Algorithm for Design and Analysis of Multilayer and Fractional-slot Stator Windings

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***Abstract*— Algorithm for design and analysis of multilayer and fractional-slot stator windings is the subject of this paper. Stator windings with different number of stator phases, different number of layers and different configuration of group of coils are considered. The process of designing the stator winding is a very important and complex task, because the characteristics and efficiency of the machine largely depend on the stator winding. Proper design and prediction of the subsequent fabrication of the stator winding with the simplest possible design and manufacturability will solve many problems that may arise in the production and operation of the synchronous motor with permanent magnets. A passes algorithm is presented in the state for various stages from setting the current density to checking for an electromagnetic field on load mode.**

Keywords*— *different number of stator phases, configuration of group of coils, electromagnetic field on load mode, proper design.

I. Introduction

The choice of stator winding in electric machines and in particular in high-efficiency electric motors takes into account many factors. The evaluation of these factors is very important, because the stator winding is one of the basic lements of the electric motor, on which depends its efficiency, performance and optimal operation. In most cases, this important element of the electric motor cannot cover all the conflicting requirements at once. A compromise must be reached. However, the choice must be made very carefully, based on different options, taking into account the strengths and weaknesses of each solution. When designing the stator winding, attention should be paid to the following factors influencing its performance - what type is the stator winding [6], [8]. What is the relationship between the number of stator slots and the number of pole pairs [3], [9] and many other factors. Taking into account all the various factors and their application is practically impossible. Therefore, before a machine is actually produced, or to create a models for learning purposes [1], its operating modes must be very well simulated. This can be done through well-known algorithms and methods for analyzing electrical machines. On the other hand, it is possible to develop old methods and algorithms or create completely new ones. It is possible to use matrices when creating the winding [7], [8]. It is possible to present the winding diagram in tabular form [5]. The above two methods allows the creation of different and diverse schemes of the stator winding, processing a large amount of information - concerning the stator winding and thus creating the optimal option. It is possible to represent magnetomotive force (m.m.f.) summing the different magnetomotive forces of the stator and rotor of the electric motor. It is possible to present it in space [2], [4], or presentation by harmonic order [10]. In a similar way can be represented and total magnetic flux.

Algorithm for design and analysis of multilayer and fractional-slot stator windings is described in this paper. The algorithm includes different iterations stages from setting the current density to checking for an electromagnetic field on load mode. On the basis of the obtained results a conclusion can be made about the properties of the studied stator windings.

II. Stator winding structure

The structure of the stator winding is presented in tabular form. The number of stator phases is given, the connection between the individual coil is presented. The symmetry of the winding is monitored along the total length of coil, for each phase (at different lengths of coil).

A. *Winding type 1*

On Fig.1. and Fig.2. is shown each of a the stator phase. In column №1 is written the number of coil, in column №2 is written the number of the stator slot, from which coil begins, and in column №3 - the number in which it ends. Column №4 represents the length of coil. At the bottom of the table (in red) is the full length coils of the stator phase. From the data in these two figures it can be seen that the stator phases contain coil of different length. A way of

A			
1	2	3	4
1	2	7	5
2	13	19	6
3	25	31	6
4	32	37	5
5	43	49	6
6	55	1	6
			34

B			
1	2	3	4
1	10	15	5
2	16	21	5
3	27	34	7
3	40	45	5
5	46	51	5
6	57	4	7
			34

C			
1	2	3	4
1	6	60	6
2	18	12	6
3	29	24	5
3	30	36	6
5	42	48	6
6	54	59	5
			34

D			
1	2	3	4
1	8	3	5
2	9	14	5
3	20	26	6
3	33	39	6
5	44	38	6
6	56	50	6
			34

Fig. 1. Stator wending- phase A, phase B, phase C and phase D.

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connecting the individual coil is chosen so that the total length of all coil is equal for all phases.

E			
1	2	3	4
1	11	5	6
2	22	17	5
3	23	28	5
3	35	41	6
5	47	53	6
6	58	52	6
			34

Fig. 2. Stator wending- phase E.

Fig. 3. shows the star of phase voltages, currents and current densities for winding type 1.

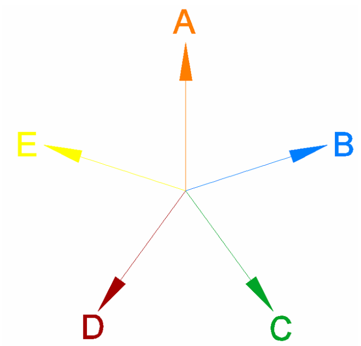

Fig. 3. Star of phase voltages, currents and current densities for winding type 1

B. *Winding type 2*

This winding is double layer and has the following advantages - the coils are the same (in shape and length) and this makes the production of the winding easier. The created electromotive force has a sinusoidal shape. However, in this winding there are coil of different phases in some of the slots. Fig. 4. shows the star of phase voltages, currents and current densities for winding type 2.

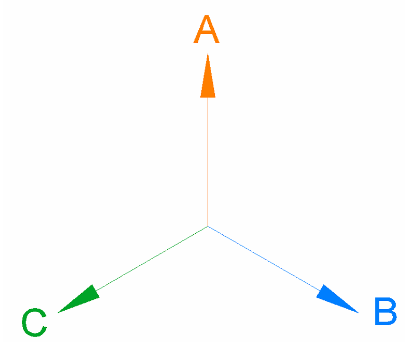

Fig. 4. Star of phase voltages, currents and current densities for winding type 2

On Fig.5. is shown the stator phase A. The other two phases are not presented, because they are identical - phase B starts from channel № 7 and phase C starts from channel № 4. In column №1 is written the number of coil, in column №2 is written the layer's type, in column №3 is written the number of the stator slot, from which coil begins, and in column №4 - the number in which it ends. Column №5 represents the length of coil. At the bottom of the table (in red) is the full length coils of the stator phase.

A				
1	2	3	4	5
1	top	1		4
	bottom		5	
2	top		6	4
	bottom	10		
3	top		5	4
	bottom	9		
4	top		10	4
	bottom	14		
5	top		15	4
	bottom	19		
6	top	14		4
	bottom		18	
7	top	19		4
	bottom		23	
8	top		24	4
	bottom	28		
9	top		23	4
	bottom	27		
10	top	28		4
	bottom		32	
11	top		33	4
	bottom	37		
12	top		32	4
	bottom	36		
13	top	37		4
	bottom		41	
14	top		42	4
	bottom	1		
15	top		41	4
	bottom	45		
				60

Fig. 5. Stator wending- phase A.

III. TOTAL MAGNETIC FLUX (FLUX LINKAGE)

Total magnetic flux is determined for different time moments, which cover its complete sinusoidal change in time. It is assigned to two different cases. The first of which is at the current density in the stator phases equal to zero. Then total magnetic flux is created only by the permanent magnets in the rotor. Later in the paper this total magnetic flux is called "total magnetic flux of the rotor". The second Total magnetic flux is created by the permanent magnets in the rotor and the stator winding, so it is further in the paper is called the "resulting total magnetic flux". Since each stator slot consists of two coils of two different layers (top and bottom) then total magnetic flux of the slot is equal to the sum of total magnetic flux of the two layers. This is illustrated by formula [1]

$$\psi_Z = \psi_{Z_T} + \psi_{Z_B}, \qquad (1)$$

where

ψ_Z total magnetic flux of the slot

ψ_{Z_T} total magnetic from top layer of the slot

ψ_{Z_T} total magnetic from bottom layer of the slot

All data shown, from now on in the paper through the graphs are presented in system per-unit.
For both types of the stator windings, for each stator slot, the total magnetic flux is removed. When the winding is type 2, the removal is done in layers. The amendment of the total magnetic flux of the rotor, for first slot and winding type 1 is shown On Fig.6.

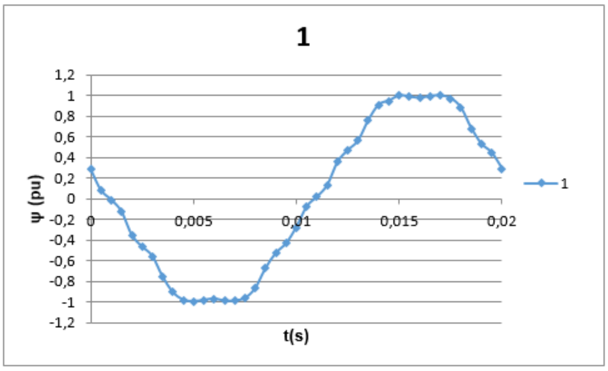

Fig. 6. Amendment of the total magnetic flux of the rotor, for first slot and winding type 2.

The amendment of the total magnetic flux of the rotor, for first four slot and winding type 2 is shown On Fig.7. and Fig.8.

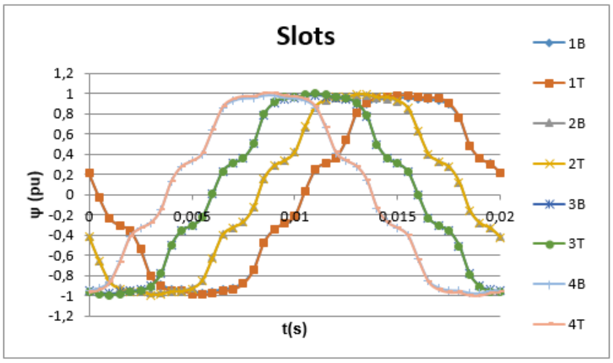

Fig. 7. Amendment of the total magnetic flux of the rotor, for first four slots and winding type 2.

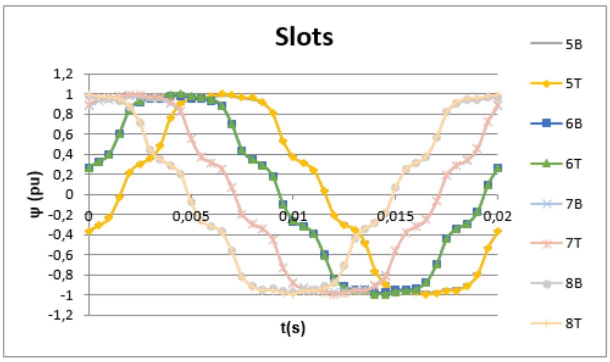

Fig. 8. Amendment of the total magnetic flux of the rotor, for second four slots and winding type 2.

After traversing all stator slots and removing total magnetic flux of the rotor (top layer then bottom layer for winding type 2), the total magnetic flux of the rotor, is obtained. The results for both windings are shown on Fig.9. and Fig.10. For winding type 1 the results for group of coils only for phase A. For winding type 2 the results for group of coils are shown for the whole stator winding.

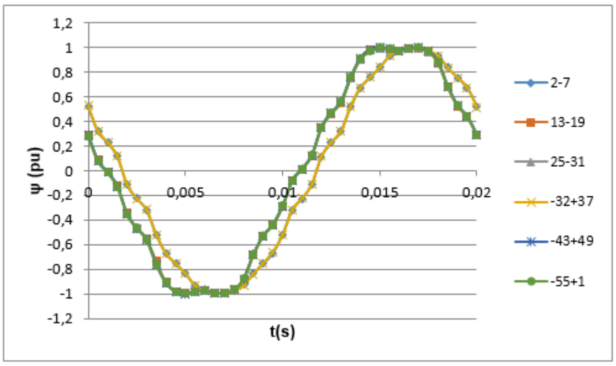

Fig. 9. Total magnetic flux of the rotor, for group of coils only for phase A (winding type 1).

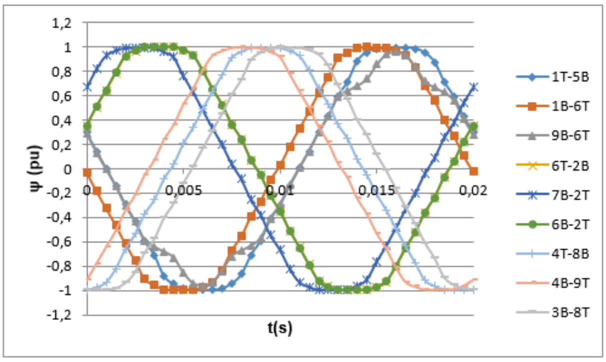

Fig. 10. Total magnetic flux of the rotor, for group of coils (winding type 2).

The results for all stator phases for total magnetic flux of the rotor are shown on Fig.11 for winding type 1 and on Fig.12 for winding type 2. From these two figures the correct choice of the sequence of arrangement of different stator phases in the stator slots is visible. This is confirmed by the fact that the time curves of the total magnetic flux of the rotor for the individual stator phases are in the following order - phase A, phase B, phase C, phase D and phase E along the time axis winding type 1. Their amplitudes are the same, they are out of phase at the same angle. From this it can be concluded that when supplying the stator winding, the current densities must have the same sequence. It is very important to take into

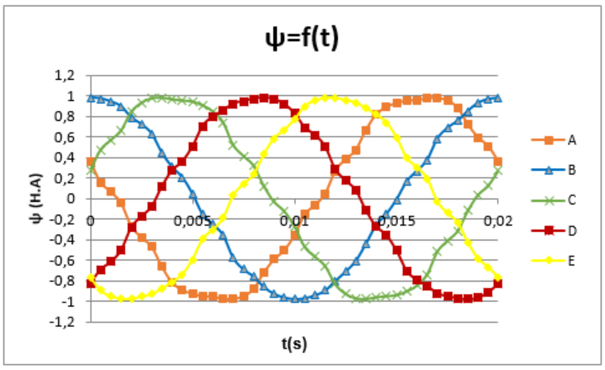

Fig. 11. Total magnetic flux of the rotor, for all stator phases, for winding type 1.

account the direction of the field created by the permanent magnets and the magnetic field created by the stator winding.

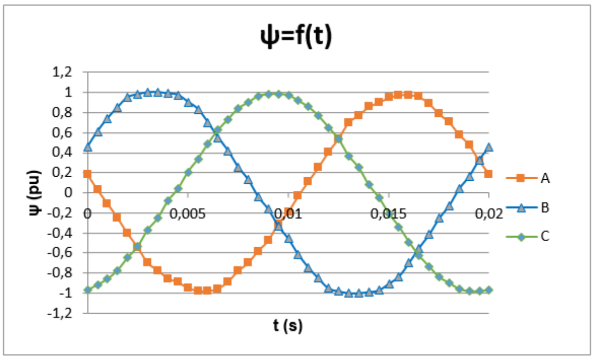

Fig. 12. Total magnetic flux of the rotor, for all stator phases, for winding type 2.

Similar tests have been performed on the removal of the resulting total magnetic flux. The resulting total magnetic flux for group of coils (winding type 2) is shown on Fig.13.

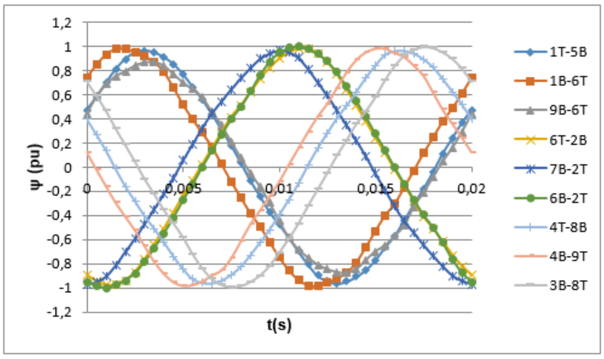

Fig. 13. The resulting total magnetic flux for group of coils for winding type 2.

Several factors can be judged for adjusting the influence of the choice of stator winding and improving the distribution of the magnetic field. One of them is the curvature of the curve of flux linkage when combining the magnetic field created by the permanent magnets and the stator winding. This example is shown for winding type 1 on Fig.14.

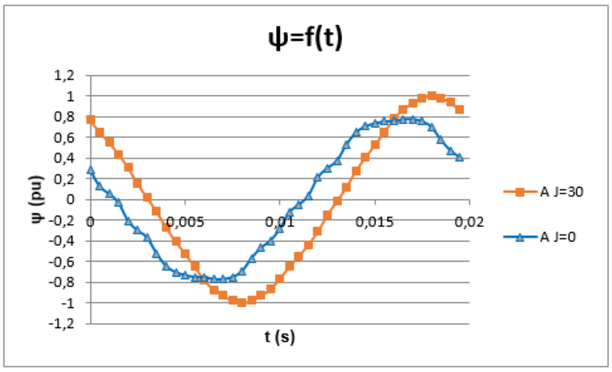

Fig. 14. Flux linkage from the stator winding and from the stator winding and the permanent magnets, for winding type 1.

IV. CONCLUSION

Algorithm for design and analysis of multilayer and fractional-slot stator windings is the subject of this paper. Stator windings with different number of stator phases, different number of layers and different configuration of group of coils are considered.

A two-layer winding and a winding with different lengths of coils were studied. For the latter, an algorithm for determining the symmetry of the entire stator winding is presented.

It is permissible to use the proposed methodology, through minor changes, for the study of the stator winding and other types of electrical machines.

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