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ANALYSIS OF METHODS OF INDUCTION MOTOR SENSORLESS VECTOR CONTROL USING ANISOTROPIC PROPERTIES

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Purpose. The article is dedicated to the analysis of the division methods for signals modulated by different anisotropic properties of an induction motor to implement its sensorless vector control. **Methodology.** Sensorless identification of angular velocity and flux linkage of induction motor suggests estimation of this values according to measured electrical state variables: current and voltage of stator windings. **Results.** Existing methods for dividing signals modulated by some anisotropic properties of the motor have been researched and some new solutions have been proposed as well. Using discrete-field modelling efficiency and accuracy of sensorless vector control system have been evaluated. **Originality.** Present sensorless evaluation methods for angular velocity and flux linkage based on high-frequency injection have been used, and new method that allows to increase the accuracy of defining non-measured state variables during the performance at low angular speed was proposed as well. **Practical value.** This research can be used in the future to develop frequency-controlled electric drives with wide range of control without using angular speed sensor on the motor shaft. Moreover, the main states of this theory can be used for development diagnostic stands of electromechanical equipment with alternative current motors. References 10, figures 7.

Key words: induction motor, vector control, anisotropy, current, filter.

АНАЛІЗ СПОСОБІВ БЕЗДАТЧИКОВОГО ВЕКТОРНОГО КЕРУВАННЯ АСИНХРОННИМИ ДВИГУНАМИ З ВИКОРИСТАННЯМ АНІЗОТРОПНИХ ВЛАСТИВОСТЕЙ

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Бездатчикове векторне керування, що передбачає визначення основних неелектричних змінних стану – кутової швидкості та потокозчеплення на основі виміряних величин напруг і струмів, є досить привабливим для широкої низки електроприводів промислових установок та технологічних комплексів. Існує два підходи до оцінювання кутової швидкості й потокозчеплення двигуна: з використанням ідеалізованої математичної моделі та з використанням анізотропних властивостей. Перший підхід передбачає використання параметрів схеми заміщення двигуна, тому, незважаючи на його простоту реалізації, не дозволяє отримати високі показники якості керування в широкому діапазоні зміни кутової швидкості, оскільки параметри двигуна змінюються під час його роботи, а при дуже низькій кутовій швидкості ідеалізована математична модель значно втрачає точність оцінювання. Тому в останній час інтенсивно розвиваються системи, що дозволяють оцінювати кутову швидкість і потокозчеплення двигуна на основі його анізотропних властивостей. До основних анізотропних властивостей належать: наявність дискретних роторних стержнів, насичення сталі машини, ексцентриситет ротора. Під їх впливом у статорному струмі машини з'являються частотні складові, виділення яких дозволяє визначити невимірювані змінні стану машини без використання параметрів схеми заміщення. За умови наявності однієї виділеної анізотропії отримання її просторової інформації досягається шляхом введення високочастотної тестової напруги до основної напруги, що живить двигун. Виконаний аналіз струмового відгуку на такий тестовий вплив показав, що складова прямої послідовності струмового сигналу не містить просторову інформацію щодо вісі анізотропії, в той час як складова зворотної послідовності у своїй фазі містить необхідні дані щодо положення наявної в машині анізотропії. Розглянуто існуючі та запропоновано нові способи розділення сигналів декількох анізотропій для підвищення точності системи бездатчикового векторного керування асинхронним двигуном при роботі на низьких кутових швидкостях.

Ключові слова: асинхронний двигун, векторне керування, анізотропія, струм, фільтр.

PROBLEM STATEMENT. Methods using basic mathematical model of induction motor during sensorless estimation consider it to be a linear object with define parameters. Practically these parameters are not always known and they also can change when the machine performs. Resistances of stator and rotor windings change considerably when the temperature of the machine changes. Besides, use of basic model of induction motor is only possible with sinusoidal distribution of the stator winding, constant value of air gap and similar properties of the iron core of the machine. All these assumptions don't work in a real machine.

Methods that are not based on the ideal model of the induction motor use its anisotropic properties that lead to occurrence of magnetic asymmetry in the air gap of the machine. The recent trends in sensorless vector control of the induction motor mean using injection of additional test signals for detection position of anisotropy of the machine. As a result, the motor currents have considerable distortions that lead to additional power losses, vibration and unwanted acoustic noise.

The magnetic properties in the induction motor are not similar in different directions of the air gap. They depend on the mechanical construction features of the stator and rotor and magnetic properties of the iron core of the machine. Thus, anisotropies can be classified into construction and physical ones. Simultaneously, these properties appear in different grade in every specific motor. The interaction between the mechanical anisotropy of the rotor and stator teeth leads to a local change of flux linkage in air gap of the machine and this influences on stator winding inductances depending on the rotor position. Thus, the stator winding change their own and mutual inductances and this change depends on the rotor position. Moreover, the magnetic field that occurs in the machine leads to iron core saturation in different directions.

EXPERIMENTAL PART AND RESULT OBTAINED. The magnetic anisotropy changes the inductances of the stator windings and mutual inductances. In most cases addition of all resulting own and mutual inductances in an equivalent matrix of inductances is enabled:

$$L_{ABC}=\begin{bmatrix} l_a & 0 & 0 \\ 0 & l_b & 0 \\ 0 & 0 & l_c \end{bmatrix}. \qquad (1)$$

The equivalent phase inductances can be written as

$$l_a = L - \Delta L\, cos\left(2\varphi_{dq'}\right); \qquad (2)$$

$$l_b = L - \Delta L\, cos\left(2\varphi_{dq'} + \frac{2}{3}\pi\right); \qquad (3)$$

$$l_c = L - \Delta L\, cos\left(2\varphi_{dq'} - \frac{2}{3}\pi\right). \qquad (4)$$

They consist of a constant component $L$and sinusoidal modulated componentΔL that depends on the anisotropic position. It is assumed that anisotropy creates a balanced three-phase modulation of resistance changing.

The three-phase induction motor model can be transformed into a two-phase model in *αβ*-axes. The transformation of the three-phase equivalent inductance in the static stator coordinate system gives a result that looks like (7):

$$A=\begin{bmatrix} 1 & cos\left(\frac{2}{3}\pi\right) & cos\left(\frac{4}{3}\pi\right) \\ 0 & sin\left(\frac{2}{3}\pi\right) & sin\left(\frac{4}{3}\pi\right) \end{bmatrix}; \qquad (5)$$

$$L_{\alpha\beta}=\frac{2}{3}A\begin{bmatrix} l_a & 0 & 0 \\ 0 & l_b & 0 \\ 0 & 0 & l_c \end{bmatrix}A^T; \qquad (6)$$

$$L_{\alpha\beta}=\begin{bmatrix} L-\frac{\Delta L}{2}cos\left(2\varphi_{dq'}\right) & -\frac{\Delta L}{2}sin\left(2\varphi_{dq'}\right) \\ -\frac{\Delta L}{2}sin\left(2\varphi_{dq'}\right) & L+\frac{\Delta L}{2}cos\left(2\varphi_{dq'}\right) \end{bmatrix}. \qquad (7)$$

The inductance matrix in *αβ*-axes that are stator static coordinate systems is described as an ellipse that rotates synchronously with the anisotropy, as shown in Fig. 1.

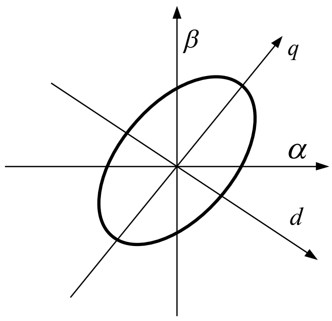

Figure 1 – Change of equivalent phase inductance in *αβ* axes

Transforming the inductance matrix in *dq* coordinate system that rotates synchronously, we obtain:

$$B=\begin{bmatrix} cos\left(\varphi_{dq}\right) & sin\left(\varphi_{dq}\right) \\ -sin\left(\varphi_{dq}\right) & cos\left(\varphi_{dq}\right) \end{bmatrix}; \qquad (8)$$

$$L_{dq}=B\begin{bmatrix} L-\frac{\Delta L}{2}cos\left(2\varphi_{dq}\right) & -\frac{\Delta L}{2}sin\left(2\varphi_{dq}\right) \\ -\frac{\Delta L}{2}sin\left(2\varphi_{dq}\right) & L-\frac{\Delta L}{2}cos\left(2\varphi_{dq}\right) \end{bmatrix}; \qquad (9)$$

$$L_{dq}=\begin{bmatrix} L-\frac{\Delta L}{2} & 0 \\ 0 & L+\frac{\Delta L}{2} \end{bmatrix}=\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}. \qquad (10)$$

It can be seen that the full inductive resistance of the machine can be described with two values L_d and L_q, that define an equivalent inductance value along the *d* axe connected with the anisotropy axe and the q axe that is perpendicular to it.

The anisotropy position is defined with the *dq* coordinate system mentioned above. The model mentioned above describes anisotropy as a change of leakage inductance that looks like an ideal ellipse. But practically this form is much more difficult. In a real motor there are a few anisotropies caused by iron core saturation of the machine and its mechanical construction. In a simple model it can be thought that the effects of different anisotropies can be described using the superposition principle. But in a real machine the interaction of several anisotropies is more difficult. Because of the fact that anisotropy can be caused by the mechanical construction of the machine or saturation, its axe corresponds to the mechanical anisotropy or the position of the electromagnetic saturation axe. Anisotropy rotates in *αβ* coordinate system with an angular speed that is multiply to the electrical or mechanical speed of the machine. As the speeds of the rotation of the rotor and field in the induction motor are different in the common case, the mechanical and magnetic anisotropies rotate with different speeds. In some cases, the mechanical anisotropy caused by the interaction of the stator slots and rotor bars and magnetic anisotropy can rotate in different directions. That's why the positions of the mechanical and magnetic anisotropies are not correlated. For sensorless control the presence of several anisotropies can be complicated. In the ideal case we consider only one elliptical modulation of inductance. As this assumption is not actual when a real motor is analyzed, unwanted component of the anisotropies should be compensated. Even if in most induction motors one strong signal of anisotropy can be filtered, the division of useful and unwanted signals of other anisotropies is a difficult problem. Using observers and harmonic compensation schemes need additional research. Besides, unwanted anisotropies can be compensated using a previously defined look-up table. In [1] it is proposed to use several synchronous filters to divide modulations of different anisotropies. An algorithm with memory that improves the quality of distorted curves at the expanse of saving the machine working data is used. The compensation of the distortions is used further for compensation of the effects cause by voltage-fed inverter nonlinearities.

For the field-oriented vector control of induction motor the information about the position of *dq* synchronous coordinate system oriented by the rotor flux linkage vector is needed. The position of the *dq* coordinate system can be found from the position of dq' anisotropic coordinate system. In [2–4] is proved that the angle between the *dq* coordinate system, that is oriented by rotor flux vector and anisotropic coordinate system depends on the load of the induction motor. The phase differencein [5, 7, 8] is compensated using a simple table, that is obtained during simple adjustment tests. Fig. 2 shows the definition of the *dq* coordinate system position that is used for vector control and dq' found with the help of the maximum and minimum values of the stator equivalent resistance.

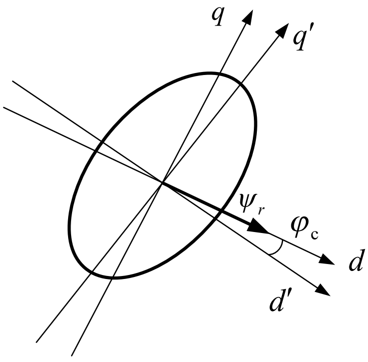

Figure 2 – Relation between the *dq'* coordinate system that is connected with anisotropy and *dq* coordinate system connected with rotor flux linkage vector

If the mechanical anisotropy that is not synchronous to *dq* coordinate system is used, for example, modulation caused by the rotor bars, the position of rotor flux vector cannot be identified directly. But the identification of the rotor position can be used further for estimation of the rotor flux linkage position as it is done in the indirect vector system orientation using speed sensor.

In this group of methods of sensorless position estimation and additional high-frequency signal of a defined frequency is injected in the main stator voltage that feeds the motor. During high-frequency supplying it is not possible to use ideal mathematical model of the induction motor.The frequency of a high-frequency signal (250 Hz–4 kHz), as a rule, is considerably higher than the frequency of the main voltage that feeds the motor.During the analysis of anisotropy of the machine only the current response caused by injected high-frequency signal is used. Therefore, the presence of back-emf can be neglected.

These methods use internal anisotropies of the machine that can be caused by its geometry, presence of rotor eccentricity, saturation of iron core of presence the discrete machine slots. Such anisotropies can be defined using test injections on the machine performance. Using its identification, it is possible to realize identification rotor position androtor flux linkage position without using equivalent scheme parameters of the machine and when performance is at very low speeds. This approach is based on the machine reaction on high-frequency voltage, that is injected in the main voltage, that feeds the motor using voltage-fed inverter. The main differences between these methods are in the form of high-frequency test signal and algorithms that analyzes response signal on test injection for identification rotor position or rotor flux linkage position.

At high frequency voltage drop on active resistance of stator winding is much less than voltage drop on reactance. Thus, the simplified equation (11) is used to describe the relationship between high-frequency voltage u_c and high-frequency current response i_c. The resulting high-frequency stator inductance is mainly determined by the leakage inductance of the winding. Stator winding inductance is different by axes d' and q' because of the anisotropy of the machine. Therefore, high-frequency stator inductance is described with a matrix, including modulation caused by the anisotropy of the machine. The equation (12) is the matrix of high-frequency stator inductance in a coordinate system dq'.

$$u_c = L_c \frac{di_c}{dt}; \tag{11}$$

$$L_{cdq'} = \begin{bmatrix} L_c - \dfrac{\Delta L_c}{2} & 0 \\ 0 & L_c + \dfrac{\Delta L_c}{2} \end{bmatrix} = \begin{bmatrix} L_{cd'} & 0 \\ 0 & L_{cq'} \end{bmatrix}. \tag{12}$$

The equations (13)–(16) show the obtaining of the voltage equation that describes the relationship between high-frequency voltage signal and resulting current response.

The equation of high-frequency voltage in dq' coordinate system:

$$\begin{bmatrix} u_{cd'} \\ u_{cq'} \end{bmatrix} = \begin{bmatrix} L_c - \dfrac{\Delta L_c}{2} & 0 \\ 0 & L_c + \dfrac{\Delta L_c}{2} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{cd'} \\ i_{cq'} \end{bmatrix}.. \tag{13}$$

Transforming the previous equation to the *αβ* static stator coordinate system, results in

$$\begin{bmatrix} u_{c\alpha} \\ u_{c\beta} \end{bmatrix} = \begin{bmatrix} cos\left(\varphi_{dq'}\right) & -sin\left(\varphi_{dq'}\right) \\ sin\left(\varphi_{dq'}\right) & cos\left(\varphi_{dq'}\right) \end{bmatrix} \begin{bmatrix} L_c - \frac{\Delta L_c}{2} & 0 \\ 0 & L_c + \frac{\Delta L_c}{2} \end{bmatrix} \times$$

$$\times \begin{bmatrix} cos\left(\varphi_{dq'}\right) & sin\left(\varphi_{dq'}\right) \\ -sin\left(\varphi_{dq'}\right) & cos\left(\varphi_{dq'}\right) \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}. \qquad (14)$$

The resulting expression for voltage in coordinate system $\alpha\beta$ is

$$\begin{bmatrix} u_{c\alpha} \\ u_{c\beta} \end{bmatrix} = \begin{bmatrix} L_c - \frac{\Delta L_c}{2} cos\left(2\varphi_{dq'}\right) & -\frac{\Delta L_c}{2} sin\left(2\varphi_{dq'}\right) \\ -\frac{\Delta L_c}{2} sin\left(2\varphi_{dq'}\right) & L_c + \frac{\Delta L_c}{2} cos\left(2\varphi_{dq'}\right) \end{bmatrix}. \qquad (15)$$

Current response on high-frequency voltage injection can be written this way:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{L_c^2 + \left(\frac{\Delta L_c}{2}\right)^2} \times$$

$$\times \begin{bmatrix} L_c + \frac{\Delta L_c}{2} cos\left(2\varphi_{dq'}\right) & \frac{\Delta L_c}{2} sin\left(2\varphi_{dq'}\right) \\ \frac{\Delta L_c}{2} sin\left(2\varphi_{dq'}\right) & L_c - \frac{\Delta L_c}{2} cos\left(2\varphi_{dq'}\right) \end{bmatrix} \int \begin{bmatrix} u_{c\alpha} \\ u_{c\beta} \end{bmatrix} dt. \qquad (16)$$

As it can be seen, the high-frequency current signal is modulated by position of anisotropic coordinate system dq'. The current response to high-frequency voltage with contains magnitude creates modulation $sin\left(2\varphi_{dq'}\right)$ and $cos\left(2\varphi_{dq'}\right)$ in the $\alpha\beta$ coordinate system.

The most popular method used to estimate the rotor position of the induction motor using magnetic anisotropy is the method that uses high-frequency injection voltage to main voltage that feeds the motor. Thus, a high-frequency (250–4000 Hz) vector with constant magnitude is injected to the main voltage vector. This vector $u_{c\alpha\beta}$ is described by the equation

$$u_{c\alpha\beta} = U_c e^{j\omega_c t}. \qquad (17)$$

The current vector caused by the action voltage vector $u_{c\alpha\beta}$ is added to the main current vector. This high-frequency current response is filtered by means of a band-pass filter from the measured current and then demodulated for restore position of rotor position of rotor flux linkage position. Those measured current values used as feedback signals for current control loop of the vector control system after filtering high-frequency component using a low-pass or a band-pass filter. Fig. 4 shows the block diagram of vector control with the injection of a high-frequency voltage vector.

As the magnitude of the high-frequency voltage injected into the main voltage feeding the motor is a constant value, the presence of anisotropy of the machine causes a correspondent current response. In the presence of one anisotropy the trajectory of rotation current response vector will be similar to the elliptic one, moreover one of the ellipse axes will coincide with anisotropic axe as shown in Fig. 3. The high-frequency voltage vector, that is injected, rotates along the circular trajectory with angular frequency ω_c. As this angular velocity is rather high compared with rated stator frequency of the motor feeding, the character of the load will be inductive and the phase difference between the current vector and the voltage vector will be about 90^0.

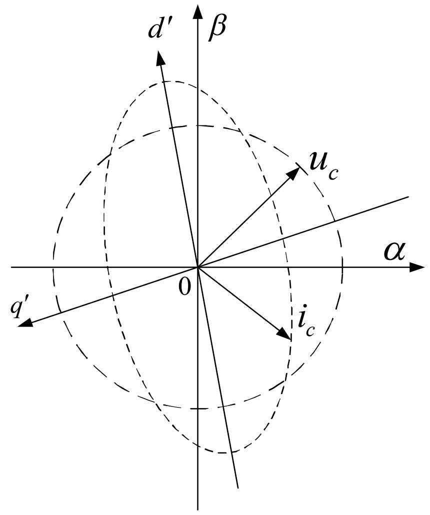

Figure 3 – Current response to high-frequency voltage injection

If the component of the active resistance of the motor that is not considerable because of the great increase of the inductive component at high frequency of the feeding voltage is neglected, the current response can be described with the following equation:

$$i_{c\alpha\beta} = L_{c\alpha\beta}^{-1} \int \left(U_c e^{j\omega_c t}\right) dt; \qquad (18)$$

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{\frac{U_c}{\omega_c}}{L_c^2 + \left(\frac{\Delta L}{2}\right)^2} \begin{bmatrix} L_c + \frac{\Delta L_c}{2} cos\left(2\theta_{dq'}\right) & \frac{\Delta L_c}{2} sin\left(2\theta_{dq'}\right) \\ \frac{\Delta L_c}{2} sin\left(2\theta_{dq'}\right) & L_c - \frac{\Delta L_c}{2} cos\left(2\theta_{dq'}\right) \end{bmatrix}; \qquad (19)$$

$$i_{c\alpha\beta} = \frac{\frac{U_c}{\omega_c} L_c}{L_c^2 + \left(\frac{\Delta L}{2}\right)^2} e^{j\left(\omega_c t - \frac{\pi}{2}\right)} + \frac{\frac{U_c}{\omega_c} \frac{\Delta L}{2}}{L_c^2 + \left(\frac{\Delta L}{2}\right)^2} e^{-j\left(\omega_c t - 2\theta_{dq'} - \frac{\pi}{2}\right)}. \qquad (20)$$

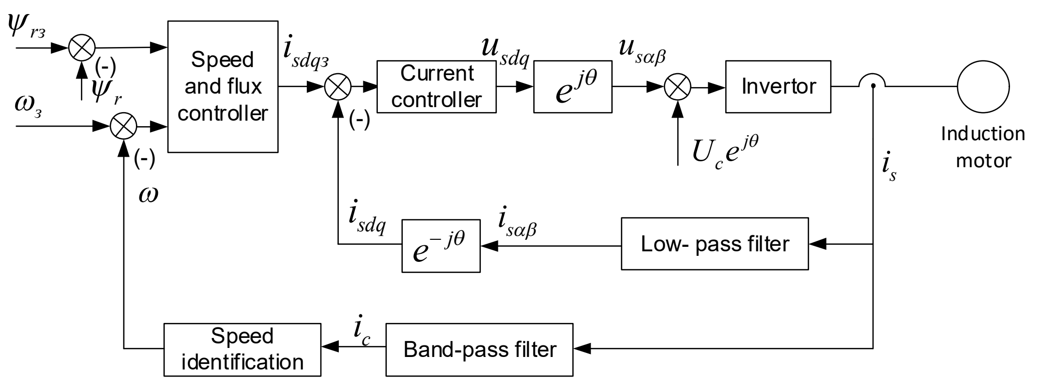

Figure 4 – Structure of the vector control system with the injection high-frequency voltage vector

$$i_{c\alpha\beta} = I_{cp} e^{j\left(\omega_c t - \frac{\pi}{2}\right)} + I_{cn} e^{-j\left(\omega_c t - 2\theta_{dq'} - \frac{\pi}{2}\right)}, \qquad (21)$$

where I_{cp}, I_{cn} are theamplitudes of positive and negative current sequences.

$$I_{cp} = \frac{\frac{U_c}{\omega_c} L_c}{L_c^2 + \left(\frac{\Delta L}{2}\right)^2};$$

$$I_{cn} = \frac{\frac{U_c}{\omega_c} \frac{\Delta L}{2}}{L_c^2 + \left(\frac{\Delta L}{2}\right)^2}.$$

From the equation (21) it can be seen, that current response to high-frequency voltage injected to the main one, consists of two rotating vectors. One component rotates with the same frequency as the vector of injected voltage and in the same direction. And the other component rotates in opposite direction to the voltage vector. Thus, I_{cp} is a component of positive sequence and it doesn't contain any information about the allocation of the anisotropy axe and I_{cn} is a component of a negative sequence which has position information in its phase and it is proportional to inductance modulated by anisotropy.

Thus, before defining the position information about the anisotropy axe the positive sequence component in current response of the system should be filtered. As the vector of positive and negative sequences components rotate in opposite directions, one of the variants how to eliminate positive sequence component is using high-frequency filter in the coordinate system rotating synchronously with the positive sequence component of carrying test signal. Fig. 5 shows the structure of the high-frequency filter in the synchronous coordinate system. This system can be implemented as an equivalent system in the static stator coordinate system.

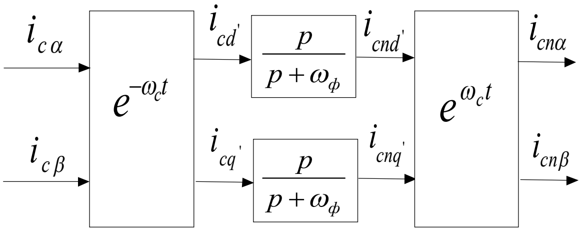

Figure 5 – The structure of the subsystem
for extraction of the negative sequence components
using a high-frequency filter

Filters using synchronous coordinate system and their equivalent systems using static stator coordinate system can be used for improving the filtration of main stator current harmonic; it can be realized with high-frequency or band-pass filter in the static coordinate system. After the elimination of the main harmonic as well as positive sequence component of carrying signal in stator current using position observer position information that is in the phase of the current negative sequence component can be obtained. Fig. 6 shows the structure scheme of the position observer that can be used for monitoring the rotor position in case the machine has anisotropy rotating synchronously with the rotor.

The error signal of this close-loop observer is formed by vector product between negative sequence current component obtained by measurement and indent vector of negative sequence signal formed from the current value of the estimated rotor position angle. As the information about the allocation of anisotropy is contained in the phase of the negative sequence signal, during the estimation of current vector of this sequence for the current value of state variable this vector is assumed as an indent vector.

Theamplitudeofthemeasuredvalueofthenegativesequencecurrentvectorand its estimation influent only on the scale of phase error obtained after vector product. As the estimation of the current vector is assumed to be the indent vector, it is unnecessary to use the parameters of equivalent motor scheme in the observer structure.

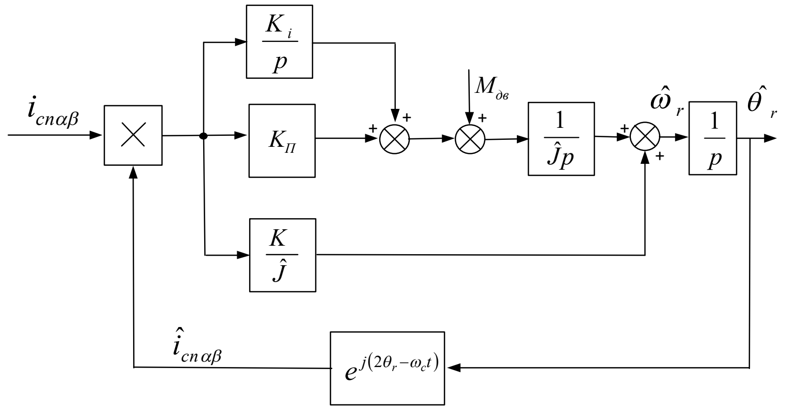

Figure 6 – The structure of the rotor position observer for an electric machine with one strong anisotropy rotating synchronously with the motor rotor

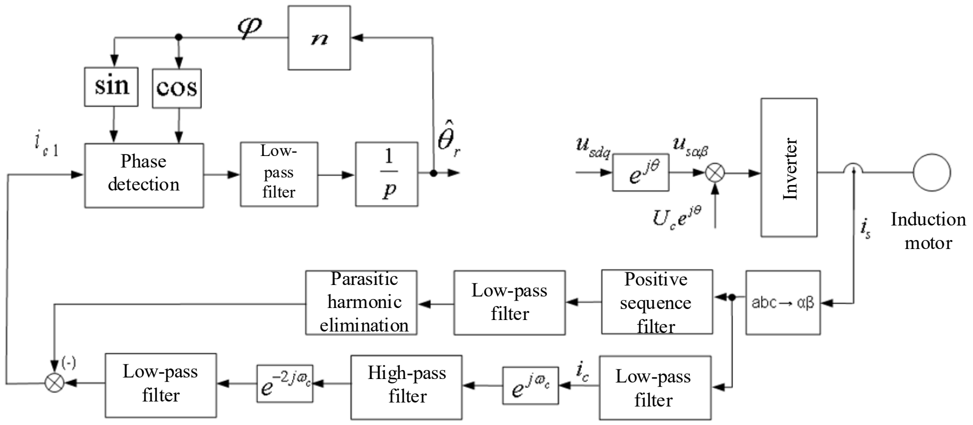

Figure 7 – The structure of sensorless vector control system of induction motor with dividing signals of different anisotropies

This method is relevant to the conditions if in the electric machine is one strong sinusoidal-distributed anisotropy. Nonlinear properties of machine steel, discrete winding and other constructive features lead to the appearance of secondary and parasitic anisotropies. The induction motors with more than one pronounced anisotropy or non-sinusoidal distributed anisotropy can be described using the principle of superposition, as the sum of individual anisotropies, decomposed in Fourier series. With the symmetrical three-phase power supply motor current can be written as

$$i_{c\alpha\beta} = I_{cp} e^{j\left(\omega_c t-\frac{\pi}{2}\right)} + \sum_{i=1}^{n} I_{cni} e^{-j\left(\omega_c t-2k_i\theta_{idq'}-\frac{\pi}{2}+\varphi_i\right)}, \quad (22)$$

where i_{cni} is magnitude of *i*-th component of negative current sequence; k_i is number of harmonic of anisotropy, that creates *i*-th component; $\theta_{idq'}$ is angular position of anisotropy that creates *i*-th component; φ_i is initial phase difference *i*-th component in relation to the reference system.

The amplitudes of positive and negative sequence component can be written as

$$I_{cp} = \frac{\sum L_c}{\sum L_c^2 + \sum\left(\frac{\Delta L_{ci}}{2}\right)^2} \frac{U_c}{\omega_c};$$

$$I_{cn} = \frac{\sum \frac{\Delta L_{ci}}{2}}{\sum L_c^2 + \sum\left(\frac{\Delta L_{ci}}{2}\right)^2} \frac{U_c}{\omega_c},$$

where ΔL_{ci} is inductance modulated by *i*-th anisotropy.

Fig. 7 shows a block diagram of sensorless identification of rotor position. Determination the position of anisotropy is done using phase-detector, loop filter and controlled generator. The implementation of this system allow to increase the accuracy of deleting signals of parasitic anisotropies.

CONCLUSIONS. Induction motor has some anisotropic properties that can be used for sensorless estimation of angular speed and flux linkage.

The advantages of such systems are lack of sensitivity to changes in the parameters of the equivalent scheme. The detection of the anisotropy axis position is possible if test vectors are applied to the stator voltage or the high-frequency signal. The current response contains information about the allocation of anisotropy. The method for dividing signals of different anisotropies has been introduced. It allows to improve present frequency-controlled drive and increased their accuracy at low angular speeds.

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АНАЛИЗ СПОСОБОВ БЕЗДАТЧИКОВОГО ВЕКТОРНОГО УПРАВЛЕНИЯ АСИНХРОННЫМ ДВИГАТЕЛЕМ С ИСПОЛЬЗОВАНИЕМ ЕГО АНИЗОТРОПНЫХ СВОЙСТВ

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Бездатчиковое векторное управление, предусматривающее определение основных неэлектрических переменных состояния – угловой скорости и потокосцепления на основе измеренных величин напряжений и токов, является весьма привлекательным для широкого ряда электроприводов промышленных установок и технологических комплексов. Существует два подхода к оценке угловой скорости и потокосцепления двигателя: с использованием идеализированной математической модели и с использованием анизотропных свойств. Первый подход предполагает использование параметров схемы замещения двигателя, поэтому, несмотря на простоту его реализации, не позволяет получить высокие показатели качества управления в широком диапазоне изменения угловой скорости, поскольку параметры двигателя изменяются во время его работы, а при очень низкой угловой скорости идеализированная математическая модель значительно теряет точность оценки. Поэтому в последнее время интенсивно развиваются системы, позволяющие оценить угловую скорость и потокосцепление двигателя на основе его анизотропных свойств. К основным анизотропным свойствам относятся: наличие дискретных роторных стержней, насыщение стали машины, эксцентриситет ротора. Под их влиянием в статорных токах машины появляются частотные составляющие, выделение которых позволяет определить неизмеряемые переменные состояния без использования параметров схемы замещения двигателя. При наличии одной выделенной анизотропии получение ее пространственной информации достигается путем введения высокочастотного тестового напряжения в основное напряжение, которое питает двигатель. Выполненный анализ токового отклика на такое тестовое влияние показал, что составляющая прямой последовательности токового сигнала не содержит пространственную информацию об оси анизотропии, в то время как составляющая обратной последовательности содержит необходимые данные о положении имеющейся в машине анизотропии. Рассмотрены существующие и предложены новые способы разделения сигналов нескольких анизотропий для повышения точности системы бездатчикового векторного управления асинхронным двигателем при работе на низких угловых скоростях.

Ключевые слова: асинхронный двигатель, векторное управление, анизотропия, ток, фильтр.

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