Analysis of Fractional-slot Permanent Magnet Synchronous Machines Used for Hybrid Vehicles

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***Abstract* — This work presents an investigation on electromagnetic torque and electromagnetic force computations in the air gap of a V-shape permanent magnet synchronous motor (SMPM). The requirements for the fractional-slot stator winding (FSW) of the considered motor are presented. The conducted analysis has been accomplished through use of the application of finite element method. The suggested approach was used for synchronous motor with integral-slot stator winding (ISW) and the obtained results are compared.**

Keywords—synchronous machine permanent magnet, finite element method-(FEMM), fractional-slot winding, electromagnetic torque ripples.

I. INTRODUCTION

One of the priority areas of the 21-st century research is energy efficiency and environmental protection. For this reason, the research on electric machines for propulsion of hybrid cars is particularly important. On the other hand, the leading automakers not only strive to have a hybrid vehicles because of their better characteristics than the classical analogues. One of the most commonly used electrical machines as a traction motor is synchronous machines whose magnets located in the rotor have V-form. This machine has number of priority: high output efficiency, huge range of speed, and high power [8, 11]. There are a lot of ways to achieve these features: a different rotor and stator design, a different type of the stator winding [1, 4] or different methods of stator current and voltage control [3]. This article present the results from a study of fractional-slot winding. This paper presents the results from electromagnetic torque and electromagnetic force computations for fractional-slot stator winding synchronous motor.

The paper presents the machine configuration and the requirements for the stator fractional-slot winding. The electromagnetic field distribution inside the machine is determined using finite element method, and the obtained results are used for electromagnetic torque and electromagnetic force computations.

II. MACHINE CONFIGURATION

The machine is whit following specifications: Number of phase - m=3, Number of stator slots - Z=45, Number of pair of poles p=5, Double layer winding, Coil-span=chorded, number of slots per pole per phase - q=3/2, Air gap=0.7 mm, Rotor stack length=90 mm, Stator inner diameter=184.2 mm, Stator outer diameter=242mm, Angle between two slots in electrical degrees=45 deg, Width of slots=7.8 mm, Height of slots=18.1 mm, Outer rotor diameter=182.8 mm [7], [12].

III. REQUIREMENTS FOR THE FRACTIONAL-SLOT WINDING

The symmetry of fractional-slot winding [6, 9, 10] requires the conditions presented by the expressions from (1) to (10) to be fulfilled:

$$q = \frac{Z}{2pm} \tag{1}$$

$$q = b + \frac{c}{d} = \frac{bd + c}{d} \quad a,b,c \in N\,, \tag{2}$$

where N- natural number

$$a,b,c \in N \quad \frac{b}{c} - correct\ fractions\ \left(b < c\right) \tag{3}$$

$$t = \gcd(Z, p) \qquad \text{gcd – greatest common divisor} \tag{4}$$

$$\left(\frac{Z}{t\,m}\right) \ \text{- without residue} \tag{5}$$

$$\frac{Z}{m} = 2pq \in N \qquad \frac{2p}{2pm} \in N \tag{6}$$

$$\frac{Z}{3t} \in N \tag{7}$$

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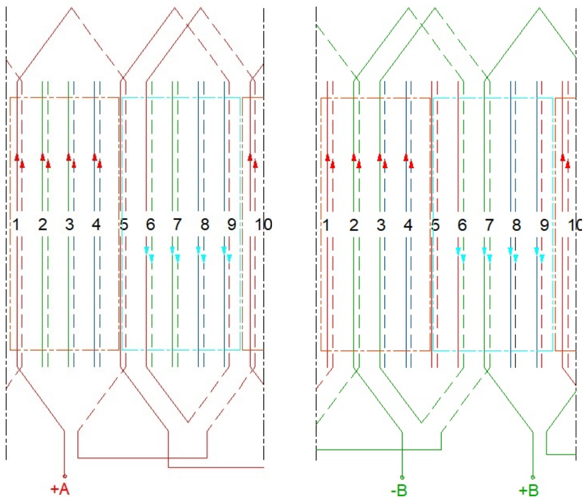
$$Z = Z_c \quad \text{- number of coils} \tag{8}$$

$$Z_{gc} = pm \quad \text{– number of group of coils} \tag{9}$$

The winding diagram for each phase for two poles is shown in Fig.1 and Fig.2 (phase A-Fig.1, phase B-Fig.1 phase C-Fig.2). Fig.3 shows the winding diagram for the whole machine, where Z is number of slot, T is top layer of the slot and B is bottom layer of the slot. 4. Diagram of coils connection is presented at Fig. 4. The first coil of phase A starts from slot №1 – top layer and ended at slot №5 – bottom layer. Next coil of this phase winding starts from slot №10 – bottom layer and ended at slot №6 – top layer. In this manner, the neighboring group of coils contains different number of coils.



phase A phase B

Fig. 1. Winding diagram

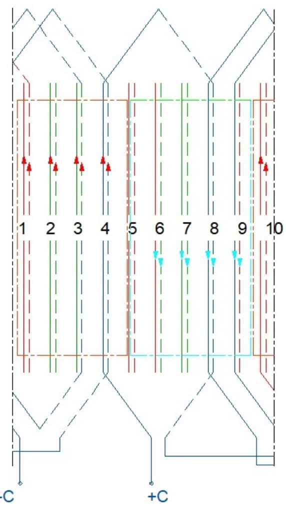


Fig. 2. Winding diagram for phase C

III. ANALYSIS

There are different numerical methods for analysis of synchronous machines shaped magnet as described above. One of the most popular in electrical machines analysis is the finite element method [2, 5]. The application of this method allows simulation of machine behavior at different loads and becomes the first step at the design stage.

Z	1	2	3	4	5	6	7	8	9
T	A+	B-	B-	C+	A-	A-	B+	C-	C-
B	A+	B-	C+	C+	A-	B+	B+	C-	A+
Z	10	11	12	13	14	15	16	17	18
T	A+	B-	B-	C+	A-	A-	B+	C-	C-
B	A+	B-	C+	C+	A-	B+	B+	C-	A+
Z	19	20	21	22	23	24	25	26	27
T	A+	B-	B-	C+	A-	A-	B+	C-	C-
B	A+	B-	C+	C+	A-	B+	B+	C-	A+
Z	28	29	30	31	32	33	34	35	36
T	A+	B-	B-	C+	A-	A-	B+	C-	C-
B	A+	B-	C+	C+	A-	B+	B+	C-	A+
Z	37	38	39	40	41	42	43	44	45
T	A+	B-	B-	C+	A-	A-	B+	C-	C-
B	A+	B-	C+	C+	A-	B+	B+	C-	A+
	N					S			

Fig. 3. Winding diagram for the whole machine

A	B	C	coil
1T	7T	4T	1
5B	11B	8B	
10B	16B	13B	2
6T	12T	9T	
9B	15B	12B	3
5T	11T	8T	
10T	16T	13T	4
14B	20B	17B	
19B	25B	22B	5
15T	21T	18T	
18B	24B	21B	6
14T	20T	17T	
19T	25T	22T	7
23B	29B	26B	
29B	34B	31B	8
24T	30T	27T	
27B	33B	30B	9
23T	29T	26T	
28T	34T	31T	10
32B	38B	35B	
37B	43B	40B	11
33T	39T	36T	
36B	42B	39B	12
32T	38T	35T	
37T	43T	40T	13
41B	2B	44B	
1B	7B	4B	14
42T	3T	45T	
45B	6B	3B	15
41T	2T	44T	

Fig. 4. Diagram of coils connection

A lot of suitable commercial and free software packages are available nowadays (Ansys Maxwell, FEMM). No matter that these products require a lot of computation resources and time the obtained results for magnetic field distribution allow electromagnetic torque (ripple and harmonic order) and electromotive force computations without physical experiments.

The research in this article is based on the application of the 2D software package FEMM 4.2. The investigation of the considered machine uses a specimen that because of the machine symmetry comprises arc segment with a pair of poles inside, Fig.5.

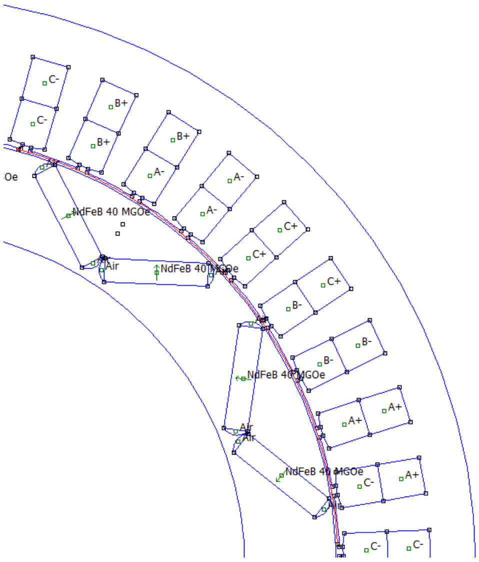


Fig. 5. Arc segment of a FSW syncronous machine

The machine is supplied by a three phase balance system of currents of densities equal to 10, 20 and 30 [A/mm^2]. The analysis starts at instant of time when the current respectively the current density in phase A equals its maximum value. At this instant of time the instantaneous values of the currents in phase C and B (respectively the current density) are equal to half their maximum values and are negative. The electromagnetic torque and the phase electromotive force is calculated for any rotor position in the range between 0^0 and 72^0. The rotor spins clockwise with an angular step of 1.8^0 that corresponds to the time variation of t=0.0005s in currents magnitudes[7], [12].

The flux lines of electromagnetic field distribution (above-integral-slot winding, down - fractional-slot winding) are presented at Fig.6.

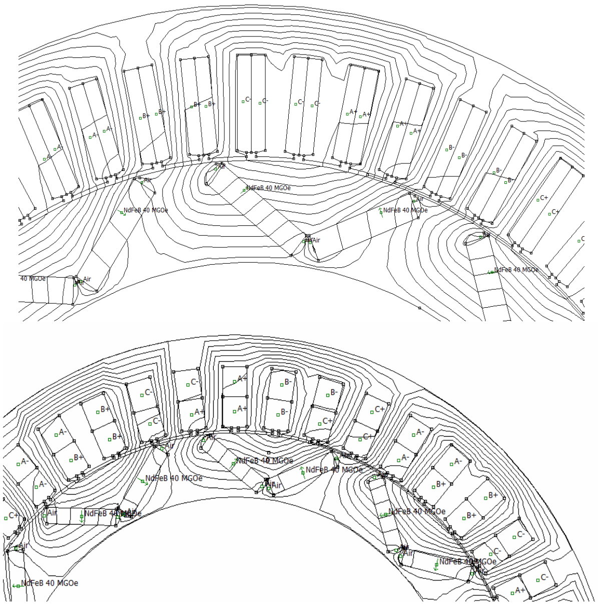


Fig. 6. Flux line path of the electromagnetic field

Some slots of the core operate with different amplitude of magnetomotive forces (mmf). This is because they contain coils of different phases (3, 6, 9) - the Fig.7. The star of slot e.m.f (in the center of the figure – 1 to 9) and star of coil emfs' for one pole (A, B, C) are presented at Fig.8. The figure shows that phase e.m.f. are symmetrical.

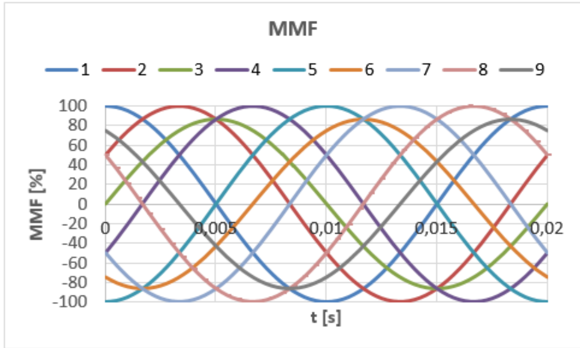


Fig. 7. MMF for slots of one pair of poles

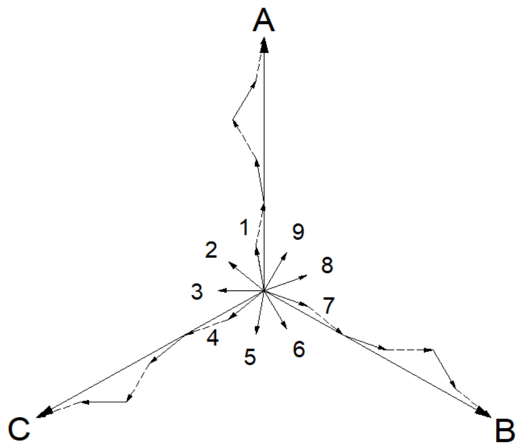


Fig. 8. The stars of slots and of coils emfs'

After determination of the coils' flux linkages and considering the number of the pair of poles the phases' flux linkages are computed. The instantaneous values of the induced phase electromotive forces are determined as a ratio of the phase flux linkages alteration and time increment (10).

$$e = \frac{\psi_{n+1} - \psi_n}{t}, \text{ V} \tag{10}$$

where ψ_{n+1}, ψ_n are flux linkages in the instants of time t_{n+1} and t_n and t= t_{n+1} - t_n. The applied Fourier analysis to the constructed in this manner electromotive wave form is presented at Fig. 9 for J=30 A/mm^2.

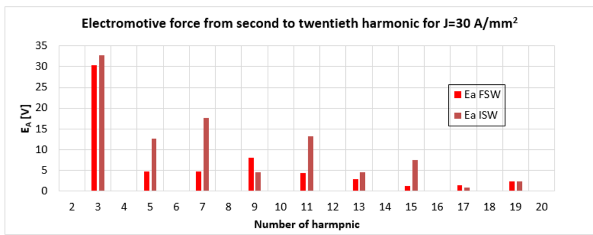


Fig. 9. Electromotive force from II to XX harmonics J=30 A/mm^2

The electromagnetic torque is computed over an arc located in the middle of the air gap. The length of the arc is equal to the geometric length of two pole divisions (Fig.5). The computations are based in the Maxwell Stress Tensor method. The applied Fourier analysis to the obtained results for the torque is presented at Fig.10.

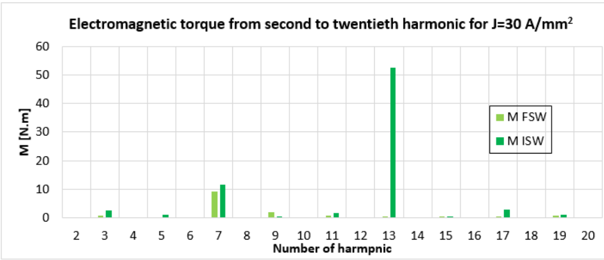


Fig. 10. Electromagnetic torque from II to XX-th harmonics

The instantaneous values of the electromagnetic torque for both machine types, computed for current density of J=30 A/mm^2 are presented at Fig.11. The electromagnetic torque ripples of ISW motor are noticeable, while the FSW motor offers lower torque pulsations.

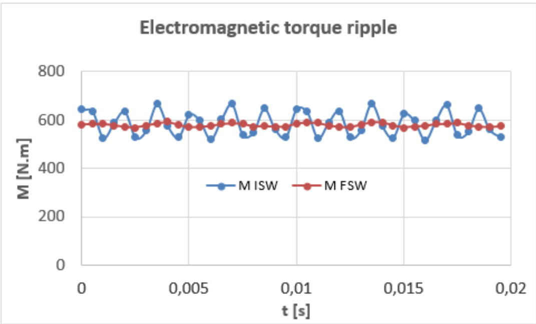


Fig. 11. Electromagnetic torque as time function

The main harmonic of the electromotive force, electromagnetic torque at different current densities are presented in Table 1.

TABLE I. RESULTS FROM ELECTROMAGNETIC TORQUE AND ELECTROMOTIVE FORCE COMPUTATIONS

E_A [V]	J [A/mm^2]		
	10	20	30
FSW	322.4	340.5	361.4
ISW	316.4	361.5	391.4
M [N.m]	J [A/mm^2]		
	10	20	30
FSW	260.2	460.1	579.3
ISW	268	467.3	586.6

IV. CONCLUSIONS

This work presents a new winding design, with slots covered by different poles (5, 14, 23, 32, 41 - Fig.3), suggested by the authors. The winding factor of machine with such winding is (k_{FSW}=0.9604), which is lower than the winding factor of the integral-slot winding machine (k_{ISW}=0.9659). The difference is 0.5 percentages. This winding type improves harmonic order, and reduces some of the higher harmonics of the electromotive force.

The amplitude of the first harmonic of the e.m.f and electromagnetic torque at the integral-slot winding is higher, but the amplitude of the torque ripples of the fractional-slot winding is significantly lower.

Using a fractional-slot stator winding is talk up for the above reasons, though it would require more complex manufacture.

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