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Arranging coil winding circuits of synchronous permanent-magnet machines on rotor

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ABSTRACT

Methodology of constructing coil winding electrical circuits for salient-pole stator of electrical permanent-magnet machines on the rotor is proposed, which is based on the required number of pole pairs (synchronous speed) and the number of phases. The methodology algorithm is based on determining the value of the number of stator teeth as the closest to the number of rotor poles number value, multiple of phase number, which provides a sufficient level of pitch coefficient and winding coefficient. The algorithm was tested by several examples of constructing synchronous machines winding circuits, known from electrical engineering theory and practice, including mass-produced ones. In all the examples, if the proposed methodology guidelines were formally and strictly followed, the correct circuit designs came out as a result. For high power motor pilot design, one and the same machine design variants were compared, having thirty six slots on stator, three-phase and nine-phase windings, synthesized according to the proposed algorithm for thirty two-pole rotor. Engine torque calculation with both circuit options performed by finite elements method showed the nine-phase winding developed torque advantage by 20%, due to less discretion of MMF slot distribution.

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1. INTRODUCTION

In the last few decades application area of permanent-magnet machines (magnetoelectric) in electric drives of various purposes has considerably increased [1]–[5]. This is happening due to large-scale production engineering of intra rare-earth alloy (IE) magnets, neodymium-base and samarium with cobalt-base. In many technical fields, in particular in unmanned aerial vehicles, manipulators, ground transport, rehabilitation technologies, their implementation brought about quantum (almost revolutionary) growth of these objects' performance characteristics.

There is a great variety of structural designs of permanent-magnet machines [6]–[9]. However, alternate-pole machines, which provide excitation flux direction change along air gap circle, deserve special attention [10]–[12]. Permanent magnets in such machines are located on the rotor and form alternating polarity poles. Compared to inductor machines [13], in which excitation flux in the air gap is not reversed, these are able to develop twice as big torque in the same dimensions.

When constructing low power, medium-power and, in frequently, high-power machines of such type, design engineers nowadays try to avoid low-tech distributed armature winding on the stator with space-intersecting end windings, and turn to a simpler variant: with lumped coils, i.e. – coil winding. Every coil of coil winding covers one salient pole-tooth of stator magnetic circuit, its slot pitch being one (y = 1). Apart from technological advantages, such solution provides high mechanical strength of the winding and stator itself, as well as better heat abstraction from end windings due to their abutment to the core surface.

The existing algorithms and methods for the formation of the armature windings circuits of electrical machines, considered in the classical theory, involve the distribution of coils under different magnetic poles and their connection into parallel branches in accordance with the rules for the formation of loop, wave or single-layer windings [10]–[12]. These algorithms are not quite suitable for the formation of coil winding circuits, since the location of the coil sides in adjacent slots leads to underutilization of winding copper due to the low value of the shortening factor, the winding coefficient as a whole in winding circuits built in accordance with their logic.

2. METHOD

The authors propose an algorithm for constructing circuits of coil windings with a high winding coefficient, due to the special logic of the distribution of coils in phase zones. In order for the pitch coefficient to be close to unity it is necessary that the number of armature teeth slightly increases the number of poles formed by rotor magnets. It is possible to fulfil this condition only by using windings with a broken number of slots per pole and phase, which is considerably less than unity and slightly 10-30% exceeding the value reciprocal to the number of phases m. By substituting y = 1 in the known expression for pitch coefficient [10], [11], we obtain:

$$K_{\mathrm{y}} = \frac{\pi p}{Z}. \tag{1}$$

Thus, irrespective of the number of phases m, in order to obtain the acceptable pitch coefficient value of the winding consisting of coils with their sides located in neighboring slots, it is necessary that the number of slots Z, in which it is housed, approximately two times exceeds the number of pole pairs p, formed by it. Hence, it is possible to establish the following sequence (algorithm) of arranging winding diagrams, consisting of coils, with coil sides located in neighboring slots.

i) Selecting the number of pole pairs 2p and phases m according to the technical requirements. The number of pole pairs p is set depending on the rated speed, frequency range of the frequency converter and the technological factor depending on the optimal ratio of the length of the pole division of the rotor to its diameter, individual for each design scheme of the rotor.
ii) Determining the number of teeth Z, as one of the closest to 2p number value,

$$Z = \frac{2p \pm d}{m}, \tag{2}$$

where d – numerator addition or diminution to the fraction integral value (2). Larger value Z option according to (2) matches coil shortening compared to polar pitch. Smaller value Z option according to (2) matches coil elongation, which is not recommended by theory and practice of electrical machines distributed winding [13], [14]due to excessive wire copper usage, however it appropriate for coil windings. Zero valued (d=0) is excluded due to unacceptable torque pulsations initiation.
iii) Phase band coil distribution. The following options are possible:
   - At uneven value Z, which is possible in low-power machines and micromachines, all the phase coils are laid out nearby and occupy one phase band, constituting 1/m part of stator circle;
   - At even value Z, coils of each phase are distributed into two phase bands of Z/(2m) nearby laid out coils on the teeth of two diametrically opposite sectors of the stator circle;
   - At Z multiple of four, a higher winding coefficient is obtained by distributing coils into four phase bands consisting of Z/(4m) coils in each one and located in sectors 90° apart from each other.
iv) Within the phase bands, coils are connected in coil groups with series back-to-back connection of the coils.
v) Coil groups are connected with each other in series back-to-back; when bypassing the stator circle - in series or in parallel.

vi) Coils of the remaining phases are connected in the same manner as the first one, incorporating into the remaining phases the coils, displaced from the initial phase coils through 360/*m* angle of electrical degrees.

3. RESULTS AND DISCUSSION

Let us consider the above sequence by several theoretical and practical examples. The simplest case is: $2p = 2$, $m = 3$ [15], [16]. According to para 2 of the algorithm $Z = 3$ is found and elementary motor design is obtained, either commutator or commutator less, which is widely used in appliances and in electromechanical toys. Coil groups here contain one coil each, their phase zones forming an arc of 120 angular degrees.

When doubling the number of pole pairs, we pass on to the known six slot-circuit diagram which is used in step drive [17]–[19]. The number of phase bands doubles, their arc length along the magnetic core circle is reduced to 60 angular degrees, if one coil per coil group and the same number of slots per pole and phase $q = \frac{1}{2}$ are maintained. At *m* phase even number for six-pole field $2p = 6$ magnets, $Z = 8$ for $m = 2$ and $m = 4$ are determined according to para 2 of the above sequence. Every winding comprises two coil groups consisting of two two-phase winding coils and one four-phase winding coil, with 90° (as shown in Figures 1(a) and 1(b)) and 45° phase bands respectively. Both circuits are often used instep drive [20], [21].

Figure 1. Two-phase machine, m = 2, 2p = 6, Z = 8: (a) winding circuit and (b) rotor structure

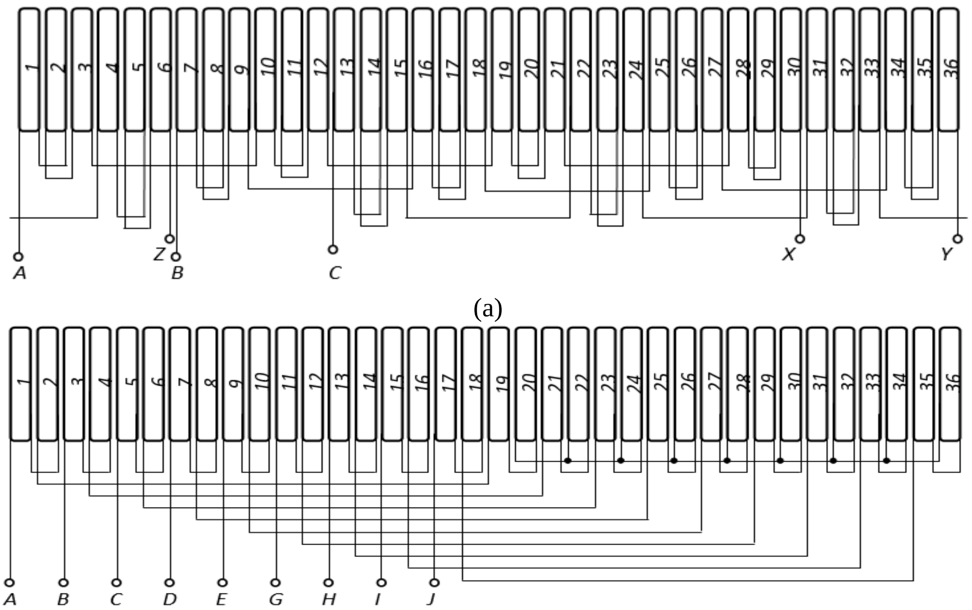
Let us consider the example of a powerful machine, its outside diameter 1100 mm. Its 850 mm outer diameter rotor contains neodymium alloy magnets (Sm_2-Co_{12}), circumferentially forming 32 alternating polarity poles. Such machine coil winding is housed in thirty-six slots with the same number of coils. They are connected in three-, six- or nine-phase wye.

According to the above algorithm, it can be determined that the number of stator slots $Z = 36$ suits three-phase winding as well as six- or nine-phase winding with relevant coil shortening $y = 0.889$. Three-and nine- phase winding coil connection circuits are shown in Figures 2(a) and 2(b) respectively. According to para 3 of the algorithm, phase coils of the former one occupies four phase bands in phase quadrature with respect to each other. Within each phase band they form coil groups of three coils connected in series back-to-back (algorithm, para 4). According to the second option, phase coils occupy the phase bands in twos forming coil groups of two back-to-back connected coils within each phase band.

Motor rotor with stator winding coils connection according to these circuits contains permanent magnet areas of alternating polarity and magnetization direction with radial and tangential magnetization direction sections. Calculations made using finite elements method [22], [23] on grid model, its fragment shown in Figure 3, show that due to better, less discrete MMF distribution, nine-phase motor torque amplitude exceeds three-phase motor torque amplitude by 20%. It constitutes 32.9 N.m per one meter of stator pack axial length, at load angle characteristic sinusoidal form, which is characteristic of non-salient pole synchronous machines.

Long-pitch windings instead of short pitch ones are practical in inverted motors with outer rotor and inner stator shown in Figures 4(a) and 4(b), respectively, closest analogue of series-produced motor EC 90 flat 607323 by Maxon Motor AG company). In these machines, reducing the number of slots allows to increase total copper slot area in tooth zone, which is rather limited at the inner stator, and to simplify winding and coil connections' structure. At twenty-two engine poles ($2p = 22$), formed by ring magnet segments on the rotor Figure 4(a), its winding coils are housed in eighteen slots ($Z = 18$ at $d = –4$), though structures with pitch reduction, Z=24, at the same number of rotor poles are known to be used as well [24].

At $Z = 18$ two coil groups are obtained with three coils in each one, located in two diametrically opposite 60 degrees length sectors as shown in Figure 5(a). Missing data shown in Table 1 are identified and a grid model is developed (Figure 5(b)) in design calculations. According to the latter one, load angle characteristics are determined as shown in Figure 6.



(a)

(b)

Figure 2. Coil winding circuit diagram, $2p$ = 32, Z = 36, (a) m = 3 and (b) m = 9

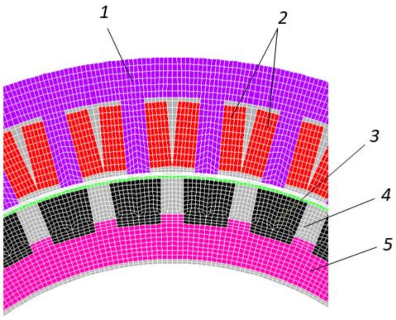


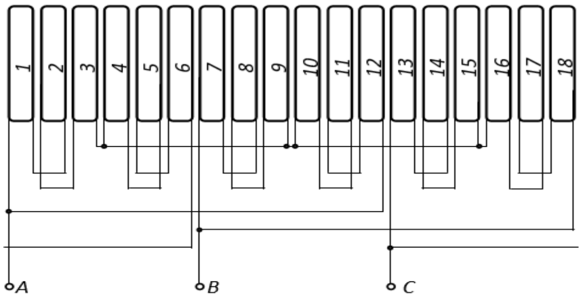
Figure 3. Fragment of motor grid model, $2p$ = 32, Z = 36, m = 3 or 9, 1 is stator magnetic circuit, 2 is winding coils, 3 is radially magnetized magnet, 4 is tangentially magnetized magnet, and 5 is rotor yoke

(a) (b)

Figure 4. Inverted motor EC 90 flat (607323) by Maxon Motor AG company, $2p$ = 22, Z = 18, m = 3, (a) with outer rotor and (b) with inner stator

Table 1. The analog of Maxon Motor AG characteristics

Name of parameter, measurement unit	Value
Torque rating (pull-out torque), N.m	0.47÷0.51
Maximum torque, N.m	1.21÷1.25
Number of poles and winding coils on stator	18
Number of rotor magnet pole pairs	11
Number of phases	3
Winding connection type	Y
Rotor outside diameter, mm	90
Rotor inside diameter, mm	80
Stator magnetic circuit inside diameter, mm	52
Stator magnetic circuit pack thickness, mm	11
Rated (maximum continuous) phase current, A	4.09
Insulated magnet wire diameter mm	0.51
Uninsulated magnet wire diameter (Russian analogue–ПЭТВ-make wire), mm	0.47
Reference current density when coils are connected in phases in a single parallel branch, A/mm^2	23.57
The same, when connected in two parallel branches, A/mm^2	11.8
High-limit ambient temperature, °C	100
Rotor circuit resistance phase-phase, ohm	0.52



(a)

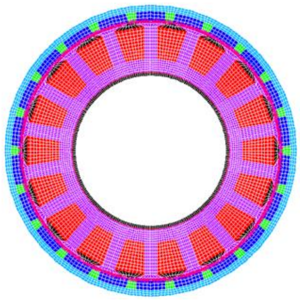

(b)

Figure 5. Inverted engine inner stator: (a) winding circuit and (b) grid model

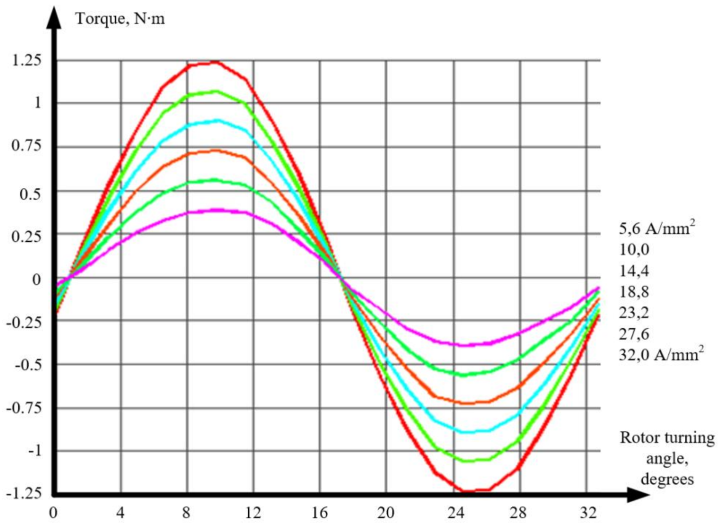


Figure 6. Motor load angle characteristics at different current density in winding phases

A complete analog of this motor is a series-produced micromotor for office equipment configuration, containing a ten-pole rotor, $2p = 10$ with three-phase winding on the stator salient poles [25]. According to the proposed algorithm, we obtain $Z = 9$ and one after one coil group of three coils, connected in series back-to-back, which occupy phase bands graded 120°. An alternative to such solution could be an option with coil shortening, at twelve slots, $Z = 12$. Herewith, coils are connected in two groups of two coils in each one, occupying two diametrically opposite 60° phase bands.

To a greater extent, the technique relates to multi-pole magnetic systems of low-speed motors. In high-speed generators of high power [26], the use of coil windings is impractical, due to the excessive length of the tooth division with a small number of slots, providing an acceptable value of the shortening coefficient. The preferred field of application of machines with the proposed winding and the described algorithm for constructing its circuit is a high-torque synchronous drive with low-speed motors, as well as generators for wind power.

4. CONCLUSION

A formalization algorithm of constructing stator coil winding circuits for synchronous permanent-magnet machines on the rotor was proposed. The algorithm was tested by examples of simple machines' winding synthesis, known from academic courses, on newly projected high-power units as well as on production-line items, and can be recommended for new developments when performing design calculations.

The use of the algorithm to improve the design of a powerful machine made it possible to synthesize a circuit with a nine-phase winding, which, as calculations by precise methods have shown, provides an increase in the specific, per unit axial length, electromagnetic moment by 20%. A more advanced winding scheme for a serial motor used to drive industrial robots is justified, which will be used in new developments.

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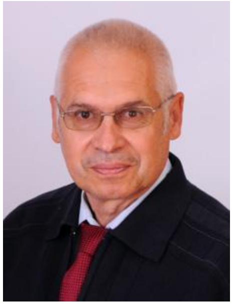

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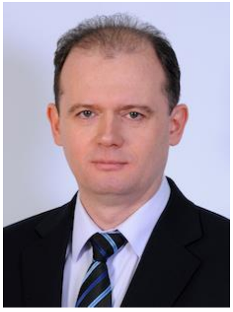

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