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Research of Electromagnetic Parameters of Single-layer Three-phase and Six-phase Chain Windings

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***Abstract*—The research of electromagnetic parameters of single-layer three-phase and six-phase chain windings was accomplished. It was determined that the instantaneous space distributions of rotating magnetomotive force in the three-phase chain winding are asymmetrical in respect of coordinate axes and symmetrical in respect of the origin of these axes. Instantaneous space distributions of rotating magnetomotive force generated by six-phase chain winding, contrary to the three-phase windings, are symmetrical in respect of coordinate axes. After accomplishing harmonic analysis of spatial rotating magnetomotive forces, it was obtained, that odd and even harmonics exist in the harmonic magnetomotive force spectrum generated by three-phase winding, and only odd harmonics in the spectrum generated by six-phase winding. The electromagnetic efficiency factors were calculated for both types of windings, and it was determined that for six-phase winding this factor is 23,7 % higher compared to three-phase winding. Furthermore, it was estimated, that the conditional amplitude of fundamental magnetomotive force harmonic in the analyzed six-phase winding is 2,13 times larger compared to the same amplitude value in the analogous three-phase winding.**

***Index Terms*—Analysis, induction machine, multi-phase, chain winding, rotating magnetomotive force, harmonic spectrum, electromagnetic efficiency factor.**

I. INTRODUCTION

During the last decade a lot of scientific investigations of alternating current six-phase machines were accomplished. In paper [1], [2] an investigation of operating stability of a multi-phase (six-phase) non-symmetric asynchronous machine, which operates in transmission mode under effect of various disturbances, was performed. Investigation was done on a theoretical basis by creating the mathematical model of this machine in a matrix form. Functions of transient processes were written using typical linear model. Using this model, a numerical modelling was accomplished and operating non-stability zones of asynchronous six-phase motor were determined.

In paper [3] a symmetric six-phase asynchronous machine was used for researching the stator windings which are displaced in space by 60°. This machine was analysed in various operating modes, while increasing its rotation speed, decreasing it, changing direction of rotation, etc. Using rotor flux control the transient process characteristics of these operating modes were created.

In work [4] a direct torque control method was presented, which is novel to a six-phase asynchronous machine. During application of this technique, a matrix converter was used together with ordinary three-phase source. Modelling results indicated the efficiency of the proposed method during analysis of six-phase asynchronous machine in dynamic and steady-state operating modes.

In paper [5], [6] the experimental investigation of six-phase synchronous generator operating in hydro power station was accomplished. It was substantiated that such generator could be loaded using two different three-phase loads, what gives it an additional advantage. It was also determined that six-phase synchronous generators have higher reliability, stability of voltage in terminals and its frequency compared to three-phase generators.

In paper [7] an analysis of magnetic field generated using different number of phase windings, while supplying them from non-sinusoidal system of voltages, was performed. It was determined that three-phase windings operating under such conditions are the most optimal.

Both of three-phase and six-phase chain windings are single-layer, i.e. each magnetic circuit slot of these windings inside the electrical machine contains only one active coil side. These windings are constructed as distributed windings, in which q = 2; 3; ..., here q – number of coils in the phase winding coil group (number of pole and phase slots). Additionally, both these windings with different number of phases are with reduced winding-span ($y < \tau$, here y – winding span; τ – pole pitch). The span of a three-phase chain winding $y = (2q + 1) < \tau$, and for six-phase winding – $y = (4q + 1) < \tau$. As it is known, winding spans of other types of single-layer three-phase windings match the pole pitches, i.e. pole pitch windings, and all single-layer six-phase windings are reduced-span windings. This is the largest advantage of these windings over single-layer three-phase windings.

The objective of this research is to analyse a single-layer six-phase chain winding of certain parameters by determining its electromagnetic factors, and then to compare them with the same factors of three-phase chain winding of

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analogical parameters.

II. Research Object

Parameters of three-phase and six-phase single-layer chain windings which were used for the purposes of investigation are presented in Table I.

TABLE I. PARAMETERS OF THREE-PHASE AND SIX-PHASE SINGLE-LAYER CHAIN WINDINGS.

Winding parameters	**Investigated windings**	
	1	**2**
Number of phases (m)	3	6
Number of poles ($2p$)	2	2
Number of pole and phase slots (q)	2	2
Number of magnetic circuit slots (Z)	12	24
Pole pitch (τ)	6	12
Winding span (y)	5	9
Slot pitch in electrical degrees (α)	30°	15°

Alternation of six-phase winding phases belongs to the positive sequence, since the fundamental rotating magnetic field harmonic induced by these windings is the first space harmonic which belongs to this sequence. Then spatial distribution of phase winding beginnings and ends of analysed winding must be as denoted here: U1; W2; X1; Z2; V1; U2; Y1; X2; W1; V2; Z1; Y2. Such arrangement is supported by Fig. 1. Given phase change sequence corresponds to one pair of poles of induced rotating magnetic field.

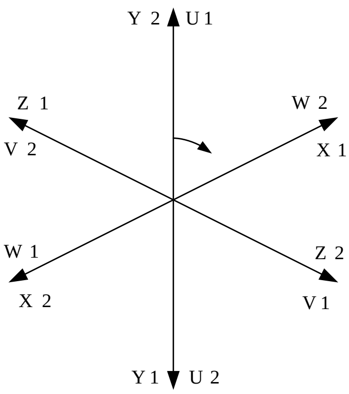

Fig. 1. Positive sequence phase change of a six-phase winding.

Distribution of the six-phase chain winding active coil sides into slots of magnetic circuit is described in Table II.

TABLE II. DISTRIBUTION OF THE SINGLE-LAYER SIX-PHASE CHAIN WINDING ACTIVE COIL SIDES INTO 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.	1; 3	2; 4	5; 7	6; 8	9; 11	10; 12
Phase change	**Y1**	**X2**	**W1**	**V2**	**Z1**	**Y2**
Slot No.	13; 15	14; 16	17; 19	18; 20	21; 23	22; 24

According to the data from Table II the electric circuit layout of the six-phase chain winding is created (Fig. 2(a)).

The electrical circuit layout of the three-phase chain winding is created (Fig. 3(a)).

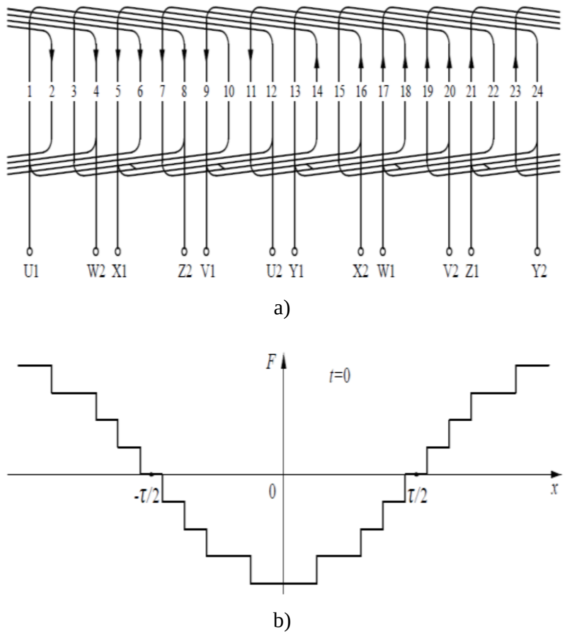

Fig. 2. Layout of electrical circuit of single-layer six-phase chain winding (a) and the distribution of its rotating magnetomotive force in the moment of time $t = 0$ (b).

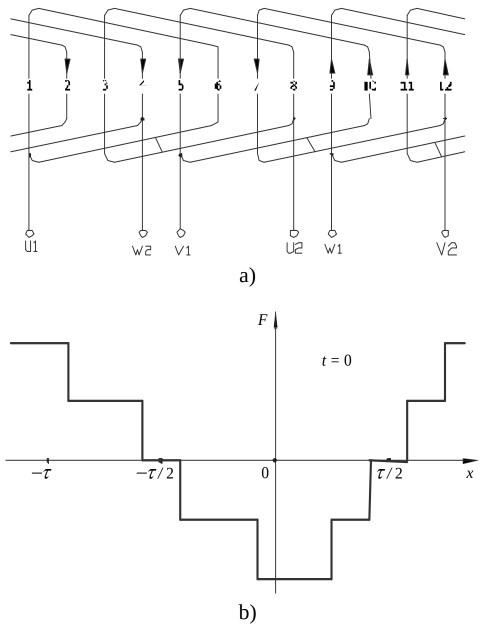

Fig. 3. Layout of electrical circuit of single-layer three-phase chain winding (a) and the distribution of its rotating magnetomotive force in the moment of time $t = 0$ (b).

III. Research Method

Research of electromagnetic factors of considered windings was accomplished using instantaneous space functions of rotating magnetomotive forces. These functions are created on the basis of electrical circuits and electric current phasor diagrams of analysed chain winding, according to which the conditional current strengths and flow directions are determined in the selected moment of time. For analysed windings, the relative magnitude of number of turns in a single coil $N^{\bullet} = 1/q = = 1/2 = 0,5$.

Amplitudes of the flowing phase currents in both windings $I^{\bullet}_{\mathrm{m}}$ are considered to be equal to unit (conditional current amplitudes). The instantaneous values of currents at time moment t = 0 would be as expressed:

$$i^{*}_{\mathrm{U}} = I^{*}_{\mathrm{mU}} \sin \omega\, t = 0, \tag{1}$$

$$i^{*}_{\mathrm{X}} = I^{*}_{\mathrm{mX}} \sin\left(\omega t - \frac{2\pi}{6}\right) = I^{*}_{\mathrm{mX}} \sin\left(-60^{\circ}\right) = -0{,}866, \tag{2}$$

$$i^{*}_{\mathrm{V}} = I^{*}_{\mathrm{mV}} \sin\left(\omega t - \frac{4\pi}{6}\right) = I^{*}_{\mathrm{mV}} \sin\left(-120^{\circ}\right) = -0{,}866, \tag{3}$$

$$i^{*}_{\mathrm{Y}} = I^{*}_{\mathrm{mY}} \sin\left(\omega t - \frac{6\pi}{6}\right) = I^{*}_{\mathrm{mY}} \sin\left(-180^{\circ}\right) = 0, \tag{4}$$

$$i^{*}_{\mathrm{W}} = I^{*}_{\mathrm{mW}} \sin\left(\omega t - \frac{8\pi}{6}\right) = I^{*}_{\mathrm{mW}} \sin\left(-240^{\circ}\right) = 0{,}866, \tag{5}$$

$$i^{*}_{\mathrm{Z}} = I^{*}_{\mathrm{mZ}} \sin\left(\omega t - \frac{10\pi}{6}\right) = I^{*}_{\mathrm{mZ}} \sin\left(-300^{\circ}\right) = 0{,}866. \tag{6}$$

Instantaneous changes of magnetomotive force below slots of magnetic circuit are calculated as

$$\pm\Delta F = \pm i^{\bullet}_{f} N^{\bullet}, \tag{7}$$

where $\pm i^{\bullet}_{f}$ – conditional instantaneous current in the phase winding.

On the basis of (7) the instantaneous space distributions of magnetomotive force in the selected moment of time are created (Fig. 2(b) and Fig. 3(b)). Obtained instantaneous rotating magnetomotive force functions are expanded using Fourier series according to the following [8]:

$$F_{\nu' m} = \frac{4}{\pi \nu'} \sum_{i=1}^{k} F_i \sin\left(\nu' \frac{\beta_i}{2}\right) \cos\left(\nu' \gamma_i\right), \tag{8}$$

$$F_{\nu'' m} = \frac{4}{\pi \nu''} \sum_{i=1}^{k} F_i \sin\left(\nu'' \frac{\beta_i}{2}\right) \sin\left(\nu'' \gamma_i\right), \tag{9}$$

where $F_{\nu'('')m}$ – amplitude of ν-th harmonic of rotating magnetomotive force; F_i – conditional height of the i-th rectangle of the stair-shaped magnetomotive force half-period; β_i – width of the i-th rectangle of the stair-shaped magnetomotive force half-period, expressed in electrical degrees; γ_i – asymmetry of the i-th rectangle of the stair-shaped magnetomotive force half-period in respect of central axis of this half-period, expressed in electrical degrees; k – number of rectangles which constitute the stair-shaped magnetomotive force half-period; ν' – series number of odd space harmonic; ν'' – series number of even space harmonic.

According to the results of harmonic analysis the electromagnetic efficiency factors of the analysed windings are calculated [8]

$$k_{ef} = 1 - \sqrt{\sum_{\nu=1}^{\infty} f_{\nu}^{2} - 1}, \tag{10}$$

where $f_{\nu} = F_{\nu'('')m} / F_{1m}$ – relative magnitude of the ν-th harmonic of rotating magnetomotive force.

IV. RESEARCH RESULTS

According to (7) and on the basis of Fig. 2(a), the conditional instantaneous changes in magnitude of magnetomotive force below the slots of magnetic circuit in the instant of time t = 0 are determined (Table III).

TABLE III. CONDITIONAL INSTANTANEOUS CHANGES OF MAGNETOMOTIVE FORCE BELOW THE SLOTS OF MAGNETIC CIRCUIT OF SIX-PHASE CHAIN WINDING IN THE MOMENT OF TIME T = 0.

Slot No.	1	2	3	4	5	6
Conditional changes	0	–0,433	0	–0,433	–0,433	–0,433

TABLE III. (CONTINUED)

7	8	9	10	11	12	13	14	15
–0,433	–0,433	–0,433	0	–0,433	0	0	0,433	0

TABLE III. (CONTINUED)

16	17	18	19	20	21	22	23	24
0,433	0,433	0,433	0,433	0,433	0,433	0	0,433	0

According to results from Table III, the space distribution of instantaneous rotating magnetomotive force in a defined moment of time was created (Fig. 2(b)).

For the analysed six-phase chain winding, the harmonic analysis equations of rotating magnetomotive force (Fig. 2(b)) in the moment of time t = 0, after substituting known magnitudes into (8) and (9), are the following:

$$F_{\nu' m} = -\frac{4}{\pi \nu'} 0{,}433\left[\sin\left(\nu' 82{,}5^{\circ}\right) + \sin\left(\nu' 67{,}5^{\circ}\right) + \right.$$
$$\left. + \sin\left(\nu' 52{,}5^{\circ}\right) + \sin\left(\nu' 22{,}5^{\circ}\right)\right], \tag{11}$$

$$F_{\nu'' \mathrm{m}} = 0. \tag{12}$$

Conditional and relative magnitudes of rotating magnetomotive force space harmonics calculated according (11) and (12) are listed in Table IV.

TABLE IV. THE RESULTS OF HARMONIC ANALYSIS OF SIX-PHASE CHAIN WINDING INSTANTANEOUS ROTATING MAGNETOMOTIVE FORCE FUNCTION AND THE RELATIVE MAGNITUDES OF ITS SPACE HARMONICS.

Series No. of space harmonic	1	5	7	11	13
$F_{\nu\,\mathrm{m}}$	–1,704	–0,038	–0,065	0,064	0,054
f_{ν}	1	0,022	0,038	0,038	0,032

TABLE IV (CONTINUED)

17	19	23	25	29	31	35
–0,027	–0,010	–0,074	0,068	0,007	0,015	0,020
0,016	0,006	0,043	0,040	0,004	0,009	0,012

According to relative magnitudes f_{ν} of rotating magnetomotive force space harmonics from Table IV, the electromagnetic efficiency factor of the six-phase chain winding calculated by (10) was $k_{\mathrm{ef}\,2}$ = 0,9085.

The conditional instantaneous changes of magnetic tension below the slots of magnetic circuit in the moment of time t = 0 are calculated using (7) and data from Fig. 3 (Table V).

According to results from Table V, the space distribution of instantaneous rotating magnetomotive force in a defined moment of time was created (Fig. 3(b)).

TABLE V. CONDITIONAL INSTANTANEOUS CHANGES OF MAGNETIG TENSION BELOW THE SLOTS OF MAGNETIC CIRCUIT OF THREE-PHASE CHAIN WINDING IN THE MOMENT OF TIME $T = 0$.

Slot No.	1	2	3	4	5	6	7	8	9	10	11	12
Conditional changes	0	–0,433	0	–0,433	–0,433	0	–0,433	0	0,433	0,433	0,433	0,433

For the analyzed three-phase chain winding, the harmonic analysis equations of rotating magnetomotive force (Fig. 3(b)) in the moment of time t = 0, after substituting known magnitudes into (8) and (9), are the following:

$$F_{\nu' m} = -\frac{4}{\pi \nu'} 0,433 \Big[\sin\left(\nu' 75^\circ\right) \cos\left(\nu' 0^\circ\right) + $$
$$+ \sin\left(\nu' 30^\circ\right) \cos\left(-\nu' 15^\circ\right) \Big], \qquad (13)$$

$$F_{\nu'' m} = -\frac{4}{\pi \nu''} 0,433 \Big[\sin\left(\nu'' 75^\circ\right) \sin\left(\nu'' 0^\circ\right) + $$
$$+ \sin\left(\nu'' 30^\circ\right) \sin\left(-\nu'' 15^\circ\right) \Big]. \qquad (14)$$

Conditional and relative magnitudes of rotating magnetomotive force space harmonics calculated according (13) and (14) are listed in Table VI.

TABLE VI. THE RESULTS OF HARMONIC ANALYSIS OF THREE-PHASE CHAIN WINDING INSTANTANEOUS ROTATING MAGNETOMOTIVE FORCE FUNCTION AND THE RELATIVE MAGNITUDES OF ITS SPACE HARMONICS.

Series No. of space harmonic	1	2	4	5	7	8	10	11	13	14	16	17
$F_{\nu m}$	–0,799	0,119	0,103	–0,043	–0,031	–0,052	–0,024	–0,073	0,061	–0,017	–0,026	0,013
f_ν	1	0,149	0,129	0,054	0,039	0,065	0,030	0,091	0,076	0,021	0,033	0,016

Series No. of space harmonic	19	20	22	23	25	26	28	29	31	32	34	35
$F_{\nu m}$	0,011	0,021	0,011	0,035	–0,032	0,009	0,015	–0,007	–0,007	–0,013	–0,007	–0,023
f_ν	0,014	0,026	0,014	0,044	0,040	0,011	0,019	0,009	0,009	0,016	0,009	0,029

According to relative magnitudes f_ν of rotating magnetomotive force space harmonics from Table VI, the electromagnetic efficiency factor of the three-phase chain winding calculated by (10) was $k_{ef\,1}$ = 0,7341.

V. CONCLUSIONS

1. The instantaneous space functions of rotating magnetomotive force in a single-layer three-phase chain winding are asymmetrical in respect of coordinate axes and symmetrical in respect of the origin of these axes; therefore this winding generates not only odd but also even (not multiples of three) magnetomotive force harmonics.
2. Instantaneous space functions of rotating magnetomotive force in a single-layer six-phase chain winding are symmetrical in respect of coordinate axes; therefore this winding generates only odd (not multiples of three) magnetomotive force harmonics.
3. The electromagnetic efficiency factor of six-phase chain winding (k_{ef2} = 0,9085) is 23,7 % higher than of the three-phase chain winding of analogical parameters (k_{e1} = 0,7341).
4. The conditional magnitude of the first rotating magnetomotive force harmonic in the six-phase chain winding (1,704) is 2,13 times larger compared to the same magnitude of the researched three-phase winding (0,799).
5. According to its electromagnetic parameters, the six-phase chain winding is significantly superior to the three-phase chain winding.
6. After performing the investigations, it was determined, that the six-phase chain winding is significantly superior to the three-phase chain winding according to its electromagnetic parameters.

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