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Electromagnetical Efficiency of the Six-phase Winding

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Introduction

Currently the six-phase voltage system is used in practice only in very rare cases. The opinion prevails that the three-phase voltage system optimally satisfies all the requirements of consumers of electrical power [1–3]. Therefore the impact of the six-phase and generally multi-phase voltage systems on the operation of respective power consumers has not been studied widely.

At the present time the multi-phase voltage system (m> > 3) is mostly used only in the current rectification circuits since the pulsation of the rectified current decreases with the increase of the number of phases.

The three-phase voltage system can be transformed to the multi-phase voltage system by using inductivity or gate-based power transducers. For example, in order to obtain the six-phase voltage system it is required to have the three-phase transformed of the required power rating containing one primary ant two secondary windings of identical parameters [2]. The primary windings of such transformer are star-connected and two secondary three-phase windings are star-connected with a common neutral node (the endpoints of the first secondary winding are short-circuited with the start points of the second secondary winding). Thus the primary windings A, B, C together with the secondary windings a_1, b_1, c_1 form a zero vector group of the transformer, and the same primary winding together with the secondary windings a_2, b_2, c_2 form a sixth vector group. So the windings of the secondary circuit create the symmetrical six-phase voltage system which can be used to supply the six-phase synchronous and asynchronous alternating current motors. Such motors are not manufactured yet in any country since it is not clear if they would have any advantages (or only disadvantages) compared to the three-phase alternating current motors. Only a few research topics regarding the analysis of the six-phase alternating current motors and their respective components were found [4, 5].

The aim of this work is to investigate the six-phase winding of particular parameters by determining its electromagnetic efficiency and to compare it with the three-phase winding of analogous parameters.

The object of the research

The two-layer preformed six-phase winding was used in the research; winding parameters were: number of poles $2p = 2$, number of sections in the group $q = 2$, number of slots in the stator magnetic circuit $Z = 2p\,m\,q = 2 \cdot 6 \cdot 2 = 24$, pole pitch $\tau = Z / (2p) = 24 / 2 = 12$, winding span $y = 5\,\tau / 6 = 5 \cdot 12 / 6 = 10$, magnetic circuit slot pitch in electrical degrees $\alpha = 360^{\circ} p / Z = 360^{\circ} \cdot 1 / 24 = 15^{\circ}$.

The distribution of the sides of active coils of this winding into the slots of magnetic circuit is given in Table 1.

Table 1. Distribution of the sides coils of two-layer preformed six-phase winding into the slots of magnetic circuit

Phase change		U1	W2	X1	Z2	V1	U2
Number of coils in a group		2	2	2	2	2	2
Slot No.	Z	1; 2	3; 4	5; 6	7; 8	9; 10	11; 12
	Z'	11; 12	13; 14	15; 16	17; 18	19; 20	21; 22
Phase change		Y1	X2	W1	V2	Z1	Y2
Slot No.	Z	13; 14	15; 16	17; 18	19; 20	21; 22	23; 24
	Z'	23; 24	1; 2	3; 4	5; 6	7; 8	9; 10

The distribution of separate phase coils of analyzed six-phase winding into the slots of magnetic circuit based on parameters indicated in Table 1 is given in Table 2.

Table 2. The distribution of separate phase coils of analyzed winding into the slots of magnetic circuit

1 phase (U)	2 phase (X)	3 phase (V)	4 phase (Y)	5 phase (W)	6 phase (Z)
→1–11 2–12	→5–15 6–16	→9–19 10–20	→13–23 14–24	→17–3 18–4	→21–7 22–8
←11–21 12–22	←15–1 16–2	←19–5 20–6	←23–9 24–10	←3–13 4–14	←7–17 8–18

According to data of Tables 1 and 2 the development of electrical circuit of two-layer preformed six-phase winding is obtained (Fig. 1, a).

Research results

Assume that the relative quantities of the electric current amplitude values of considered six-phase winding are

$$I_{m1}^* = I_{m2}^* = ... = I_{m6}^* = 1 . \qquad (1)$$

Then the instantaneous current values of the phase windings in the moment of time $t = 0$ would be:

$$i_1^* = I_{m1}^* \sin \omega t = 0 ; \qquad (2)$$

$$i_2^* = I_{m2}^* \sin\left(\omega t - \frac{2\pi}{6} \right) = I_{m2}^* \sin\left(-60^\circ\right) = -0{,}866 ; \qquad (3)$$

$$i_3^* = I_{m3}^* \sin\left(\omega t - \frac{4\pi}{6} \right) = I_{m3}^* \sin\left(-120^\circ\right) = -0{,}866; \qquad (4)$$

$$i_4^* = I_{m4}^* \sin\left(\omega t - \frac{6\pi}{6} \right) = I_{m4}^* \sin\left(-180^\circ\right) = 0 ; \qquad (5)$$

$$i_5^* = I_{m5}^* \sin\left(\omega t - \frac{8\pi}{6} \right) = I_{m5}^* \sin\left(-240^\circ\right) = 0{,}866 ; \qquad (6)$$

$$i_6^* = I_{m6}^* \sin\left(\omega t - \frac{10\pi}{6} \right) = I_{m6}^* \sin\left(-300^\circ\right) = 0{,}866. \qquad (7)$$

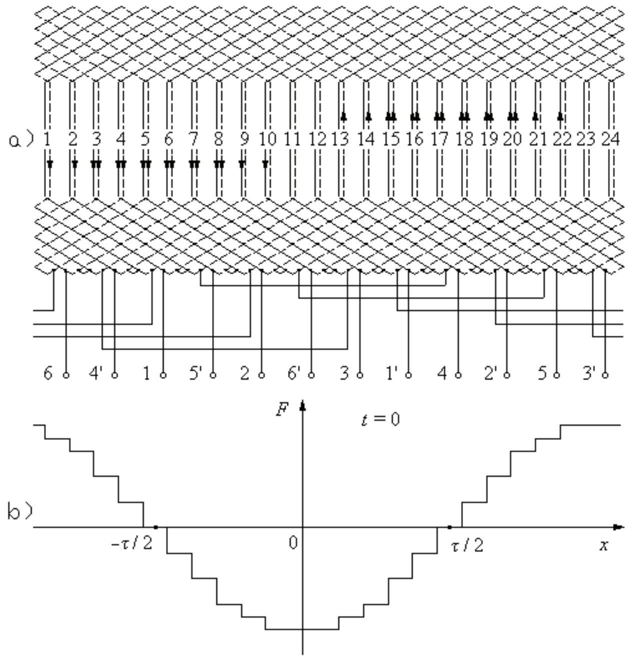

Fig. 1. Development of electrical circuit of two-layer preformed six-phase winding, in which q = 2, (a) and the distribution of its rotating magnetomotive force in the moment of time t = 0 (b)

The relative size of effective conductors of one slot of magnetic circuit of the considered two-layer preformed six-phase winding with $q = 2$

$$N_g^* = N_1^* / q = 1/2 = 0{,}5 ; \qquad (8)$$

here $N_1^* = 1$ – the relative size of effective conductors of magnetic circuit slot of the concentrated multi-phase winding.

Then the relative quantity of turns of single coil of two-layer winding

$$N_c^* = N_g^* / 2 = 0{,}5 / 2 = 0{,}25 . \qquad (9)$$

The expression of conditional change of magnetomotive force in the slot of two-layer winding is the following

$$F_g^* = F^* + F^{*\prime} = i_i^* N_c^* + i_i^{*\prime} N_c^* ; \qquad (10)$$

here $F^*, F^{*\prime}$ – changes of magnetomotive forces induced in the slot of active sides of upper and lower coils; $i_i^*, i_i^{*\prime}$ – relative quantities of instantaneous current values flowing through the upper and lower sides of coils located in the slots of respective phase windings.

From formulas (2÷7), (9) and (10) and also no the base of Fig. 1, a, the conditional changes of magnetomotive force in the slots of magnetic circuit are determined (Table 3).

Table 3. Conditional changes of magnetomotive force in the slots of magnetic circuit in the moment of time t = 0

Slot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Conditional changes of magnetomotive force	–0,216	–0,216	–0,433	–0,433	–0,433	–0,433	–0,433	–0,433	–0,216	–0,216	0	0	0,216	0,216	0,433	0,433	0,433	0,433	0,433	0,433	0,216	0,216	0	0

According to the results in Table 3 the spatial distribution of instantaneous rotating magnetomotive force in the set moment of time (t = 0) is determined (Fig 1, b). The obtained results allow to state that the symmetric six-phase current system in the distributed symmetric six-phase winding will induce the stair-shaped curves of magnetomotive force which move in space and periodically vary over time. The step functions of such rotating magnetomotive force will have only odd harmonics since they will be symmetrical in respect of coordinate axes in any moment of time. After application of the principle of superposition such amplitudes of odd harmonics of instantaneous rotating magnetomotive force can be calculated according to the following equation [6]

$$F_{s\nu} = \frac{4}{\pi} \frac{F_{1s}}{\nu} \sin \nu \frac{\beta_1}{2} + \frac{4}{\pi} \frac{F_{2s}}{\nu} \sin \nu \frac{\beta_2}{2} + ... + \frac{4}{\pi} \frac{F_{ks}}{\nu} \sin \nu \frac{\beta_k}{2} = \frac{4}{\pi \nu} \sum_{i=1}^{k} F_{is} \sin \nu \frac{\beta_i}{2} ; \qquad (11)$$

here F_{is} – conditional height of the i-th rectangle of the stair-shaped curve of instantaneous rotating magnetomotive force; β_i – width of the i-th rectangle, expressed in electrical degrees of the fundamental space harmonic; k – the number of rectangles which constitute the stair-shaped curve of instantaneous rotating magnetomotive force; v – series number of odd space harmonic.

On the base of Table 4 and Fig. 1, b the parameters of positive half-period of instantaneous rotating magnetomotive force of the considered winding are the following: $k = 5$; $F_{1s} = 0{,}433$; $F_{2s} = 0{,}433$; $F_{3s} = 0{,}433$; $F_{4s} = 0{,}2165$; $F_{5s} = 0{,}2165$; $\beta_1 = 165^\circ$; $\beta_2 = 135^\circ$; $\beta_3 = = 105^\circ$; $\beta_4 = 75^\circ$; $\beta_5 = 45^\circ$.

Based on these parameters of rotating magnetomotive force function the conditional magnitudes $F_{s\,v}$ and relative magnitudes f_v of the space harmonics of magnetomotive force created by six-phase winding were calculated using expression (11) (Table 4).

Table 4. Harmonic analysis results of rotating magnetomotive force space function of two-layer preformed six-phase winding with $q = 2$ and the relative magnitudes of its space harmonics

No. of space harmonics	1	5	7	11	13
$F_{s\,v}$	1,767	–0,02	0,011	–0,021	–0,018
$f_v = F_{s\,v} / F_{s\,1}$	1	0,011	0,006	0,012	0,010

Table 4 (continued)

17	19	23	25	29	31	35	37
0,005	–0,005	0,077	–0,071	0,003	–0,003	0,007	0,006
0,003	0,003	0,044	0,040	0,002	0,002	0,004	0,003

In essence the magnetomotive forces of the higher-order space harmonics have a negative impact on the operation of the alternating current electrical machines, consequently they and their absolute relative magnitudes can be considered as negative. Negative relative magnitudes of magnetomotive force of the higher-order harmonics can be combined into a single equivalent relative magnitude which has to be compensated by magnetomotive force of the fundamental space harmonic. On the basis of this reasoning the six-phase windings, similarly as three-phase windings, from the electro-magnetical point of view can be evaluated using the electromagnetical efficiency factor which is expressed as [7]

$$k_{ef} = 1 - \sqrt{\sum_{v=1}^{\infty} f_v - 1}; \qquad (12)$$

here f_v – the relative magnitude of the v-th harmonic of rotating magnetomotive force.

On the basis of results of f_v presented in Table 5 the electromagnetical efficiency factor of two-layer preformed six-phase winding calculated according to expression (12) is $k_{ef} = 0{,}930$. This determined factor will be compared to the electromagnetical efficiency factor of the analogous three-phase winding.

For the purpose of comparison of analyzed winding the two-layer preformed three-phase winding of the following parameters was used: number of poles $2p = 2$, number of sections in the group $q = 2$, number of slots of stator magnetic circuit $Z = 2p\,m\,q = = 2 \cdot 3 \cdot 2 = 12$, pole pitch $\tau = Z / (2p) = 12 / 2 = 6$, winding span $y = 5\,\tau/6 = 5 \cdot 6 / 6 = = 5$, magnetic circuit slot pitch in electrical degrees $\alpha = = 360^\circ p / Z = 360^\circ \cdot 1 / 12 = 30^\circ$. The development of the electrical circuit of this winding and the spatial distribution of its rotating magnetomotive force in the moment of time $t = 0$ is shown in Fig. 2 [8].

For this three-phase winding the relative magnitudes of the number of effective conductors of single magnetic circuit slot and number of coil turns are the same as in case of the analyzed six-phase winding. The instantaneous values of the phase winding currents expressed in relative magnitudes in the moment of time $t = 0$ will be the following:

$$i_U^* = I_{m\,U}^* \sin \omega t = 0; \qquad (13)$$

$$i_V^* = I_{m\,V}^* \sin\left(\omega t - \frac{2\pi}{3}\right) = I_{m\,V}^* \sin\left(-120^\circ\right) = -0{,}866; \qquad (14)$$

$$i_W^* = I_{m\,W}^* \sin\left(\omega t - \frac{4\pi}{3}\right) = I_{m\,W}^* \sin\left(-240^\circ\right) = 0{,}866. \qquad (15)$$

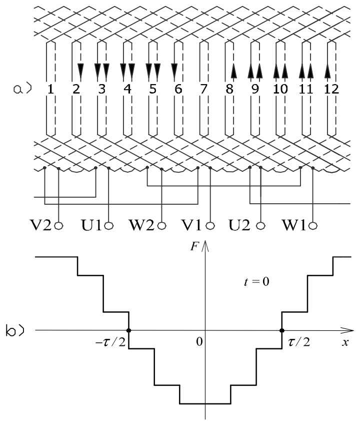

Fig. 2. Development of electrical circuit of two-layer preformed three-phase winding, in which $q = 2$, (a) and the distribution of its rotating magnetomotive force in the moment of time $t = 0$ (b)

The changes of magnetomotive force in the slots of magnetic circuit calculated according to expression (10) are graphically illustrated in Fig. 2, b. The harmonic analysis of instantaneous rotating magnetomotive force function of three-phase winding was performed on the basis of expression (11). The parameters of negative half-period of this magnetomotive force space function are such: $k = 3$; $F_{1s} = -0{,}2165$; $F_{2s} = -0{,}433$; $F_{3s} = -0{,}2165$; $\beta_1 = 180^\circ$; $\beta_2 = 120^\circ$; $\beta_3 = 60^\circ$ [8].

Conditional magnitudes $F_{s\,v}$ and relative magnitudes f_v of the space harmonics of rotating magnetomotive force created by the three-phase winding are given in Table 5.

Table 5. Harmonic analysis results of instantaneous rotating magnetomotive force space function of two-layer preformed three-phase winding with $q = 2$ and the relative magnitudes of its space harmonics

No. of space harmonics	1	5	7	11	13
$F_{s\,v}$	–0,891	0,013	–0,009	0,081	–0,069
$f_v = F_{s\,v} / F_{s\,1}$	1	0,015	0,010	0,091	0,077

Table 5 (continued)

17	19	23	25	29	31	35	37
0,004	–0,003	0,039	–0,036	0,002	–0,002	0,025	–0,024
0,004	0,003	0,044	0,040	0,002	0,002	0,028	0,027

On the basis of calculation results of f_v presented in Table 5 the electromagnetical efficiency factor of two-layer preformed three-phase winding calculated according to expression (12) is $k_{ef} = 0{,}856$.

After comparing the electromagnetical efficiency factors of two windings it is determined that this factor for the six-phase winding is 8,64 % higher that in case of the three-phase winding. Furthermore, the conditional magnitude of rotating magnetomotive force of the fundamental harmonic of the six-phase winding is 1,983 times higher compared to the three-phase winding.

Conclusions

1. The theory of the three-phase windings is suitable for the creation of the six-phase windings of alternating current electrical machines.
2. Since in the symmetrical six-phase voltage system the angles between adjacent phase vectors is 60°, thus the beginnings of the phases of the six-phase winding are allocated in space every 60 electrical degrees.
3. The rotating magnetomotive force created by the six-phase winding becomes closer to the sine distribution due to increased number of steps in its spatial distribution, compared to the rotating magnetomotive force of the three-phase winding of analogous parameters.
4. The electromagnetical efficiency factor of the six-phase winding ($k_{ef} = 0{,}930$) is 8,64 % higher than of the three-phase winding of analogous parameters ($k_{ef} = 0{,}856$).
5. The amplitude value of the fundamental harmonic of rotating magnetomotive force of the six-phase winding ($F_{m1} = 1{,}767$) is almost two times higher that the amplitude value of rotating magnetomotive force of the three-phase winding ($F_{m1} = 0{,}891$).

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The investigation of electromagnetical efficiency of the two-layer preformed six-phase winding is presented. At first the variation of phases of the six-phase windings was determined and, on the basis of the theory of three-phase windings, the development of the electrical circuit of the analyzed winding was formed. In order to determine the harmonic spectrum of rotating magnetomotive force created by the six-phase winding the instantaneous space function of rotating magnetomotive force was formed by using the created circuit and instantaneous values of the phase currents in the moment of time $t = 0$. The harmonic analysis of this function was performed and according to its results the electromagnetical efficiency factor of the analyzed six-phase winding was calculated. The obtained factor was compared to the electromagnetical efficiency factor of the two-layer preformed three-phase winding of analogous parameters and it was determined that it is 8,64 % higher than in the three-phase winding case. Additionally it was obtained that the amplitude value of the fundamental harmonic of rotating magnetomotive force of the analyzed six-phase winding is 1,983 times higher that the amplitude value of rotating magnetomotive force of the analogous three-phase winding. This means that the power factors of the alternating current electrical machines with the six-phase windings should be notably higher compared to the three-phase machines. Ill. 2, bibl. 8, tabl. 5 (in English; abstracts in English and Lithuanian).

J. Bukšnaitis. Šešiafazės apvijos elektromagnetinis efektyvumas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 3(119). – P. 3–6.

Atliktas dvisluoksnės forminės šešiafazės apvijos elektromagnetinio efektyvumo tyrimas. Pirmiausia nustatyta šešiafazių apvijų fazių kaita ir, remiantis trifazių apvijų teorija, sudaryta nagrinėjamos apvijos elektrinės schemos išklotinė. Šešiafazės apvijos kuriamos sukamosios magnetovaros harmoniniam spektrui nustatyti, pasinaudojus sudaryta schema ir fazinių srovių laiko momentu $t = 0$ akimirkinėmis vertėmis, sudaryta sukamosios magnetovaros akimirkinė erdvinė funkcija. Atlikta šios funkcijos harmoninė analizė ir pagal jos rezultatus apskaičiuotas nagrinėjamos šešiafazės apvijos elektromagnetinio efektyvumo koeficientas. Gautas koeficientas palygintas su analogiškų parametrų dvisluoksnės forminės trifazės apvijos elektromagnetinio efektyvumo koeficientu ir nustatyta, kad jis 8,64 % didesnis už pastarąjį. Be to, gauta, kad išnagrinėtos šešiafazės apvijos pagrindinės magnetovaros harmonikos amplitudinė vertė 1,983 karto didesnė už analogiškos trifazės apvijos šią amplitudinę vertę. Tai reiškia, kad kintamosios srovės elektros mašinų su šešiafazėmis apvijomis energiniai rodikliai turėtų būti pastebimai didesni nei trifazių mašinų. Il. 2, bibl. 8, lent. 5 (anglų kalba; santraukos anglų ir lietuvių k.).