S. M. Peresada, Dr. Sc. (Eng.), Prof.; V. M. Trandafilov

SUBSTANTIATION OF THE STRUCTURE OF THE OBSERVER, INVARIANT TO THE VARIATIONS OF ROTOR RESISTANCE

Problem of the synthesis and substantiation of the structure of the observer, invariant to the variations of the resistance of the observer rotor circle of rotor magnetic-flux linkage vector, that provides local exponential stability at limited variations of parametric perturbation, is considered.

Key words: *asynchronous motor, invariant observer, magnetic-flux linkage of the rotor, sliding mode, variations of rotor resistance.*

Introduction

Efficiency of field-oriented vector control systems of asynchronous motor (AM) greatly depends on the accuracy of the information, regarding the resistance of the rotor, which in AM with short-circuited rotor is not measured and can change 1.5 – 2 times during operation in loaded state. Variations of rotor resistance violate the conditions of field-orientation, that leads to worsening of the quality of mechanical coordinates regulation and increase of active losses in electric machine [1].

Compensation of the impact of rotor resistance variations can be performed on the basis of one of two approaches: adaptation or robustification. Rodustified algorithms, as a rule, provide simpler solutions than the adaptive ones, but they do not solve the problem of the accurate control of rotor magnetic-flux linkage vector by the module at variations or rotor circle resistance in the range of minor velocities [2], [3]. In [4] the method of synthesis of the algorithms of AM direct vector control is suggested, this method enables to provide invariance to variations of rotor circle resistance. Invariance of vector control algorithms is achieved as a result of invariant observer of the vector of rotor magnetic-flux linkage. Also, serviceability of the given method was experimentally proved in [4]. Proceeding from the results, obtained in [4], it is expedient to perform substantiation of the generalized structure of invariant observer, providing corresponding commentaries, regarding the choice of the type of its correcting signals. The solution of this problem is the aim of the given paper.

Observation problem set-up

Mathematical model of AM electric part, presented in the system of coordinate (d-q), that rotates with angular velocity ω_0, is set by the equations [1]

$$\begin{aligned} \dot{i}_d &= -\gamma_n i_d + \omega_0 i_q + \alpha_n \beta \psi_d + \beta\omega\psi_q + u_d/\sigma + \Delta\alpha\beta(\psi_d - L_m i_d), \\ \dot{i}_q &= -\gamma_n i_q - \omega_0 i_d + \alpha_n \beta \psi_q - \beta\omega\psi_d + u_q/\sigma + \Delta\alpha\beta(\psi_q - L_m i_q), \end{aligned} \qquad (1)$$

$$\begin{aligned} \dot{\psi}_d &= -\alpha_n \psi_d + (\omega_0 - \omega)\psi_q + \alpha_n L_m i_d - \Delta\alpha(\psi_d - L_m i_d), \\ \dot{\psi}_q &= -\alpha_n \psi_q - (\omega_0 - \omega)\psi_d + \alpha_n L_m i_q - \Delta\alpha(\psi_q - L_m i_q), \end{aligned} \qquad (2)$$

where $(i_d, i_q)^T$ – vector of stator current, $(u_d, u_q)^T$ – vector of stator control voltage, $(\psi_d, \psi_q)^T$ – vector of rotor magnetic-flux linkage, ω – angular velocity of the rotor, ε_0 – angular position of coordinate system (d-q) relatively stationary coordinate system (a-b). Positive constants in (1), (2), connected with electric parameters of AM, are determined in the following way:

$$\alpha = \left(\frac{R_{2n}}{L_2} + \frac{\Delta R_2}{L_2}\right) = \alpha_n + \Delta\alpha > 0;\ \beta = \frac{L_m}{\sigma L_2};\ \gamma_n = \frac{R_1}{\sigma} + \alpha_n \beta L_m;\ \sigma = L_1 - \frac{L_m^2}{L_2},$$

where L_m – inductance of magnetized loop, R_1, L_1 – resistance and inductance of the stator, L_2 –

rotor inductance, $R_{2n}, \Delta R_2$ – nominal value and deviation of rotor resistance, so that $R_2 = R_{2n} + \Delta R_2 > 0$. Without loss of generality in (1), (2) one pair of poles is taken.

For vector of state $\mathbf{x} = (i_d, i_q, \psi_d, \psi_q)^T$ vector of evaluated variables equals $\hat{\mathbf{x}} = (\hat{i}_d, \hat{i}_q, |\hat{\psi}_2|, 0)^T$, $\hat{\psi}_d = |\hat{\psi}_2|$, $\hat{\psi}_q = 0$, and vector of evaluation errors – $\tilde{\mathbf{x}} = \mathbf{x} - \hat{\mathbf{x}} = (\tilde{i}_d, \tilde{i}_q, \tilde{\psi}_d, \tilde{\psi}_q)^T$, где $\tilde{\psi}_d = \psi_d - |\hat{\psi}_2|$, $\tilde{\psi}_q = \psi_q$. Let us assume that:

A.1. Voltages of the stator, currents of the stator and angular velocity are limited known functions, stator currents and angular velocity having limited derivatives of the first order.

A.2. All the parameters in (1), (2) are known and stable, except deviation ΔR_2, which is unknown, stable and limited.

In conditions of assumptions A. 1 and A. 2 it is necessary to synthesize the observer of the module and position of magnetic-flux linkage which provides:

O. 1. Asymptomatic evaluation of real module and the position of the vector of rotor magnetic-flux linkage, so that $\lim\limits_{t\to\infty}(\tilde{\psi}_d, \tilde{\psi}_q) = 0$.

O. 2. Invariance to variations of rotor resistance.

Synthesis of invariant observer

We will define the family of observers of the vector of AM rotor magnetic-flux linkage in the following form:

$$\begin{aligned} \dot{\hat{i}}_d &= -\gamma_n \hat{i}_d + \omega_0 \hat{i}_q + \alpha_n \beta |\hat{\psi}_2| + u_d / \sigma + v_{1d}, \\ \dot{\hat{i}}_q &= -\gamma_n \hat{i}_q - \omega_0 \hat{i}_d - \beta \omega |\hat{\psi}_2| + u_q / \sigma + v_{1q}, \end{aligned} \tag{3}$$

$$\begin{aligned} |\dot{\hat{\psi}}_2| &= -\alpha_n |\hat{\psi}_2| + \alpha_n L_m \hat{i}_d + v_{2d}, \\ \dot{\varepsilon}_0 &= \omega_0 = \omega + [\alpha_n L_m \hat{i}_q + v_{2q}] / |\hat{\psi}_2|, \ |\hat{\psi}_2| > 0, \end{aligned} \tag{4}$$

where $v_{1d}, v_{1q}, v_{2d}, v_{2q}$ – correcting signals, to be formed further.

It should be noted that general form of the observer (3), (4) corresponds to generalized Vergeze observer [5], represented in coordinate system (d-q).

Equation of the dynamic of evaluation errors from (1), (2) and (3), (4) will be written:

$$\begin{aligned} \dot{\tilde{i}}_d &= -\gamma_n \tilde{i}_d + \alpha_n \beta \tilde{\psi}_d + \beta \omega \tilde{\psi}_q + \Delta\alpha\beta(\psi_d - L_m i_d) - v_{1d}, \\ \dot{\tilde{i}}_q &= -\gamma_n \tilde{i}_q + \alpha_n \beta \tilde{\psi}_q - \beta \omega \tilde{\psi}_d + \Delta\alpha\beta(\psi_q - L_m i_q) - v_{1q}, \end{aligned} \tag{5}$$

$$\begin{aligned} \dot{\tilde{\psi}}_d &= -\alpha_n \tilde{\psi}_d + (\omega_0 - \omega)\tilde{\psi}_q + \alpha_n L_m \tilde{i}_d - \Delta\alpha(\psi_d - L_m i_d) - v_{2d}, \\ \dot{\tilde{\psi}}_q &= -\alpha_n \tilde{\psi}_q - (\omega_0 - \omega)\tilde{\psi}_d + \alpha_n L_m \tilde{i}_q - \Delta\alpha(\psi_q - L_m i_q) - v_{2q}. \end{aligned} \tag{6}$$

For further analysis of the system (5), (6) we will consider the properties of disturbance $(\psi_d - L_m i_d)$. We will take into account the properties, that emerge in the system of direct field-oriented control [5]. As a result of usage of proportional-integral (PI) regulator of evaluated flux $|\hat{\psi}_2|$, it will move to the set ψ^*. In its turn, after completion of magnetization process, that is at $\psi^* = const$, the set flux will be $\psi^* \cong L_m i_d^*$, and at sufficiently great values of PI current regulators coefficients by axis d, real current i_d will be equal the set current i_d^*. Then, we will obtain

$$\psi_d - L_m i_d = \tilde{\psi}_d + |\hat{\psi}_2| - L_m i_d \cong \tilde{\psi}_d + \psi^* - L_m i_d^* \cong \tilde{\psi}_d. \tag{7}$$

Taking into account (7), after transformations, the system (5), (6) will be written

$$\dot{\tilde{i}}_d = -\gamma_n \tilde{i}_d + \alpha\beta\tilde{\psi}_d + \beta\omega\tilde{\psi}_q - v_{1d},$$
$$\dot{\tilde{i}}_q = -\gamma_n \tilde{i}_q + \beta\left[\alpha\tilde{\psi}_q - \omega\,\tilde{\psi}_d - \Delta\alpha L_m i_q\right] - v_{1q}, \tag{8}$$

$$\dot{\tilde{\psi}}_d = -\alpha\tilde{\psi}_d + (\omega_0 - \omega)\tilde{\psi}_q + \alpha_n L_m \tilde{i}_d - v_{2d},$$
$$\dot{\tilde{\psi}}_q = -\omega_0\tilde{\psi}_d - \left[\alpha\tilde{\psi}_q - \omega\tilde{\psi}_d - \Delta\alpha L_m i_q\right] + \alpha_n L_m \tilde{i}_q - v_{2q}. \tag{9}$$

General form (8), (9) allows to make the following conclusions, regarding the choice of correcting signals of the observer. First, in the system (8), (9), unlike the system (5), (6) disturbance is present only in equations of errors dynamics $\tilde{i}_q$ and $\tilde{\psi}_q$. In such case, the expediency of correction signal introduction in the first equation of the subsystem (9) no longer arises, that is, we assume $v_{2d} = 0$. Secondly, it is easy to note, that the signal $(\alpha\tilde{\psi}_q - \omega\tilde{\psi}_d - \Delta\alpha L_m i_q)$ is a part of the equation of errors dynamics $\tilde{i}_q$ and $\tilde{\psi}_q$. This enables to perform its compensation in the equation of error dynamics $\tilde{\psi}_q$, as the value of this signal can be obtained , from the equation of error dynamics $\tilde{i}_q$, if we form v_{1q} in such a way the condition $\tilde{i}_q \equiv d\tilde{i}_q/dt \equiv 0$ be fulfilled in quasi-steady state mode. In simpler case, this can be achieved at the expense of sliding mode [6] at $v_{1q} = \delta sign(\tilde{i}_q)$, where $\delta > 0$ – is a parameter, value of which is responsible for sliding mode providing . Sliding mode in the equation of error dynamics $\tilde{i}_q$ emerges at $\delta > \max\{|\alpha\beta\tilde{\psi}_q - \beta\omega\tilde{\psi}_d - \Delta\alpha\beta L_m i_q|\}$. The condition $\tilde{i}_q \equiv d\tilde{i}_q/dt \equiv 0$ will be fulfilled in sliding mode during finite time. This condition reduces the order of the system and gives the possibility to obtain the equivalent control [6]:

$$v_{1q.eq} = \beta[\alpha\tilde{\psi}_q - \omega\tilde{\psi}_d - \Delta\alpha L_m i_q]. \tag{10}$$

Having chosen the correcting signal $v_{2q} = v_\varepsilon - v_{1q}/\beta$ and using instead of the signal v_{1q} its equivalent value (10), we obtain:

$$\dot{\tilde{i}}_d = -\gamma_n \tilde{i}_d + \alpha\beta\tilde{\psi}_d + \beta\omega\tilde{\psi}_q - v_{1d},$$
$$\dot{\tilde{\psi}}_d = -\alpha\tilde{\psi}_d + (\omega_0 - \omega)\tilde{\psi}_q + \alpha_n L_m \tilde{i}_d, \tag{11}$$
$$\dot{\tilde{\psi}}_q = -\omega_0\tilde{\psi}_d - v_\varepsilon.$$

In [4] it is shown that under condition of execution of the conditions of persisting excitation and choice of correcting signals of the type $v_{1d} = \mathrm{k}_{id1}\tilde{\mathrm{i}}_d$, $k_{id1} > 0$ and $v_\varepsilon = \tilde{i}_d(\omega_0 + \gamma_1\omega)/\beta$, $\gamma_1 = (R_1/\sigma + \mathrm{k}_{id1})/\alpha_n > 0$ the system (11) will be globally exponentially stable at $\Delta R_2 = 0$ and at variations $\Delta R_2 \neq 0$ it will be locally exponentially stable and invariant to these variations.

Remark 1. Analysis, based on physical properties of AM, shows that conditions of persisting excitation are fulfilled in all operation modes of AM, except direct current excitation, that is, at $\omega_0 = 0$.

Remark 2. Unlike the existing observers with sliding mode [2], which have breaking right parts in two equations of stator current vector components evaluation in the suggested observer, break control is used only in one equation of current evaluation by the axis q.

Conclusions

The structure of the observer of rotor magnetic-flux linkage vector with the properties of invariance to the variations of rotor circle resistance and local exponential stability is theoretically substantiated. Local exponential stability of the observer at limited variations of rotor resistance remains in all operation modes of AM, except direct current excitation, that is, in case of stationary field of the rotor. Serviceability of the synthesized observer is proved by the results of mathematical modeling (not presented in the paper), which with sufficient degree of accuracy coincide with corresponding results of experimental research, presented in [4].

REFERENCES

1. Пересада С. М. Векторное управление в асинхронном электроприводе: аналитический обзор / С. М. Пересада // Вестник Донецкого государственного технического университета. Серия: "Электротехника и энергетика". – 1999. – №4. – С. 1 – 23.

2. Пересада С. М. Метод синтеза и робастность наблюдателей потокосцепления асинхронного двигателя, работающих в скользящих режимах / С. М. Пересада, В. Н. Трандафилов // Електромеханічні і енергозберігаючі системи. Тематичний випуск «Проблеми автоматизованого електропривода. Теорія й практика» науково-виробничого журналу. – 2012. – № 3 (19). – С. 40 – 44.

3. Пересада С. М. Робастность алгоритмов косвенного векторного управления асинхронными двигателями к вариациям активного сопротивления ротора / С. М. Пересада, В. С. Бовкунович // Наукові праці Донецького національного технічного університету. – 2011. – № 11 (186). – С. 296 – 300.

4. Пересада С. М. Метод синтеза инвариантных к вариациям активного сопротивления ротора алгоритмов прямого векторного управления асинхронным двигателем / С. М. Пересада, В. Н. Трандафилов // Вісник Національного технічного університету «ХПІ». Збірник наукових праць. Серія: проблеми автоматизованого електроприводу. Теорія і практика. – 2013. – №36 (1009). – С. 59 – 63.

5. Пересада С. М. Обобщенный алгоритм прямого векторного управления асинхронным двигателем / С. М. Пересада, С. Н. Ковбаса // Технічна електродинаміка. – 2002. – № 4. – С. 17 – 22.

6. Utkin V. I. Sliding mode control in electromechanical systems. 2nd ed. / V. I. Utkin, J. Guldner, J. Shi // Boca Raton, London: CRC Press, Taylor & Francis, 2009. – 485 p.

Peresada Sergiy – Dr. Sc. (Eng.), Professor, Head of the Chair of Automation of Electromechanical Systems and Electric Drive, tel.: (044) 236-99-30, e-mail: peresada@i.com.ua;

Trandafilov Volodymyr – Post Graduate with the Department of Automation of Electromechanical Systems and Electric drive, tel.: (044) 406-83-56, e-mail: trandafilov_vn@mail.ru

National Technical University of Ukraine «Kyiv Polytechnic Institute».