Research of Six-Phase Induction Motor Windings

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Abstract—**Advantages of multi-phase motors raise interest in its construction. The article deals with elaboration of schemes of six-phase induction motor winding, calculation and analysis of magnetomotive forces and comparison of two type six phase motor windings: concentrated double layer full pitch coil six-phase winding and short pitch coil six-phase winding.**

Index Terms—**Six-phase induction motor, magneto motive force, six-phase winding, Fourier spectrum.**

I. INTRODUCTION

In early 1990s, study on multiphase machines accelerated until the beginning of recent century, it became practical in industries.

Multiphase motor drives have been proposed for different applications. Some of the most suitable applications are electric, hybrid electric vehicles and locomotive traction [1], [2], the concept of „more – electric" aircraft [3], ship propulsion [4]. Other suitable applications are aerospace and high power applications (including nuclear power plants) [5].

Multi-phase machines drive has many advantages over conventional three-phase drive such as increased torque per ampere for the same volume machine, reduced stator copper losses, reduced rotor harmonic currents, high power handling capability by dividing the required power between multiple phases, reduced torque pulsations and higher reliability [6], [7]. In particular, unlike in a three phase drive, the loss of stator phase does not prevent the machine from starting and running [8].

A comprehensive survey of the state-of-the-art in development and investigation of multiphase induction motors is presented in [9]. Advantages of those motors raise some specific problems to be solved and investigations of the motors continued including numerous cases of control modes. As multiphase motor for a while cannot be purchased in the store, usually it is made by rewinding of three phase motors with greater number of slots. Therefore multiphase motor has smaller number of slots per phase than three-phase motor; this causes a great number of spatial harmonics, increasing heat loss in the motor. Suitable choice of winding type allows increasing the fundamental harmonic

and reducing spatial harmonics, which are able to cause torque pulsations.

This paper presents investigation of two types windings for six-phase induction motor, shows elaborated connection of winding sections and comparison of two types concentrated double layer windings: short pitch coil six-phase winding and full pitch coil six-phase winding, calculation and analysis of developed magnetomotive forces and spatial harmonics.

II. WINDINGS OF SIX-PHASE INDUCTION MOTOR

Double layer windings have many advantages over single layer windings: easier to manufacture and lower cost of coils, fractional-slot can be used, chorded-winding is possible, lower leakage reactance and therefore, better performance of the machine [10], [11]. Parameters of stator winding are: total number of slots $S = 48$, number of poles $2P = 8$, number of phase $m = 6$, pole pitch $= 6$, slot angular pitch $x = 30°$, number of slots per pole per phase $q = 1$, coil pitch $y = 5$, phase spread $† = 60°$, angle between stator current phasors is $60°$. Elaborated connection scheme of winding sections is presented in Fig. 1.
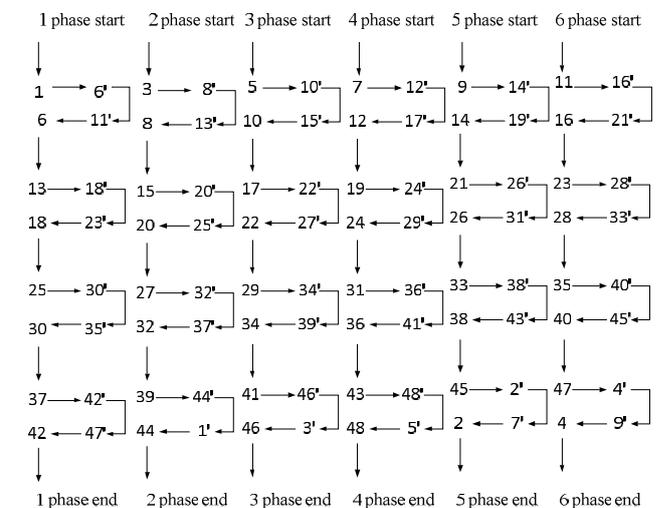

Fig. 1. Connection of winding sections.

Concentrated double layer short pitch coil six-phase winding and magnetomotive force is presented in Fig. 2.

In the case of concentrated double layer short pitch coil

six-phase winding, instantaneous current values, at the pole pitch margins, are the same in upper and lower levels of five slots and only once the values of instantaneous current in upper and lower levels are different.

The other type stator winding parameters are: total number of slots $S = 48$, number of poles $2P = 8$, number of phase $m = 6$, pole pitch $\tau = 6$, slot angular pitch $\chi = 30°$, number of slots per pole per phase $q = 1$, coil pitch $y = 6$, phase spread $\dagger = 60°$, angle between stator current phasors is $60°$. Connection of winding sections is presented in Fig. 3. Concentrated double layer full pitch coil six-phase winding and its magnetomotive force is presented in Fig. 4.

In case of concentrated double layer full pitch coil six-phase winding, instantaneous current values, at the pole pitch margins, are the same in all upper and lower levels of slots.
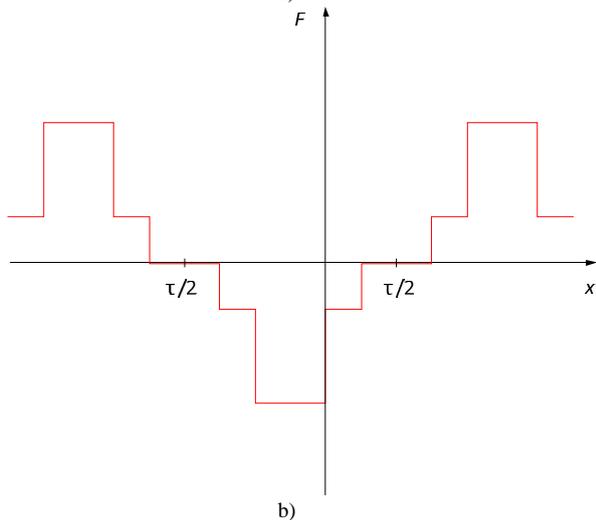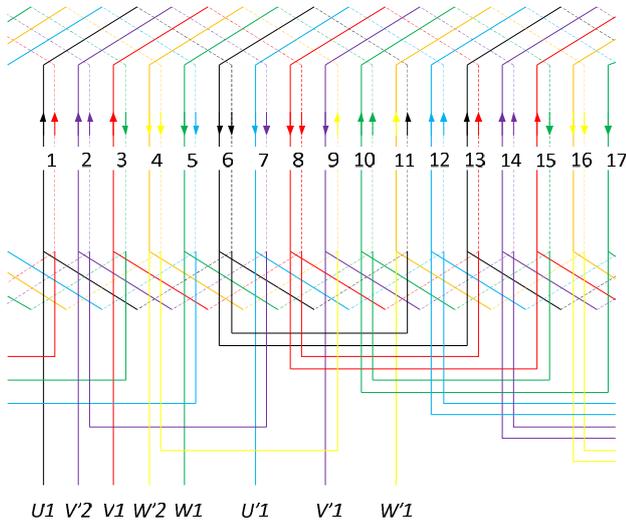

Fig. 2. Concentrated double layer short pitch coil six-phase winding: a – section of winding, b – magnetomotive force of that section.

Analysis of the considered short pitch coil winding indicates, that during one pole pitch the relative magnetomotive force $F_1(\ )$ has the shape, shown in Fig. 5.

Space harmonic spectrum of each winding magnetomotive force can be obtained on the base of Fourier series [12]. The Fourier transform coefficients of the function $F_1(\ )$, shown in Fig. 5 are calculated in this way [13], [14]

$$b_{1,k} = \frac{2A_1}{f} \int\limits_{f/6}^{5f/6} \sin k\text{W}\, d\text{W} + \frac{2A_2}{f} \int\limits_{f/3}^{2f/3} \sin k\text{W}\, d\text{W} =$$

$$= \frac{4}{fk}\left(A_1 \sin\frac{fk}{3} + A_2 \sin\frac{fk}{6}\right)\sin\frac{fk}{2}, \qquad (1)$$

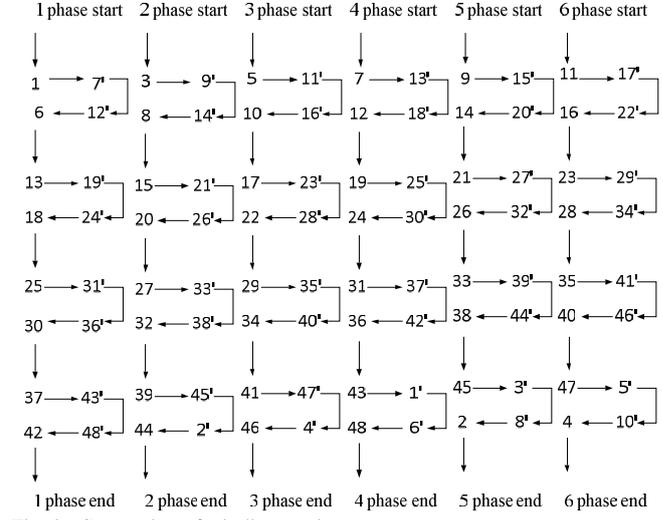where $A_1 = 1/3$ and $A_2 = 2/3$ are amplitudes of relative magnetomotive force components.

Fig. 3. Connection of winding sections.

The Fourier series coefficients were calculated according to (1).

The Fourier series is expressed as [12]

$$F_{1,\Sigma K} = \sum_{k=0}^{K} b_{1,k} \sin k\text{W}. \qquad (2)$$

Fourier series of function $F_1(\ )$ at $k = 0, 1,\ldots, 50$ is presented in Fig. 5 and denoted as $F_{1,\ 50}(\ )$.

Analysis of the full pitch coil winding shows, that relative magnetomotive force $F_2(\ )$ in the one pole pitch displacement varies in the way, shown in Fig. 6.

Fourier series coefficients of function $F_2(\ )$ are calculated in the form

$$b_{2,k} = \frac{2A_1}{f} \int\limits_{f/4}^{3f/4} \sin k\text{W}\, d\text{W} + \frac{2A_2}{f} \int\limits_{5f/12}^{7f/12} \sin k\text{W}\, d\text{W} =$$

$$= \frac{4}{fk}\left(A_1 \sin\frac{fk}{4} + A_2 \sin\frac{fk}{12}\right)\sin\frac{fk}{2}, \qquad (3)$$

where $A_1 = 1/2$ and $A_2 = 1/2$ are amplitudes of relative magnetomotive force components.

In accordance with (3) the series can be rewritten in the form

$$F_{2,\Sigma K} = \sum_{k=0}^{K} b_{2,k} \sin k\text{W}. \qquad (4)$$

Fourier series of function $F_2(\ )$ at $k = 0, 1, \ldots, 50$ is presented in Fig. 6 and denoted as $F_{2,\ 50}(\ )$.

Analysis of magnetomotive forces gives information about higher harmonics, appearing in the air gap.
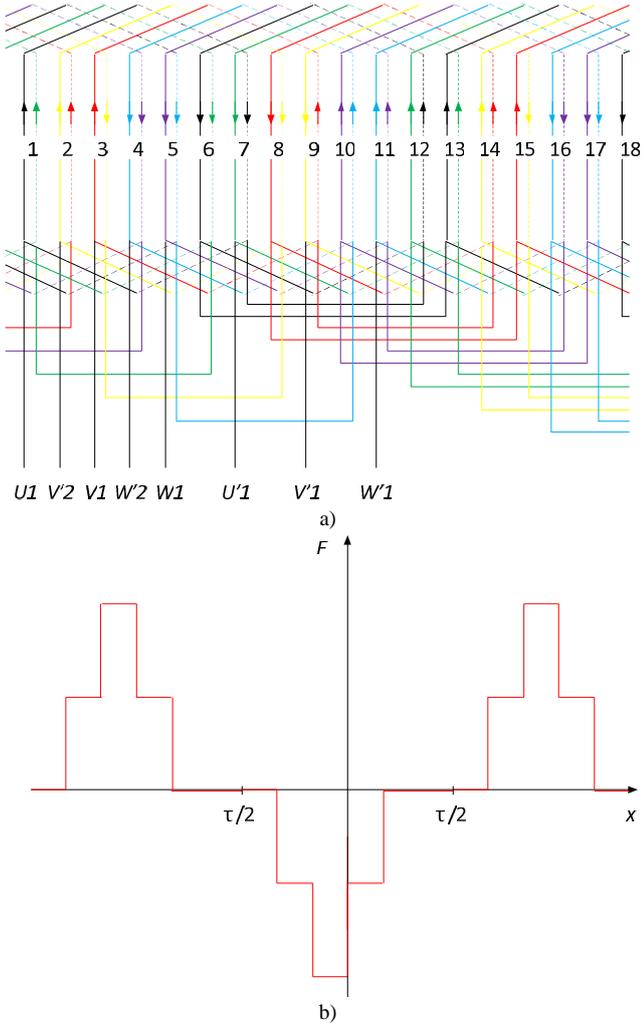
a)

b)

Fig. 4. Concentrated double layer full pitch coil six-phase winding: a – section of winding, b – magnetomotive force of that section.
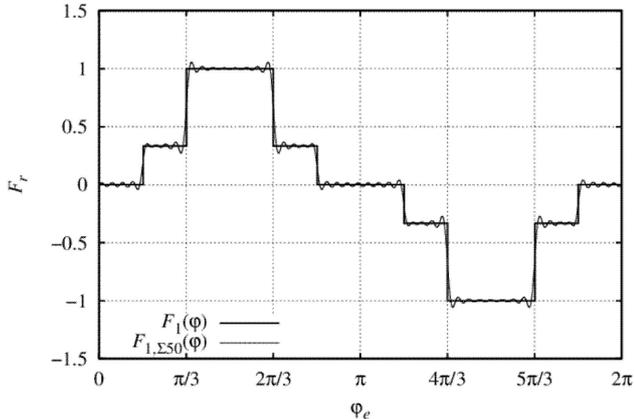

Fig. 5. Relative magnetomotive force $F_1(\ )$ and its approximation by Fourier series $F_{1,\ 50}(\ )$ of short pitch coil winding.

Comparing the amplitude b_{2k} of k-th harmonic magnetomotive force $F_2(\ )$ with amplitude b_{1k} of k-th harmonic magnetomotive force $F_1(\ )$, the difference between those is calculated and expressed in percent as

$$u_k = \frac{\left|b_{2,k}\right| - \left|b_{1,k}\right|}{b_{1,1}}100\%. \qquad (5)$$

Figure 6 indicates, that the short pitch coil six-phase winding has significantly greater the first harmonic (by

22 %). Analysis of (1) and (2) shows, that the first harmonic of this winding approximately is equal to 0.8 and that of the full pitch coil six-phase winding is smaller – reaches 0.6 as shown in Fig. 8. So from the point of view of the first harmonic the motor with the short pitch coil six-phase winding will have higher efficiency.

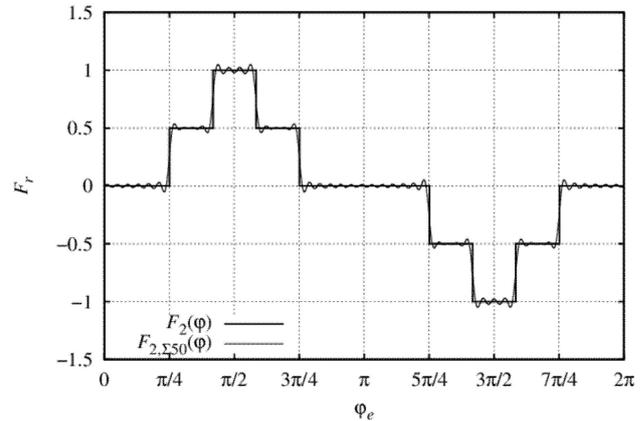Analysis shows, that even harmonics have the same amplitude. According to (1) and (3), they are equal to zero.

Fig. 6. Relative magnetomotive force $F_2(\ )$ and its approximation by Fourier series $F_{2,\ 50}(\ )$ of full pitch coil winding.

The spectrum of magnetomotive forces for short pitch coil six phase winding and full pitch winding is presented accordingly in Fig. 7 and Fig. 8.
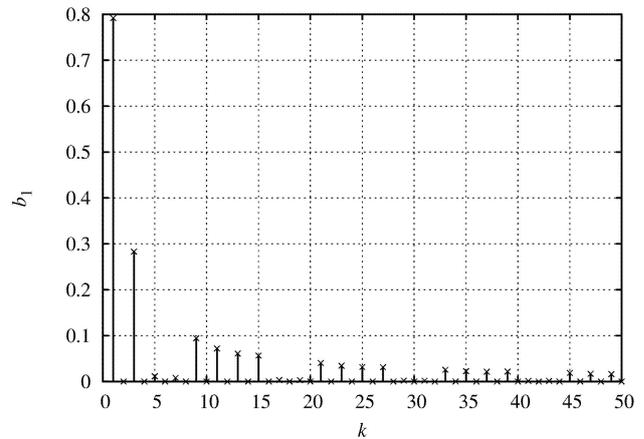

Fig. 7. The spectrum of magnetomotive force harmonics of short pitch coil six phase winding.

From Fig. 7 and Fig. 8 can be evidently seen, that difference of higher odd harmonics $|b_{2,1}| - |b_{1,1}| > 0$. That indicates the odd higher harmonics of full pitch coil winding having greater amplitude. While the higher harmonics increase torque oscillations and heat loss, it is possible to state, that the short pitch coil winding has greater efficiency.

Dependence of harmonic amplitude difference $_k$ against harmonic number k is shown in Fig. 9. The first harmonic of full pitch coil winding is smaller by 22 % from that of short pitch coil winding, while the third, fifth, seventh and ninth harmonics are greater, but no more than 5 %, the eleventh and thirteen are smaller about 2 %.

Research indicated that according to the harmonic spectrum, the short pith coil winding has greater efficiency than full pith coil winding.
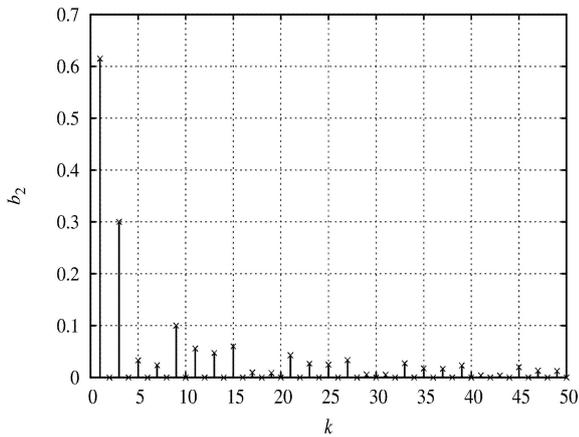
Fig. 8. The spectrum of magnetomotive force harmonics of short pitch coil six phase winding.

Experimental motor was made according to concentrated double layer short pitch coil six-phase winding connection scheme.
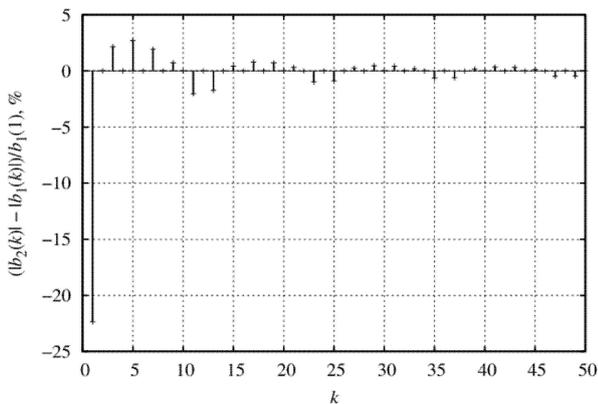

Fig. 9. Dependence of harmonic amplitude difference $_k$ against harmonic number k.

Figure 10 shows general view of stator with concentrated double layer short pitch coil six-phase winding.
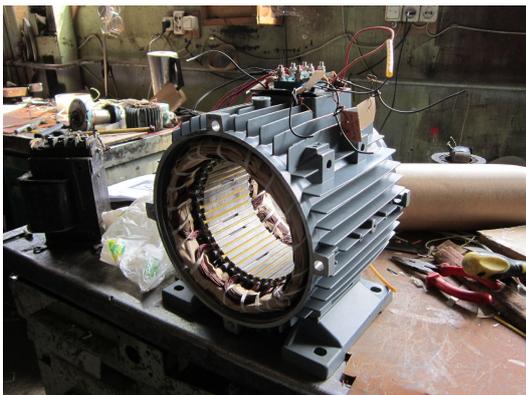

Fig. 10. Experimental six-phase induction motor with concentrated double layer short pitch coil winding.

Each section of experimental induction motor winding consist of 160 turns with wire diameter of 0.4 mm. Six-phase induction motor with concentrated double layer short pitch coil winding was successfully tested.

III. CONCLUSIONS

Two types of six phases motor windings connections are proposed: concentrated double layer short pitch coil winding and concentrated double layer full pitch coil winding.

The relative magnetomotive forces are calculated. Space harmonic spectrum of each winding magnetomotive force was obtained on the base of Fourier series.

Analysis of Fourier special spectrum shows, that even harmonics for concentrated double layer short pitch coil six phase winding and concentrated double layer full pith coil six phase winding are equal to zero.

Concentrated double layer short pith coil six phase winding has the first harmonic greater by 22 % compared with concentrated double layer full pith coil six phase winding.

Research indicated that according to the harmonic spectrum, the short pith coil winding has greater efficiency than full pith coil.

Experimental six-phase induction motor with concentrated double layer short pitch coil winding was made and successfully tested.

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