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SENSORLESS CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

In the paper a problem of speed and position estimation in sensorless control of PMSM drive is discussed. A presented concept is a modification of solution based on detecting back EMF, induced in stator windings. A new structure of adaptive observer with proportional-integral function of corrector was introduced. Both simulation and experimental results show good properties of proposed observer structure.

Introduction. Permanent Magnet Synchronous Motors (PMSM) are taken into account in many industrial drive applications due to their high power factor, high torque density, high efficiency and small size. PMSM control requires position sensor like encoder or resolver. Such sensors increase the overall cost of the drive system and decrease its reliability and noise immunity and this seems to be one of the main drawbacks hindering wider application of PMSMs.

Elimination of position sensor is an open question for researchers and is a subject of investigations in many scientific centers. Several approaches to this problem are reported in literature, which base on states observer [4], extended Kalman filters [3], sliding-mode observer [2, 7, 10], or some new method basing on motor saliency [6]. State observers and Kalman filters base on complex motor model with electrical and mechanical equations. Proper accuracy requires complex computational operations, what always creates some problems in real time realization. Some new approaches apply the motor magnetic saliency and detect the rotor position by measurement of the phase inductances. These methods give proper solution for small speed as well as for standstill operation but requirements according hardware and software are high.

A new more general structure of observer was proposed in the paper. The observer structure bases on a modified concept of detecting back EMF. Into this observer structure a complex corrector function different than traditional proportional one was introduced. The structure includes instead of proportional correction of Luenberger observer a corrector with proportional-integral function. Nonlinear character of observer, shown in the paper, required adaptive change of observer corrector settings. Such observer structure was implemented on DSP microprocessor and experimentally verified.

Description of observer structure. Assuming ordinary simplified assumptions, the mathematical model of PMSM in $\alpha\beta$ orthogonal coordinates can be described as follows [3, 7]:

$$\begin{aligned}
\frac{di_\alpha}{dt} &= -\frac{R}{L} i_\alpha - \frac{1}{L} e_\alpha + \frac{1}{L} v_\alpha \\
\frac{di_\beta}{dt} &= -\frac{R}{L} i_\beta - \frac{1}{L} e_\beta + \frac{1}{L} v_\beta \\
\frac{d\omega}{dt} &= \frac{1}{J}\left(\psi_\beta i_\alpha - \psi_\alpha i_\beta - T_L\right) \\
\frac{d\theta}{dt} &= \omega
\end{aligned} \tag{1}$$

where v_α , v_β , i_α , i_β , ψ_α , ψ_β e_α , e_β are components of stator voltage, stator current, stator flux and induced back EMF in $\alpha\beta$ coordinates; R and L are the stator windings resistance and inductance, ω and Θ are rotor speed and position, J is moment of inertia and T_L is a load torque.

According to the method presented in [3, 7] it is convenient to use only first two electrical equations, in which back EMF components are considered as disturbances. In such a case extended state formula can be written in matrix form as [7]:

$$\dot{x}_E = A_E x_E + B_E u \ , \qquad y = C_E x_E$$

$$\text{where:} \tag{2}$$

$$x_E = \left[i_\alpha, i_\beta, e_\alpha, e_\beta \right]^T, \quad y = \left[i_\alpha, i_\beta \right]^T, \quad u = \left[v_\alpha, v_\beta \right]^T$$

For presented system it is possible to use ordinary Luenberger observer [4] with correction based on error between measured and calculated currents value. In [3, 7] it was assumed for simplicity that derivative of disturbances is equal zero. Such a simplified formula does not show a nonlinear character of observer structure. In the paper a modified mathematical description is proposed. On the base of well known formulas for calculation of back EMF (3) and (4)

$$\sin\hat{\Theta} = -\frac{\hat{e}_\alpha}{|\hat{e}|} \qquad \cos\hat{\Theta} = \frac{\hat{e}_\beta}{|\hat{e}|} \tag{3}$$

where

$$|\hat{e}| = \sqrt{\hat{e}_\alpha^2 + \hat{e}_\beta^2} \qquad |\hat{\omega}| = \frac{|\hat{e}|}{k_e} \tag{4}$$

it is possible to calculate derivative of EMF [7]:

$$\begin{aligned} \frac{de_\alpha}{dt} &= e_\alpha \cdot \frac{1}{\omega} \cdot \frac{d\omega}{dt} - e_\beta \cdot \omega \\ \frac{de_\beta}{dt} &= e_\beta \cdot \frac{1}{\omega} \cdot \frac{d\omega}{dt} + e_\alpha \cdot \omega \end{aligned} \tag{5}$$

After proper transformations one can obtain modified extended state formula for observer:

$$\begin{aligned} \frac{d\hat{i}_\alpha}{dt} &= -\frac{R}{L}\hat{i}_\alpha - \frac{1}{L}\hat{e}_\alpha + \frac{1}{L}v_\alpha + K_{i\alpha}\left(\hat{i}_\alpha - i_\alpha\right) \\ \frac{d\hat{i}_\beta}{dt} &= -\frac{R}{L}\hat{i}_\beta - \frac{1}{L}\hat{e}_\beta + \frac{1}{L}v_\beta + K_{i\beta}\left(\hat{i}_\beta - i_\beta\right) \\ \frac{d\hat{e}_\alpha}{dt} &= \hat{e}_\alpha \cdot \frac{1}{\hat{\omega}} \cdot \left(\frac{\Delta\hat{\omega}}{T_S}\right) - \hat{e}_\beta \cdot \hat{\omega} + K_{e\alpha}\left(\hat{i}_\alpha - i_\alpha\right) \\ \frac{d\hat{e}_\beta}{dt} &= \hat{e}_\beta \cdot \frac{1}{\hat{\omega}} \cdot \left(\frac{\Delta\hat{\omega}}{T_S}\right) + \hat{e}_\alpha \cdot \hat{\omega} + K_{e\beta}\left(\hat{i}_\beta - i_\beta\right) \end{aligned} \tag{6}$$

or in matrix form

$$\dot{\hat{\mathbf{x}}}_E = \mathbf{A}_E \hat{\mathbf{x}}_E + \mathbf{B}_E \mathbf{u} + \mathbf{K}\left[\Delta \mathbf{i}\right] \tag{7}$$

In the formula (6) is visible that right sides of two equations for EMF derivative are nonlinear functions of estimated speed and its derivative ($\Delta\omega/T_S$ in discreet form). This fact has significant influence on observer stability and synthesis procedure of observer corrector.

A correction of ordinary Luenberger observer bases on multiplication of an observer error by constant coefficients – matrix **K** in (7), and can be called a proportional correction. The authors proved in their earlier works [8, 9] that a significant improvement of observer operation can be gained due to introduction of corrector with more complex function than a proportional one. In such observer the corrector operation is of proportional-integral type. This leads to a new general concept of observer, which formula can be written as:

$$\dot{\hat{\mathbf{x}}}_{\mathrm{E}} = \mathbf{A}_{\mathrm{E}}\hat{\mathbf{x}}_{\mathrm{E}} + \mathbf{B}_{\mathrm{E}}\mathbf{u} + \mathbf{F}[\Delta\mathbf{i}] \tag{8}$$

where **F**[Δ**i**] is a corrector function of observer.

Fig. 1 shows a block diagram of general observer structure. Inner structure of observer depends on function **F**[Δ**i**].

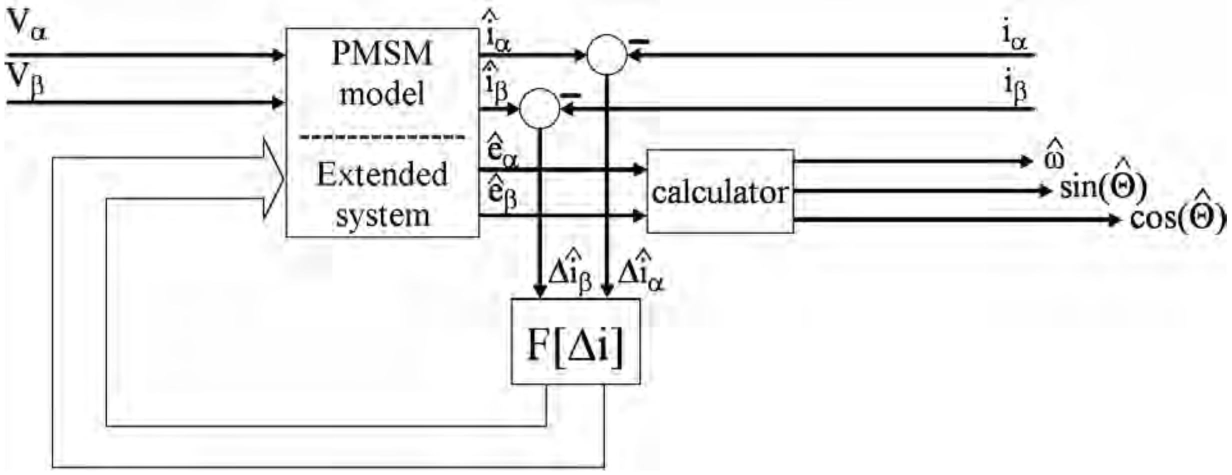

Fig. 1. General structure of observer

On the base of many simulation tests a proportional-double integral (PII^2) corrector structure was proposed [8, 9]:

$$\mathbf{F}_2[\Delta\mathbf{i}] = \mathbf{K}_{\mathrm{p}}[\Delta\mathbf{i}] + \mathbf{K}_{\mathrm{i}}\int[\Delta\mathbf{i}]\,\mathrm{dt} + \mathbf{K}_{\mathrm{ii}}\int\left[\int[\Delta\mathbf{i}]\,\mathrm{dt}\right]\mathrm{dt} \tag{9}$$

where the matrixes **K**$_{\mathrm{p}}$, **K**$_{\mathrm{i}}$ and **K**$_{\mathrm{ii}}$ are:

$$\mathbf{K}_p = \begin{bmatrix} K_{p11} & 0 \\ 0 & K_{p22} \\ K_{p31} & 0 \\ 0 & K_{p42} \end{bmatrix} \quad \mathbf{K}_i = \begin{bmatrix} K_{i11} & 0 \\ 0 & K_{i22} \\ K_{i31} & 0 \\ 0 & K_{i42} \end{bmatrix} \quad \mathbf{K}_{ii} = \begin{bmatrix} K_{ii11} & 0 \\ 0 & K_{ii22} \\ K_{ii31} & 0 \\ 0 & K_{ii42} \end{bmatrix} \tag{10}$$

Integral and double integral component of observer corrector leads to astatic character of observation (estimation) during transient process with fast change of currents. Estimation of back EMF signals by means of observer creates possibility to calculate rotor speed and position on the base of formulas (3) and (4).

Adaptive procedure of a corrector parameter selection. The synthesis of the observer corrector consists in selecting the coefficients values of the matrixes **K**$_{\mathrm{p}}$, **K**$_{\mathrm{i}}$, **K**$_{\mathrm{ii}}$ in (9). Proper selection is of great importance for the observer stability, static estimation accuracy and good dynamic behaviour.

Yet, the synthesis poses some difficulties due to the non-stationary character of the observer. The number of the selected coefficients equals 12, but fortunately the mathematical model of the motor assumed in the observer has a symmetrical structure with reference to the axis $\alpha\beta$. Due to this symmetry the coefficients of the observer corrector have equal values on both axes, which reduces the number of the selected values to 6. The process of synthesis was optimized by means of the random weight change (RWC) procedure [1]. This procedure is fast and robust against the local minimum of the optimised criterion. The criterion of observer optimization is formulated as:

$$Q = \int_{t_1}^{t_1+\tau} e_{\Theta}^{2}(t)\,dt + \Delta e_{\Theta}(\tau) \tag{11}$$

where e_{Θ} is the position estimation error, Δe_{Θ} is the range of the error value changes of the estimated position during the transient process, t_1 and $t_1 + \tau$ are the time boundaries of the integral calculation.

The optimization procedure was performed "*off-line*" by simulating a transient process. The optimization procedure was repeated for different points of operation, which were determined by the steady state speed value. At each step of optimization the transient process of the step response to speed reference changes in the selected point of operation was simulated, and during this process the value of the criterion (16) was calculated in the time range from t_1 to $t_1 + \tau$. According to the RWC procedure a new set of corrector settings is randomly selected at each step but only the set which gives estimation improvement (smaller criterion value) is stored. As a result of such "*off-line*" optimization a set of optimal values of corrector coefficients is found for each point of operation as shown in fig. 2.

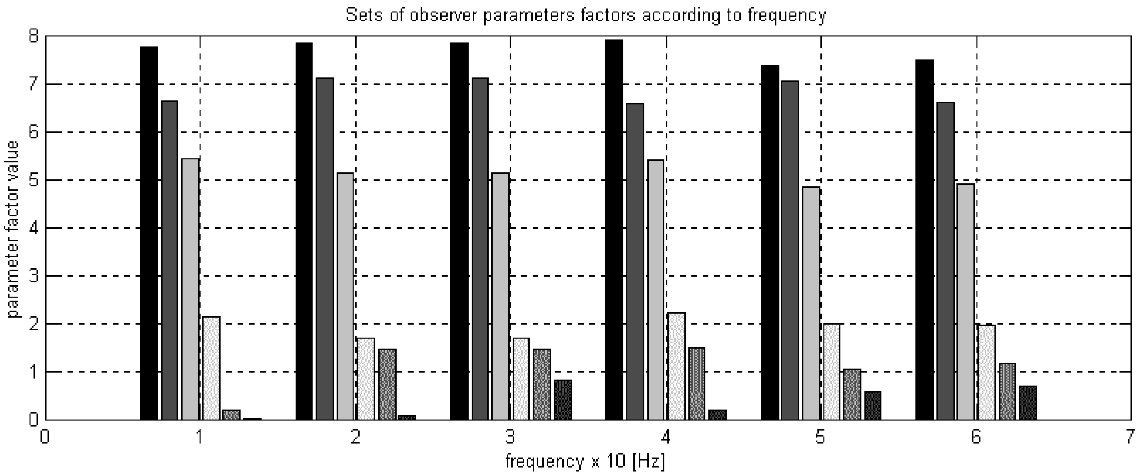

Fig. 2. The optimal values of observer corrector coefficients

The diagram gives only discreet optimal values as a result of finite number of optimization tests. In such a case some interpolation of coefficients values is needed during observer calculation in real time. In the paper fuzzy logic base interpolator was used with six membership input functions determined in the range of speed control. These membership functions suit speed steady state values for which optimization process was done. Input membership functions are shown in fig. 3. For each step of observer calculations the set of optimal settings is determined by applying Mamdani implication method and defuzzification procedure of high method.

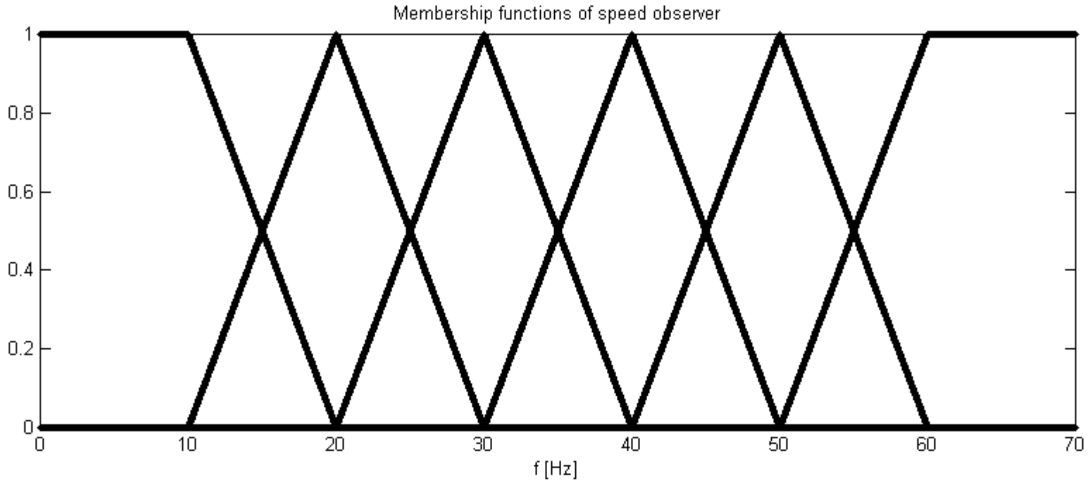

Fig. 3. Input membership functions

Results of experimental investigations. The laboratory stand consists of PMSM motor supplied from PWM inverter and controlled by means of microprocessor system with floating point DSP of SHARC family. The control system was equipped with current and voltage sensors (LEM) and resolver. As a result of simulation test the observer of PII^2 type was selected for laboratory experiment. The observer algorithms as well as control algorithms were implemented on DSP processor.

Experimental tests confirmed good properties of investigated version of observer. Fig. 4 presents test of position estimation accuracy gained for observer with constant settings, selected for speed equal to 105 rad/s. The maximum estimation error reaches 2.23^o for ω = 105 rad/s and value equal to 4.6^o for ω = 37.7 rad/s. This means that in operating point assumed for selection of observer settings better accuracy is gained. Fig. 5 shows transient process involved by step change of speed reference (0 rad/s → 209 rad/s → 105 rad/s → 0 rad/s) for sensor and sensorless control system. Very similar waveforms of speed, observed speed and current i_q confirmed proper operation of sensorless systems.

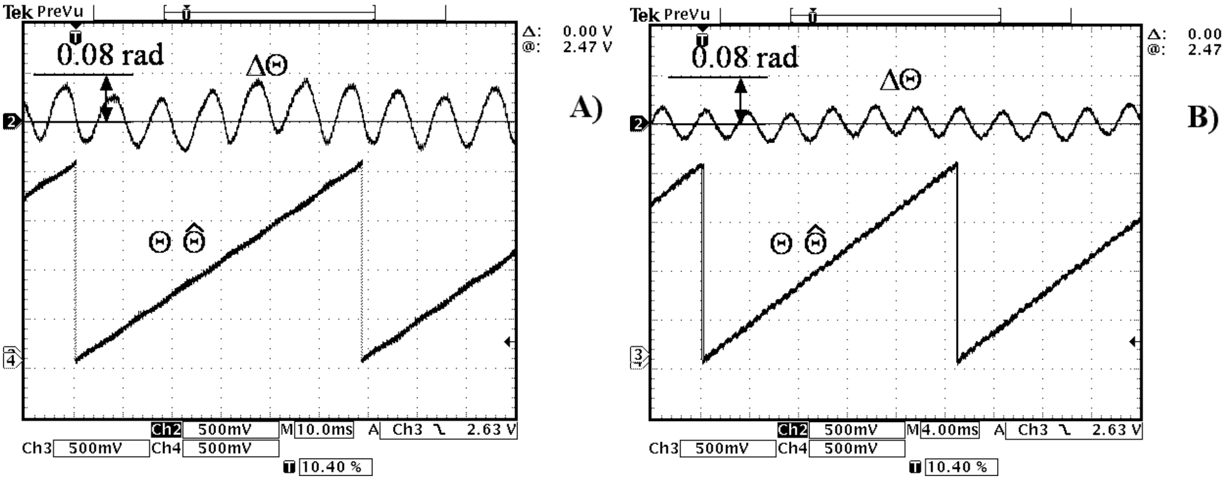

Fig. 4. Test of position estimation accuracy with observer setting selected for ω = 105 rad/s:
A – ω = 37.7 rad/s; B – ω = 105 rad/s

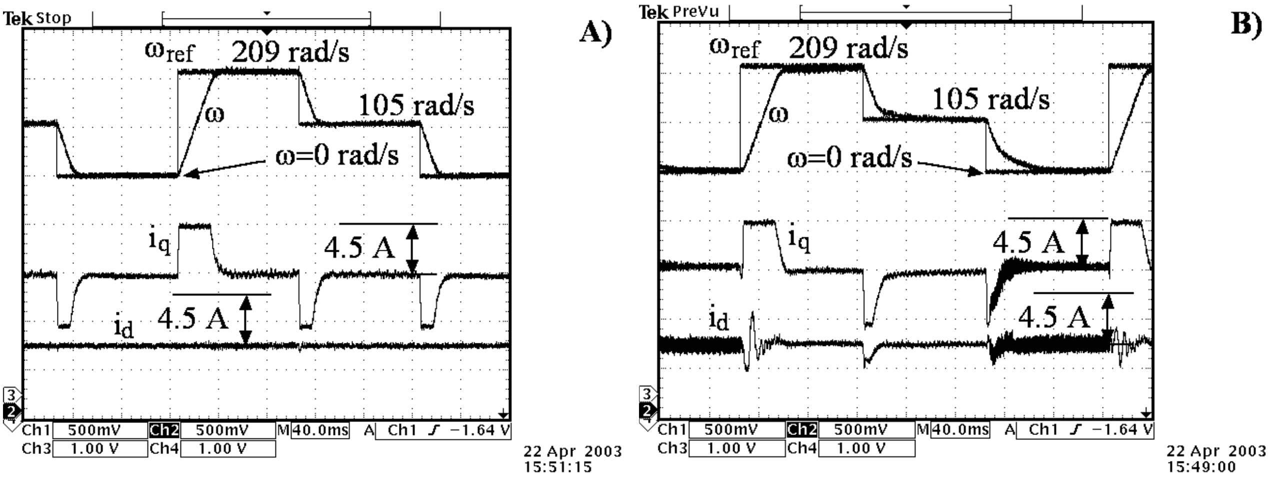

Fig. 5. Waveforms of speed, reference speed, real current in axis d and q involved by step change of reference: 0 rad/s → 209 rad/s → 105 rad/s → 0 rad/s A – sensor control; B – sensorless control

Only remarkable difference is visible in waveforms of current i_d – for sensorless system, as a result of some observation error, current i_d is not equal zero but its value reaches 1.3 A, what is equal 29 % I_R. Waveforms presented on this figure give possibilities to make comparison between starting process of both analyzed systems. Special starting procedure guarantees proper starting for sensorless system so showed processes are similar.

Conclusions. In the paper a new structure of observer of rotor speed and position for PMSM was proposed. The novelty of this observer structure is included in its complex corrector function of proportional-integral type and adaptive change of corrector settings. This structure implemented on DSP processor showed proper operation confirmed by experimental results.

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МОДЕЛИРОВАНИЕ СХЕМЫ МАТРИЧНОГО ПРЕОБРАЗОВАТЕЛЯ ЧАСТОТЫ

Наведені деякі результати досліджень матричного перетворювача частоти. Показана можливість забезпечення безпечної комутації транзисторів при використанні алгоритму, що розподіляє функції ключів без контролю напрямку струму у вихідних фазах, а також доцільність використання релейного регулятору струму, що забезпечує синусоїдну форму вихідного струму.

Some results of researches of a matrix converter of frequency are given. The opportunity of support of safe switching of transistors is shown at use of algorithm with division of functions of switches without the control of a direction of a current in output phases, and also expediency of use of a relay regulator of a current for maintenance of the sine wave form of an output current.

Постановка проблемы. Несмотря на широкое распространение преобразователей частоты (ПЧ) с промежуточным звеном постоянного тока и автономным инвертором напряжения (АИН) на IGBT в последнее десятилетие во всем мире, судя по многочисленным публикациям, возродился, утраченный было, интерес к ПЧ с непосредственной связью. В последнее время он получил название матричный преобразователь (МП).

Однако вопрос практической реализации МП до сих пор не решен, что связано с обеспечением «безопасной» коммутации (без к.з. и разрывов тока) транзисторов схемы, разработкой удобных в реализации и работоспособных алгоритмов управления.

Анализ последних исследований. Существующие решения, в той или иной форме, основаны на принципах программного или раздельного управления ключами с использованием информации о полярности выходного тока или напряжении питающей сети [1, 2]. Большинство авторов в процессе формирования выходного напряжения рассматривают однократную модуляцию (ОМ). При этом складывается впечатление, что автомати-