Andrzej POPENDA

Czestochowa University of Technology

A concept of control of PMSM angular velocity

***Abstract**. In the paper the control system of PMSM angular velocity is presented. This control system is partially based on the structure known from the literature sources. However, the own concept of calculation of motor reference current components is applied in order to optimize time changes of both PMSM output torque and angular velocity as well as to minimize the ratio of motor current to output torque. The electromechanical transformer synchro together with synchro decoder is also used in order to transform the current components and estimate motor angular velocity.*

***Streszczenie.** W pracy zaprezentowano układ regulacji prędkości kątowej silnika synchronicznego wzbudzanego magnesami trwałymi (PMSM). Prezentowany układ regulacji jest częściowo oparty na strukturze znanej z literatury, jednak zastosowano własną koncepcję obliczania zadanych składowych prądu silnika w celu optymalizacji przebiegów momentu elektromagnetycznego i prądów fazowych PMSM, jak również w celu minimalizacji stosunku prądu silnika do momentu elektromagnetycznego. Zastosowano także elektromechaniczny przetwornik „synchro" w celu transformacji składowych prądu i oszacowania prędkości kątowej silnika. (**Pewna koncepcja regulacji prędkości kątowej PMSM**).*

Keywords: permanent magnet synchronous motor (PMSM), resolver and synchro, control systems, optimization.
Słowa kluczowe: silnik synchroniczny z magnesami trwałymi (PMSM), transformatory położenia kątowego, układy regulacji, optymalizacja.

Introduction

In the paper [1] the control strategy of BLDC motor was proposed. A control system based on the proposed strategy includes the PWM-controlled voltage source inverter, such as the inverters used in converter-fed AC drives with induction motor or synchronous motor. However, the feedbacks applied in the proposed structure cause that rotational speed of BLDC motor is controlled by changes of feeding voltage, whereas rotational speed of induction and synchronous motors is controlled by changes of frequency. In the proposed structure the electromechanical transducer synchro [2] replaced Hall sensors, that are widely used in order to estimate the rotor position angle of BLDC motor.

The proposed control strategy [1] may be classified as the method of vector control. In contrast to the standard control structures of BLDC motor, the proposed control strategy allows achieving a good dynamic of controlled motor, without pulsation of output torque and with reduced distortions of phase currents especially for the low-frequency harmonics. The sinusoidal type of BLDC motor is required for the proper operation of control system based on the proposed control strategy. The difference between trapezoidal and sinusoidal motors comes from the inter-connection of coils in the stator windings giving the different types of back electromotive force (EMF). In contrast to the different types of BLDC motors, permanent magnet synchronous motors (PMSM) are sinusoidal.

Three Hall sensors, that in standard control structure of BLDC motor [1] generate square pulses changing by leaps between two values at every 180 electrical degrees, allow to determine the rotor position angle with accuracy corresponding to the 60 electrical degrees only. Such accuracy is not sufficient in order to realize the vector control strategy of permanent magnet motor. The rotor position measurement accuracy of optical encoders is very high but they cause many problems in the usage because they are not resistant to vibration, strokes, dust and damp as well as permanent operation under high temperature. The alternative solution is to apply the electromechanical transformers: resolvers or synchros, that accuracy of rotor position measurement is not as high as accuracy of optical encoders, but they are much resistant and require less expanded conversion unit.

Description of the concept

The proposed BLDC control strategy [1] is not suitable for PMSM, due to the significant difference in the relative value of stator reactance between BLDC motor and PMSM. This fact is shown in the exemplary time changes of motor output torque (τ_e), angular velocity (ω) and phase current (i) during reversing a PMSM (Fig. 1). In the model-simulation investigations the following parameters of PMSM were taken into account: 4 kW, 400 V, 3000 rpm, 7.5 A, 1 Ω, 73 mH (L_q); 26 mH (L_d); 136 V (back EMF); 0,005 kgm^2 and technological load torque depending on squared angular velocity: $\tau_m = \Delta\tau_m + \tau_n(\omega/\omega_n)^2\mathrm{sgn}\,\omega$.

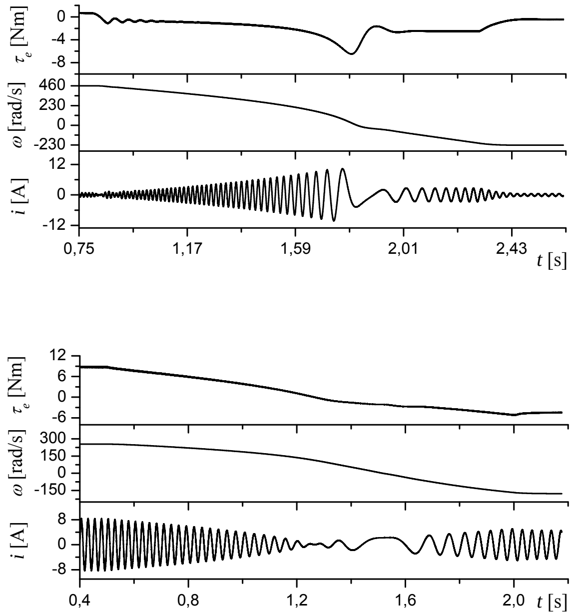

Fig. 1. Time changes of the selected variables during reversing a PMSM controlled with the use of strategy presented in [1]: at the top – the unloaded motor, at the bottom – the loaded motor (u_{ref}: $+U \rightarrow -U/2$)

The application of reference voltage vector $\underline{u}_{ref}$ instead of its module u_{ref} in order to control a PMSM gives the significant improvement of dynamic properties of PMSM-based drive system. The application of reference voltage vector module u_{ref} was completely sufficient in the case of BLDC motor [1]. The application of reference voltage vector $\underline{u}_{ref}$ in order to control a PMSM allows for independent adjusting the motor voltage vector components u_d, u_q in reference frame (coordinate system) 0dq connected to the PMSM rotor. The appropriate control of time changes of the above-mentioned voltage components allows to optimize the time changes of output torque and angular velocity (non-oscillating changes with several percent over-regulation at minimal duration of reaching the steady-state value). For this purpose time changes of reference voltage vector components u_{dref}, u_{qref} have to be determined. These components depend on a few factors e.g. motor load. In practice there is a simpler manner to determine the abovementioned components as a result of application of feedbacks (closed loops) for motor current vector components i_d, i_q in reference frame 0dq. The considered structure is known from the literature sources e.g. [3-5]. In that structure the reference current component i_{qref} is proportional to the output of angular velocity controller, whereas, for the determined range of angular velocity, the component i_{dref} is equal to zero. For greater values of angular velocity the component i_{dref} is the nonlinear function of angular velocity.

In Fig. 2 the PMSM angular velocity control system is presented. This control system is partially based on the structure known from the literature sources [3-8]. However, in the proposed control system the own concept of calculation of motor reference current components i_{dref}, i_{qref} by the Dynamic & Nonlinear block 1 is applied:

(1) $$i_{qref} = \frac{U_{phn}}{X_{qn}} \sin\delta_{ref}, \quad i_{dref} = \frac{U_{phn}\cos\delta_{ref} - E_{fn}}{X_{dn}}$$

The nonlinear functions (1) of reference angle δ_{ref} were obtained on the basis of the static dependencies between motor current vector components in 0dq reference frame and the position angle δ of the feeding voltage vector with reference to axis q. The abovementioned static dependencies come from the vector diagram of PMSM currents, voltages and fluxes (Fig. 3). The motor rated parameters were taken into account and the stator resistance was neglected ($R = 0$). The reference angle δ_{ref} in functions (1) is assumed to be the output of motor angular velocity controller (Fig. 2). An application of functions (1), calculating the reference current components, allows to keep proportions between the respective components of currents, voltages and fluxes corresponding with rated working conditions of motor.

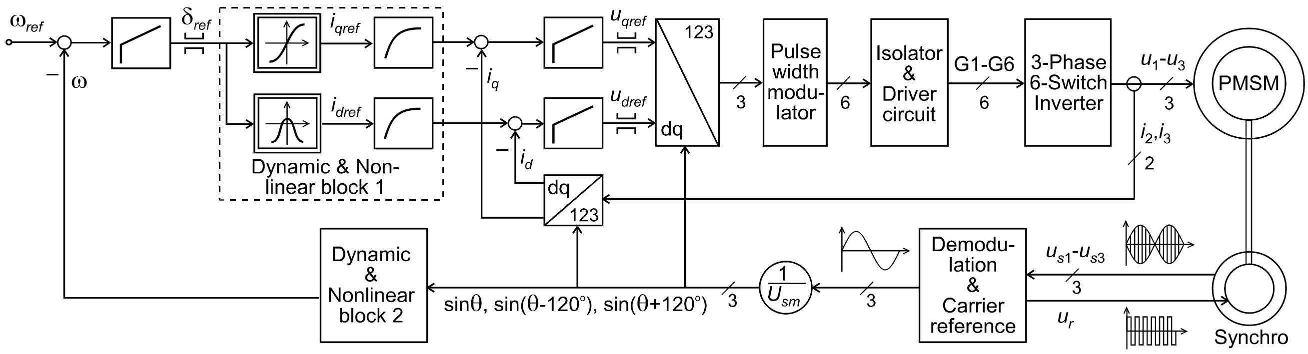

Fig. 2. The block diagram of PMSM angular velocity control system including the structure of dynamic-nonlinear block that calculates the reference components of motor current vector in reference frame 0dq

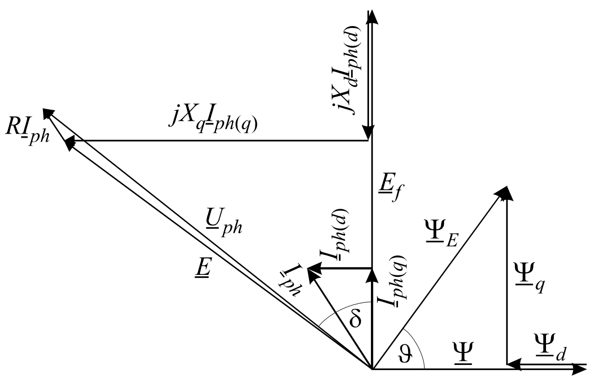

Fig. 3. The vector diagram of PMSM currents, voltages and fluxes

The following modification of the reference current component in axis d allows to minimize the no-load current of motor at the cost of greater influence of motor load on its rotational speed:

(2) $$i_{dref} = \frac{E_{fn}}{X_{dn}}\left(\cos\delta_{ref} - 1\right)$$

The reference current components, calculated according to the functions (1) or (2), are filtered with the use of first order low-pass filters for limitation of sudden changes of these components causing oscillating processes with significant magnitude.

The following approximations for $-\pi/2 \le \delta \le +\pi/2$, instead of trigonometric functions, may be applied in functions (1) and (2) in order to simplify the calculation in real control systems:

(3) $$\sin\delta \approx f_s(\delta) = \frac{4\delta}{\pi}\left(1 - \frac{|\delta|}{\pi}\right)$$

(4) $$\cos\delta \approx f_c(\delta) = \left(1 - \frac{2\delta}{\pi}\right)\left(1 + \frac{2\delta}{\pi}\right)$$

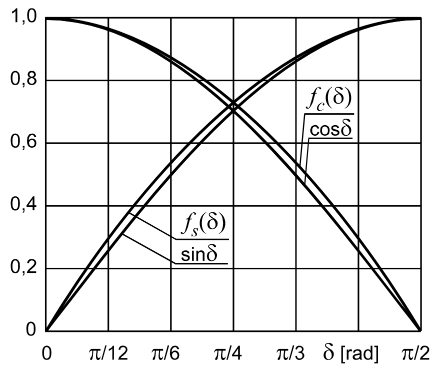

Fig. 4. Trigonometric functions $\sin\delta$ and $\cos\delta$ as well as the proposed approximations of these functions using dependencies (3) and (4)

The graphs of trigonometric functions $\sin\delta$ and $\cos\delta$ as well as the proposed approximations of these functions using dependencies (3) and (4) are shown in Fig. 4.

In the proposed control structure (Fig. 2) a three-phase synchro decoder [1,2] produces the periodical functions of angle θ depending on rotor position angle γ_m: $\theta = p_b\gamma_m + 180°$, where p_b is number of pole pairs. Three demodulators of synchro decoder (one for each modulated synchro output) separate the carrier frequency from the modulation frequency (motor rotation). The abovementioned periodical functions are used in order to transform the current components from the stationary phase coordinates 1,2,3 to the rotating coordinate system 0dq (Fig. 2):

$$\begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} -\sin\theta & -\sin(\theta-120°) & -\sin(\theta+120°) \\ \cos\theta & \cos(\theta-120°) & \cos(\theta+120°) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \tag{5}$$

In three-phase circuit without the neutral conductor there is no the zero component of current vector, thus:

$$i_1 + i_2 + i_3 = 0 \tag{6}$$

The reverse transformation is also used in the control system (Fig. 2). The transformations applied in the proposed structure are power invariant.

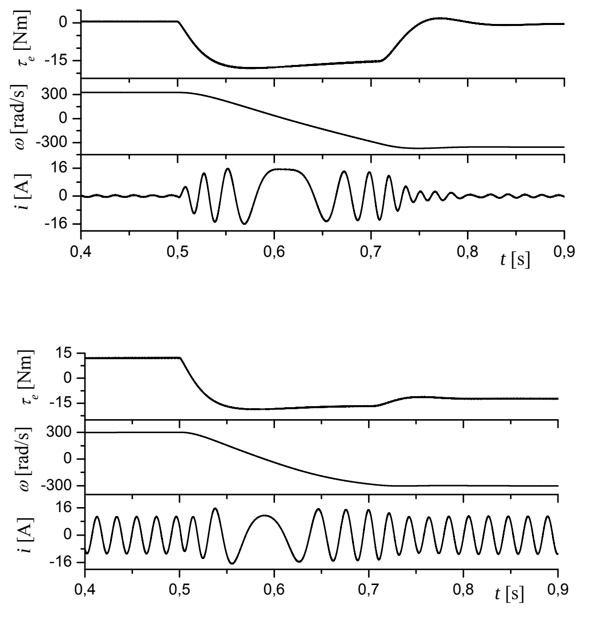

Fig. 5. Time changes of the selected variables during reversing a PMSM controlled according to the proposed concept (Fig. 2): at the top – the unloaded motor, at the bottom – the loaded motor (ω_{ref}: $+\omega_n \rightarrow -\omega_n$)

The Dynamic & Nonlinear block 2 is applied to estimate motor angular velocity on the basis of the abovementioned periodical functions, produced by synchro decoder, according to the following dependency:

$$\omega = \sin\theta \frac{\mathrm{d}(-\cos\theta)}{\mathrm{d}t} + \cos\gamma \frac{\mathrm{d}(\sin\theta)}{\mathrm{d}t} \tag{7}$$

$$\cos\theta = \frac{1}{\sqrt{3}}\left(\sin(\theta+120°) - \sin(\theta-120°)\right)$$

In Fig. 5 the exemplary time changes of motor output torque (τ_e), angular velocity (ω) and phase current (i) during reversing a PMSM, controlled according to the proposed concept (Fig. 2), are shown in Fig. 5.

Conclusions

The proposed method of calculation of the reference current components i_{dref}, i_{qref} on the basis of the angular velocity controller output δ_{ref} allows to optimize time changes of PMSM output torque and angular velocity. Additionally, the method allows to minimize the ratio of motor current to output torque, as well.

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***Author**: dr hab. inż. Andrzej Popenda, prof. PCz, Politechnika Częstochowska, Instytut Elektrotechniki Przemysowej, Al. Armii Krajowej 17, 42-200 Częstochowa, E-mail: popenda@el.pcz.czest.pl.*