нелінійних об'єктів за математичними моделями локальних контурів як у лінійних системах. Дослідження векторної системи керування синхронним двигуном виконувалось при дії параметричних і координатних збурень, які пов'язані зі зміною активного опору обмотки статора, індуктивності обмотки статора по осях d і q, постійного магнітного потоку і моменту інерції. Запропоновані алгоритми керування забезпечують заданий астатизм за керуючою дією та відсутність статичних помилок при зміні навантаження.

Ключові слова: робастне керування, синхронна машина з постійними магнітами, кутова швидкість, алгоритми керування, параметричні збурення.

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РОБАСТНОЕ УПРАВЛЕНИЕ УГЛОВОЙ СКОРОСТЬЮ РОТОРА СИНХРОННОГО ДВИГАТЕЛЯ С ПОСТОЯННЫМИ МАГНИТАМИ

Предложено робастное регулирование угловой скорости ротора синхронной машины с постоянными магнитами в условиях параметрической неопределенности. Возмущения связаны с неполной информацией о структуре математической модели и с параметрами объекта управления. Вследствие чего в векторной системе управления наблюдаются деградация переходных процессов электрических и механических координат. Улучшение показателей качества переходных процессов в системе с каскадным управлением решается с помощью применения алгоритмов управления, которые основаны на концепции обратных задач динамики в сочетании с минимизацией функциональных локальных мгновенных значений энергии.

Ключевые слова: робастное управления, синхронная машина с постоянными магнитами, угловая скорость, алгоритмы управления, параметрические возмущения.

Introduction. Advantages of the surface mounted permanent magnet synchronous machine (SPMSM) are of their high torque to inertia and high performance [1]. Vector-controlled synchronous motors combine the simplicity of control inherent in DC motors, and the advantages of non-contact constructions of AC machines.

High dynamic performances of the system of the electric drive coordinates regulation are achieved at the expense by using field oriented control (FOC). The vector control strategy is based on the independence of the electromagnetic torque of the motor from the direct component of the stator vector i_{1d}. But the practical implementation of the vector control system of the synchronous motor from standard control algorithms requires complete information about the structure and parameters of the mathematical model. This is caused by the fact that the standard algorithms have a compensating type. The transfer functions of the controllers compensate the corresponding sections of the control object to obtain the required transfer functions of the control loop.

However, manufacturers usually provide insufficient information on the characteristics of the machine, which are needed to calculate the parameters of the replacement scheme. In addition, during operation, the synchronous motor is heated as the result changes the electric resistance of the windings of the stator [2].

Variations of parameters of the control object and of the coordinate perturbations lead to a deterioration in the quality of control, requiring application of robust or adaptive control algorithms [3-4], which have a weak sensitivity to parametric and coordinate uncertainty. But these automatic control methodologies increase the unwieldy of control systems as a result of the use of additional algorithms for parameterization, adaptation and compensation.

An analysis of modern methods of management in the conditions of uncertainty of the mathematical model of the object, shows that the above problems can be solved using the concept of inverse problems of dynamics combined with the minimization of the local instantaneous energy values functional [5-6].

The purpose of the paper is to improve the quality of vector control of the coordinates of cascade drives with SPMSM in the conditions of parametric and coordinate perturbations by developing control algorithms that provide robustness to parametric uncertainties and provide dynamic decomposition of the interconnected system.

The stated purpose has determined the following research tasks:

1. Develop of vector control system of the SPMSM with of control algorithms based on the concept of inverse problems of dynamics combined with the minimization of the local instantaneous energy values functional.

Fundamental concept. The concept of control is based on of the reciprocity of the direct Lyapunov method in the study of stability allows us to find control algorithms in which a closed-loop control loop has a predetermined Lyapunov function, which serves as the instantaneous value of energy [6].

The object of the local control loop is described by the following differential equation (1)

$$x^{(h)}=\sum_{k=0}^{g} b_k u^{(k)}-\sum_{i=0}^{(h-1)} a_i x^{(i)}, \tag{1}$$

where x – regulatory coordinate;

u – control function;

b_k , a_i – coefficients of the equation;

h , g – the order of the left and right sides of the differential equation, with $h > g$.

The reference quality control of the coordinate the close-loop is given by the ordinary differential equation

$$z^{(n)}+\sum_{i=0}^{(n-1)} \gamma_i z^{(i)}=\sum_{j=0}^{m}\beta_j x^{*(j)}, \tag{2}$$

where z – intermediate coordinate;

γ_i , β_j – coefficients that determine the nature and duration of the transition process;

x^* – coordinate reference;

n , m – the order of the left and right sides of the equation, with $n \geq m$.

The local functional is the degree of approach of the real control process to the reference one and represents the normalized, instantaneous value of the generalized energy

$$\begin{gathered} G(u)=0.5\left[z^{(n)}-x^{(h)}\right]^2; \\ \frac{dG(u)}{du}=-\frac{\partial f\left(u,x^{(i)}\right)}{\partial u}\left[z^{(n)}-x^{(h)}\right]. \end{gathered} \tag{3}$$

Minimization of the functional (3) is carried out according to the gradient law of the first order (4).

The condition of the convergence of the process minimization of the functional (4) is (5).

As result of minimization, the general control algorithm has the form (6).

$$\begin{gathered} \frac{du}{dt}=-\eta\frac{dG(u)}{\partial u}, \eta>0; \\ \frac{dG(u)}{du}=-\frac{\partial f\left(u,x^{(i)}\right)}{\partial u}\left[z^{(n)}-x^{(h)}\right]; \\ k=\eta\frac{\partial f\left(u,x^{(i)}\right)}{\partial u}=\text{const}>0. \end{gathered} \tag{4}$$

$$\begin{gathered} G(u)\rightarrow 0; \frac{dG(u)}{dt}=-k\frac{\partial f\left(u,x^{(i)}\right)}{\partial u}\left[z^{(n)}-x^{(h)}\right]^2; \\ \text{sign}(k)=\text{sign}\left(\frac{\partial f\left(u,x^{(i)}\right)}{\partial u}\right), t\rightarrow\infty. \end{gathered} \tag{5}$$

$$\begin{gathered} u=k\left[z^{(n-1)}-x^{(h-1)}\right]; \\ z^{(n-1)}=\sum_{j=0}^{(m-1)}\beta_j x^{*(j)}-\sum_{i=0}^{(n-2)}\gamma_i z\, x^{(i)}. \end{gathered} \tag{6}$$

Method and calculation. The method for the development of the algorithms to control the coordinates of the electric drive for FOC is presented. During the study standard limitations and assumptions were made in the mathematical models of the inverter and electric machine [1, 7]: the stator winding SPMSM produce sinusoidal magnetomotive force distribution in the air-gap (*d* and *q*-axis inductance $L_s = L_{sd} = L_{sq}$); the mechanical system is modelled as one-mass system; the slip frequency is zero because the motor always runs at synchronous speed ω_e ; the magnetizing current i_{sd}^* because the rotor flux is supplied the permanent magnets.

The mathematical model of the SPMSM in (*dq*) the rotor coordinate system, oriented by the i_f vector, can be described by the differential equations system (7)

$$\begin{gathered} \frac{di_{sd}}{dt}+\frac{R_s}{L_s}i_{sd}=\frac{u_{sd}}{L_s}-\omega_e i_{sq}=\frac{u_{sd}}{L_s}+P_{sd}; \\ \frac{di_{sq}}{dt}+\frac{R_s}{L_s}i_{sq}=\frac{u_{sq}}{L_s}-\omega_e i_{sd}-\frac{\omega_e\psi_{pm}}{L_s}=\frac{u_{sd}}{L_s}+P_{sq}; \\ \psi_{sd}=L_{sd}i_{sd}+\psi_{pm}=\psi_{pm}; \psi_{sq}=L_{sq}i_{sq}; \\ T_e=1.5\,p_n\psi_{pm}i_{sq}=k_{Te}i_{sq}; \\ \frac{d\omega_m}{dt}+\frac{B_m}{J_m}\omega_m=\frac{T_e}{J_m}-\frac{T_{load}+T_{cf}}{J_m}=\frac{T_e}{J_m}+P_\omega; \\ \omega_e=p_n\omega_m; \frac{d\theta_e}{dt}=\omega_e, \end{gathered} \tag{7}$$

where R_s – stator resistance; L_s – stator inductance;

ω_e , ω_m – electrical and mechanical angular rotor speeds;

p_n – pole couples number;

ψ_{pm} –permanent magnet flux;

J_m – the total inertia moment;

T_e , T_{load} , T_{cf} – electromagnetic torque, mechanical load torque and combined coulomb friction coefficient of the drive system;

B_m – combined viscous damping coefficient motor and load;

θ_e – electrical angular speed;

ψ_{sd} , ψ_{sq} – (*dq*) components of the stator flux linkage;

u_{sd} , u_{sq} – (*dq*) components of the stator voltage vector;

i_{sd} , i_{sq} – *d* and *q*-axis of the stator current;

P_{sd} , P_{sq} , P_{ω} – indeterminate that reflecting the coordinates interrelation.

At the expense of dynamic decomposition the coordinate perturbations should be limited at value

$$P_{sd} \le P_{sd}^0, P_{sq} \le P_{sq}^0, P_{\omega} \le P_{\omega}^0.$$

The control variables are sufficient to compensate perturbations

$$\frac{u_{sd}}{L_s} > P_{sd}^0, \frac{u_{sq}}{L_s} > P_{sq}^0, \frac{T_e}{J_m} > P_{\omega}^0.$$

The control algorithms of vector system have developed applying the proposed concept (1-7) have such structure:

▪ current controllers

$$\begin{aligned} u_{sd} &= k_i \left(\gamma_i \int \left(i_{sd}^* - i_{sd} \right) dt - i_{sd} \right); \\ u_{sq} &= k_i \left(\gamma_i \int \left(i_{sq}^* - i_{sq} \right) dt - i_{sq} \right), \end{aligned} \tag{8}$$

where $k_i = \eta_{is} L_s^{-1} = \text{const}$ – the gain coefficient of the current.

A control time of the current continuous transient t ≈ 3 / γ_i is defined by a coefficient $\gamma_i < 1/\tau_{\mu} + L_s^{-1} R_s$, which depends on small uncompensated time constant of the voltage source inverter.

▪ speed controller

$$i_{sq}^* = k_{\omega} \left(\gamma_{\omega} \int \left(\omega_m^* - \omega_m \right) dt + \beta_{\omega} \omega_m^* - \omega_m \right); \tag{9}$$

where $k_{\omega} = \eta_{\omega_m} J_m^{-1} = \text{const}$ – the gain coefficient of the speed.

Simulation results. The synchronous motor (Siemens SPMSM) of PROTEC 1FT6084-8SH7 type have the following the manufacturer parameter parameters [7]: P_r = 9.4 kW, I_r = 24.5 A, f_r = 300 Hz, ω_r = 471,2 rad/sec – rated power, current, frequency, mechanical angular speed; J_{SPMSM} = 0.0048 kg·m^2 – inertia constant; T_r = 20 kNm – rated torque; R_s = 0.18 Ohm – active resistance of the stator; L_{sd} = L_{sq} = 0.002 H – *d* and *q*-axis inductance; Ψ_{PM} = 0.123 Wb – permanent magnet flux-linkage; p_n = 4 – pole pairs.

Control algorithms have the following parameters: current controller i_s: γ_i = 700, k_i = 100; speed controller ω: γ_{ω} = 30, β_{ω} = 1, k_{ω} = 3.

The sequence the simulation execution is shown in Fig. 1.

Solid line Fig. 2 shows the graphs of the transient processes of the electric mechanical system coordinates in case of rated parameters of SPMSM and dotted line

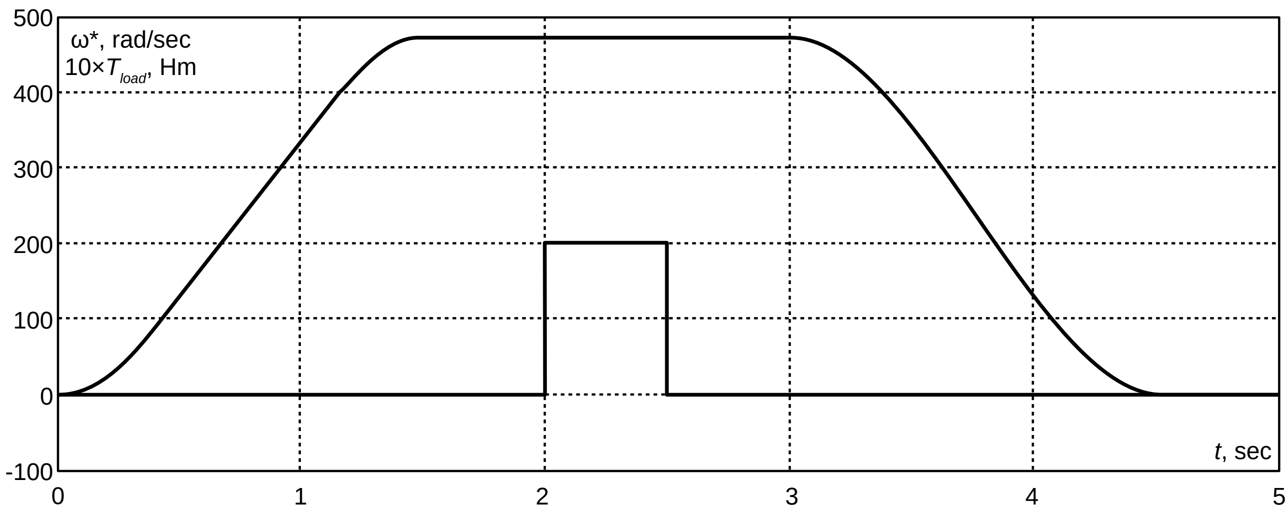

Fig. 1. Speed reference ω_m^* band torque profile T_{load}

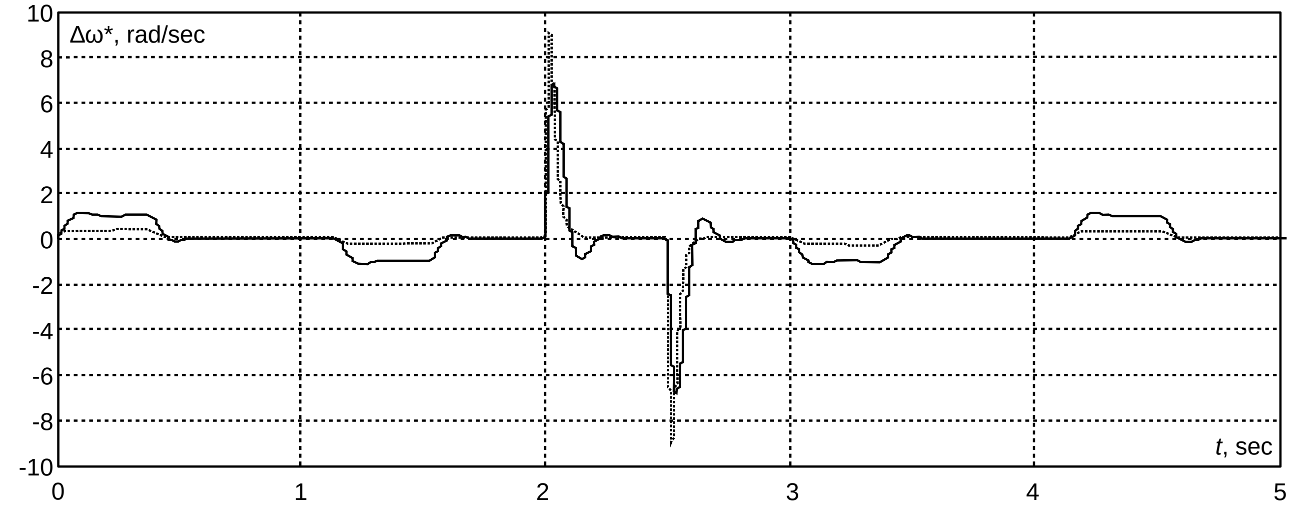

Fig. 2. Transients of the speed error $\Delta\omega_m^*$

shows the graph of the transient processes in case of the of action of parametric perturbations (active electric resistance of stator winding has increased to 0.19 Om, *d* and *q*-axis inductance has increased to 0.0022 H, permanent magnet flux-linkage has decreased to 0.012258 Wb, moment of inertia the installation has increased *d* to 0.0146 $kg \cdot m^2$).

Graphs of transient processes in the Fig. 2 show that the suggested system provides the no static error by of speed in both cases. The maximum speed dynamic error during the start-up period is decreased from 1.14 to 0.32 rad/s and is increased from 6.84 to 9.05 rad/s after a load applied. Compensation time decreased from 0.203 to 0.109 sec after a load applied.

Conclusions. The proposed method of the design of the control algorithms for the synchronous drive with of cascade control, based on the concept of inverse problems of dynamics, provides the high control quality under conditions of parametric uncertainty without additional algorithms for adaptation and compensation. The system provides the desirable astatism and absence of the static errors at the moment the load toque change.

As it is seen Fig. 2 the considerable degradation of transient processes of electrical mechanic coordinates is missing in the system during the parametric disturbance.

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Received 27.06.2019

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