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Control of a six-phase synchronous reluctance motor

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Abstract. The results of the research on control of high-speed and low-speed six-phase synchronous reluctance motor are presented in this paper. Two control variants of SynRM are considered: two galvanically isolated three-phase windings and one six-phase winding connected in the wye. The mathematical description, mathematical models, and results of synthesis of control systems for two considered variants of control of SynRM are given. The problems encountered by the authors are considered and the ways of their solution are presented. The results of practical research and comparison of the variants considered in controlling six-phase SynRM are presented. Conclusions about advantages and disadvantages of various control variants of a SynRM are made on the basis of theoretical and practical research and the obtained results. The presented results of mathematical description and synthesis of control system and also results of experimental research at control of prototypes of SynRM can be used at synthesis of control systems of any types of multiphase electric machines.

1 Introduction

When implementing electric actuators with high installed capacity, problems usually arise from the design of electric converters, taking into account the limitations imposed on the parameters of the used power semiconductor elements of the frequency converter. For the use of semiconductor devices available on the electrical market for the realisation of a regulated electric actuator with a high installed power there are only two options: on the basis of a three-phase electric machine and a cascade frequency converter; or using a multi-phase electric machine and a multi-phase electric frequency converter. In this case, when using a multiphase electrical machine, it is possible to control several independent, usually three-phase windings or to control one multiphase wye.

2 Methods

Much attention has been paid to the control of electric drives based on AC multi-phase electric machines. Thus, in a number of sources adaptations of known control methods to multiphase electric machines are carried out [1-6]. However, practically all of them do not

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take into account the problems connected with insignificant difference of both winding parameters and imperfection of electric converters and inaccuracy of synthesis of required voltage values. So, practically at implementation of known methods of control of six-phase SynRM with use of method with two galvanically untied three-phase windings, the significant influence of one three-phase winding on another up to triggering of maximum current protection in electric converter was started. At implementation of known methods of control of a six-phase SynRM - two wyes with common zero point - nonsymmetrical (not equal) currents were flowing through different windings of the electric machine - zero current was flowing from one three-phase star to another.

2.1 Control of a SynRM with two galvanically isolated three-phase windings

Figure 1 shows the power diagram of an electric drive based on a six-phase SynRM with two galvanically isolated three-phase windings.

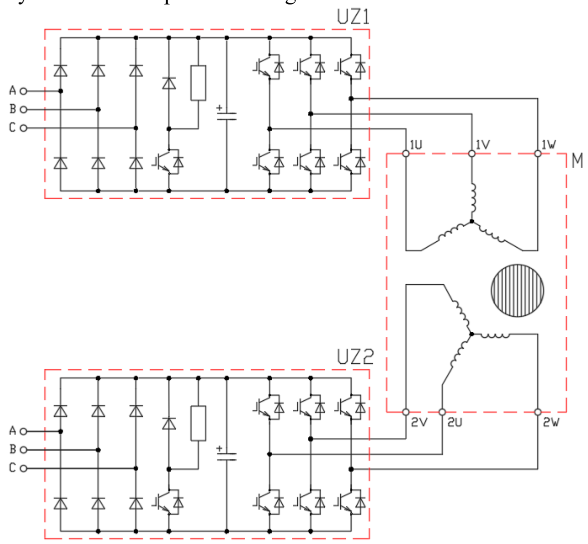

Fig. 1. Power diagram of an electric drive based on a six-phase SynRM with two galvanically isolated three-phase windings.

The equations of a six-phase SynRM can be represented as follows:

$$L_S \cdot p\mathbf{I1}_S + p\left\{\mathbf{D1}_S{}^{\mathrm{T}}(\gamma)\cdot\mathbf{L}_{SS}\cdot\left(\mathbf{D1}_S(\gamma)\cdot\mathbf{I1}_S + \mathbf{D2}_S(\gamma)\cdot\mathbf{I2}_S\right)\right\} + R_S\cdot\mathbf{I1}_S = \mathbf{U1}_S\,; \quad (1)$$

$$L_S \cdot p\mathbf{I2}_S + p\left\{\mathbf{D2}_S{}^{\mathrm{T}}(\gamma)\cdot\mathbf{L}_{SS}\cdot\left(\mathbf{D1}_S(\gamma)\cdot\mathbf{I1}_S + \mathbf{D2}_S(\gamma)\cdot\mathbf{I2}_S\right)\right\} + R_S\cdot\mathbf{I2}_S = \mathbf{U2}_S\,, \quad (2)$$

where L_S is stator winding leakage inductance, $\mathbf{L}_{SS} = \begin{bmatrix} L_{dd} & 0 \\ 0 & L_{qq} \end{bmatrix}$ is matrix of main stator phase winding inductances, R_S is stator winding resistance, $\mathbf{I1}_S = \left[i1_u \quad i1_v \quad i1_w\right]^T$ and $\mathbf{I2}_S = \left[i2_u \quad i2_v \quad i2_w\right]^T$ are stator currents, $\mathbf{U1}_S = \left[u1_u \quad u1_v \quad u1_w\right]^T$ and

$\mathbf{U2}_S = \begin{bmatrix} u2_u & u2_v & u2_w \end{bmatrix}^T$ are stator phase voltages,

$$\mathbf{D1}_S(\gamma) = \begin{bmatrix} \cos(-\gamma) & \cos\left(\frac{2\cdot\pi}{3} - \gamma\right) & \cos\left(\frac{4\cdot\pi}{3} - \gamma\right) \\ \sin(-\gamma) & \sin\left(\frac{2\cdot\pi}{3} - \gamma\right) & \sin\left(\frac{4\cdot\pi}{3} - \gamma\right) \end{bmatrix},$$

$$\mathbf{D2}_S(\gamma) = \begin{bmatrix} \cos(\tau-\gamma) & \cos\left(\frac{2\cdot\pi}{3} + \tau - \gamma\right) & \cos\left(\frac{4\cdot\pi}{3} + \tau - \gamma\right) \\ \sin(\tau-\gamma) & \sin\left(\frac{2\cdot\pi}{3} + \tau - \gamma\right) & \sin\left(\frac{4\cdot\pi}{3} + \tau - \gamma\right) \end{bmatrix}$$ — phase matrices,

τ is an angle between the three phase windings.

To compose the machine equations in the axes d and q, let us introduce the variables:

$$\mathbf{I1}_{dq} = \begin{bmatrix} i1_d \\ i1_q \end{bmatrix} = \frac{2}{3}\cdot\mathbf{D1}_S(\gamma)\cdot\mathbf{I1}_S;\ \mathbf{I2}_{dq} = \begin{bmatrix} i2_d \\ i2_q \end{bmatrix} = \frac{2}{3}\cdot\mathbf{D2}_S(\gamma)\cdot\mathbf{I2}_S,$$

$$\mathbf{U1}_{dq} = \begin{bmatrix} u1_d \\ u1_q \end{bmatrix} = \frac{2}{3}\cdot\mathbf{D1}_S(\gamma)\cdot\mathbf{U1}_S;\ \mathbf{U2}_{dq} = \begin{bmatrix} u2_d \\ u2_q \end{bmatrix} = \frac{2}{3}\cdot\mathbf{D2}_S(\gamma)\cdot\mathbf{U2}_S,$$

After a few simple transformations we obtain the following equations:

$$L_d \cdot p\{ia_d\} - L_q \cdot ia_q \cdot \omega + R_S \cdot ia_d = ua_d;$$
$$L_q \cdot p\{ia_q\} + L_d \cdot ia_d \cdot \omega + R_S \cdot ia_q = ua_q;$$
$$L_S \cdot p\{ib_d\} - L_S \cdot ib_q \cdot \omega + R_S \cdot ib_d = ub_d;$$
$$L_S \cdot p\{ib_q\} + L_S \cdot ib_d \cdot \omega + R_S \cdot ib_q = ub_q,$$

where $L_d = L_S + 3 \cdot L_{dd}$; $L_q = L_S + 3 \cdot L_{qq}$; $ia_d = i1_d + i2_d$; $ia_q = i1_q + i2_q$; $ib_d = i1_d - i2_d$; $ib_q = i1_q - i2_q$; $ua_d = u1_d + u2_d$; $ua_q = u1_q + u2_q$; $ub_d = u1_d - u2_d$; $ub_q = u1_q - u2_q$.

Electromagnetic torque is given by the formula [10]:

$$M = \frac{p_p \cdot 3}{4} \cdot \left(L_d - L_q\right) \cdot ia_d \cdot ia_q,$$

where p_p is a number of pole pairs of a SynRM.

It can easily be shown that the maximum value of torque, for a given stator current, is achieved if the following equations are fulfilled: $ib_d = 0$; $ib_q = 0$;

Thus, to control this machine, four control loops must be used: magnetisation loop for current ia_d, momentum circuit for current ia_q, current maintenance circuit ib_d equal to zero, current maintenance circuit ib_q equal to zero. The control is implemented according to the structural diagram shown in Figure 2.

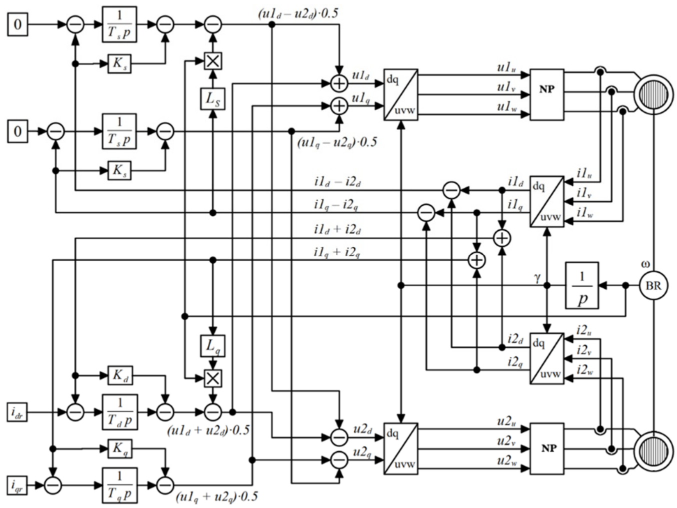

Fig.2. Schematic diagram for drive control based on a six-phase SynRM with two galvanically isolated three-phase windings.

2.2 Control of a six-phase SynRM with two three-phase windings sharing a common zero point

Figure 3 shows a power diagram of a six-phase SynRM with two three-phase windings sharing a common zero point.

If the windings share a common zero point, the sum of the currents in the three phase windings is not zero. We define this sum as i_0:

$$i0 = i1u + i1v + i1w = -i2u - i2v - i2w.$$

To obtain the equation that this sum satisfies, sum the rows of the matrix equation (1) or (2). We obtain the following scalar equation:

$$L_S \cdot pi_0 + R_S \cdot i_0 = u_0,$$

where $u0 = u1u + u1v + u1w = -u2u - u2v - u2w$.

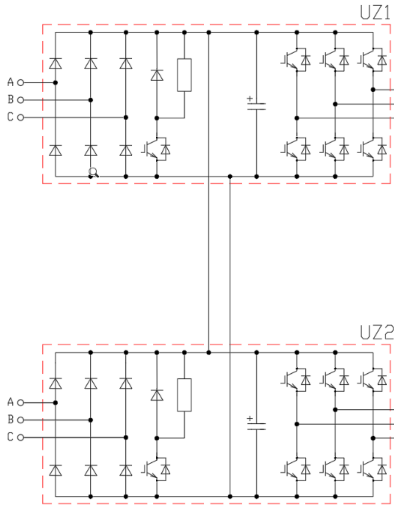

Fig. 3. Power diagram of an electric drive based on a six-phase SynRM with two three-phase windings having a common zero point.

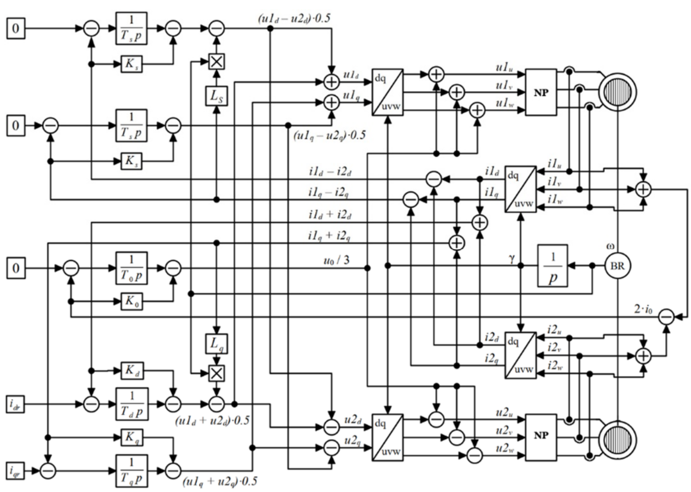

Fig.4. Schematic diagram for drive control based on a six-phase SynRM and two three-phase windings with a common zero point

Current value i_0 has no effect on the electromagnetic torque produced by the machine. However, a non-zero value results in additional losses and a reduction in the limiting dynamic characteristics of the machine.

Therefore, in order to control this machine, a fifth circuit must be added to the four circuits shown above to maintain the current i_0 equal to zero. The control is implemented according to the structural diagram shown in Figure 4.

SynRM-1630-0.66-300 M4

Parameter name	Value
rated technical shaft power, kW	1630
rated line voltage, V	660
rated frequency of supply voltage, Hz	50
frequency control range of supply voltage, Hz	0…100
number of windings and connection diagram	YY (shifted 30°el.)
rated current, A	2 x 949*
power factor	0.77*
COP, %	97.0*
rated speed of rotation, rpm	300
rated torque, kNm	51.888*
number of outputs	6 (1U, 1V, 1W, 2U, 2V, 2W
winding insulation class	F
operating mode according to GOST IEC 60034-1	S1
mass, kg	18000**

SynRM-1700-0.66-1000 M4

Parameter name	Value
rated technical shaft power, kW	1700
rated line voltage, V	660
rated frequency of supply voltage, Hz	50
frequency control range of supply voltage, Hz	0…100
number of windings and connection diagram	YY (shifted 30°el.)
rated current, A	2 x 919*
power factor	0.83*
COP, %	97.0*
rated speed of rotation, rpm	1000
rated torque, kNm	16.235*
number of outputs	6 (1U, 1V, 1W, 2U, 2V, 2W)
winding insulation class	F
operating mode according to GOST IEC 60034	S1
mass, kg	6800**

Fig.5. Tested prototypes of reactive electrical machines.

3 Results

For this research the prototypes of reactive electric machines with anisotropic magnetic conductivity of the rotor were used, general view and technical characteristics are presented in Table 1. This type of electrical machines and control methods and algorithms are presented in more detail in literature [7-9].

At practical realisation of the stated control algorithms the shortcomings inherent in the known or modified methods of control were eliminated. The control systems worked out the set sums and differences on currents.

4 Discussion

The proposed control algorithms allow to obtain the desired static and dynamic behaviour of a six-phase electric machine with anisotropic magnetic conductivity of the rotor at various connection schemes of its windings. Thus to control the electric drive on the base of a six-phase SynRM and two three-phase windings which are galvanically isolated it is necessary to use four control loops (sum of magnetizing currents, sum of loading currents, difference of magnetizing currents, difference of loading current) and to control the electric drive on the base of a six-phase electric machine with anisotropic magnetic conductivity of the rotor and two three-phase windings which have common zero-point it is necessary to use two control loops. The drive version with two galvanically separated three-phase windings has the additional advantage of high reliability because a failure in the frequency converter of one star will not lead to a failure of the complete drive.

5 Conclusion

These variants of control with several independent stars or with common neutral point of windings and the proposed control approach can be used in synthesis of control systems of any types of electric machines of alternating current.

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