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Comparative research of different structures of a permanent-magnet excited synchronous machine for electric vehicles

***Abstract.** This paper presents a permanent-magnet motor with single teeth windings and a brushless auxiliary direct current control system for electric vehicle drives. The main advantage of this motor is its possibility to realize the field weakening by high speeds. In order to determine the key electric and magnetic parameters of the motor, finite-element analyses were carried out. Different variants of the main structure of the motor have been described and compared.*

***Streszczenie.** W artykule zaprezentowano silnik z magnesami trwałymi z uzwojeniami na pojedynczych zębach oraz dodatkowym bezszczotkowym systemem sterowanym prądem stałym, dedykowany do napędu pojazdów elektrycznych. Główną zaletą takiego silnika jest możliwość osłabienia pola magnetycznego przy wysokich prędkościach obrotowych. W celu określenia głównych parametrów elektrycznych i magnetycznych silnika przeprowadzona została analiza przy pomocy metody elementów skończonych. Ponadto opisano i porównano różne warianty struktur silnika. (**Analiza porównawcza różnych struktur synchronicznej maszyny elektrycznej z magnesami trwałymi dla pojazdów elektrycznych**)*

Keywords: electric vehicles, permanent magnet excited synchronous machines, field weakening.
Słowa kluczowe: pojazdy elektryczne, maszyny synchroniczne wzbudzane magnesami trwałymi, osłabianie pola.

Introduction

Electrical motors for automotive applications should fulfill many specific restrictions and requirements [1-4]. As drives for electrical vehicles different machine topologies can be used. This task can be realized by induction machines as well as permanent magnet excited or electrically excited synchronous machines or even transverse flux machines. Last experiences show that the permanent-magnet excited synchronous machines (PMSM) feature most advantages in automotive applications as: high efficiency, high power density, high drive performance e.g. On the other hand PMSM feature a intense demand in the field weakening region at high speeds due to the high internal magnetic resistance and potentially dangerous short-circuit currents (reduced impedances). Hybrid and electrical vehicles require electrical drives of small sizes and weights with high overload and extreme field weakening capability. An optimal drive design for electro-mobiles should offer a field weakening capability in the range of about 1:4. The common technique for field weakening is based on a phase shift in the stator current in such a way, that a part counteracts the excitation field. This requires an unfavorable over sizing of the machine and current convertor. This task can favorably be solved by a machine where the field weakening is realized with a stator fixed DC-coil (Electric Controlled Permanent Magnet Excited Synchronous Machine: ECPSM). Such machines having a conventional three-phase armature winding have already been analyzed in [5-9]. This paper describes the features of a modified ECPSM structure with single teeth windings.

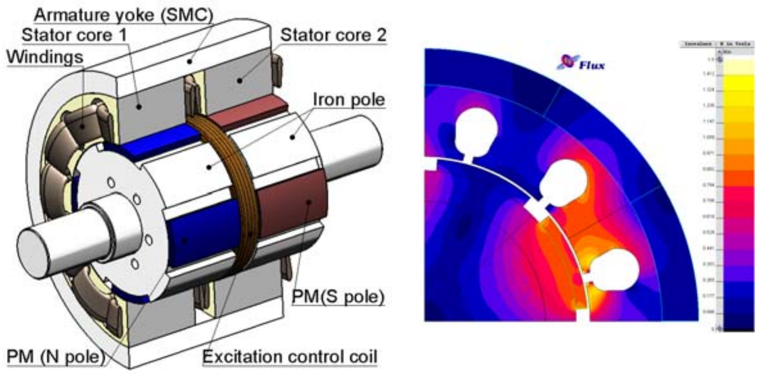

Fig.1. ECPSM with the surface-mounted PM rotor and three phase single tooth armature winding with additional stator fixed auxiliary excitation control coil (left). 2D magnetic field distribution (color coded absolute values) of the ECPSM − cross sectional view of one period (right)

Design of the ECPSM

Figure 1 (left) shows the main structure of the proposed ECPSM with single tooth winding in detail. To control the field in the range from zero up (high speed) to maximal values (high torque), the stator fixed coil (auxiliary coil) has to be fed by a simple DC-chopper. Figure 1 (right) presents the 2D magnetic field distribution within the original structure of the ECPSM without the DC-current coil operation.

Comparison of different structures of the ECPSM

The main geometrical dimensions of the machine under study are defined by the application requirements. The fundamental structure of the machine can then be modified by taking different number of slots per pole N_{sp} and number of poles p into account. All models were tested for the same cross section area of the armature conductors and effective turns per phase. Following parameter were defined as main design parameters: the air-gap flux, the electromotive force, the cogging torque, the stator resistance/phase and inductance (self and mutual). The strategic target for the machine design was the maximization of the torque and the best high speed performance (the field weakening). In order to perform the analysis of the magnetic field, a finite-element model of the machine was developed taking the B-H non-linearity into account.

Figure 2 shows four structures of the ECPS-machine with single teeth windings and the brushless auxiliary direct current control system under the assumption that each of them have the same: the external dimensions, the rated output power 5 kW, the rated voltage 400 V, the rated speed 3000 rpm and rotor data as inner diameter 40 mm, length of one part of the rotor 70 mm and thickness of magnet 5 mm. Fundamental differences in all the structures are based on different quantities of poles numbers p and slots numbers per pole N_{sp}.

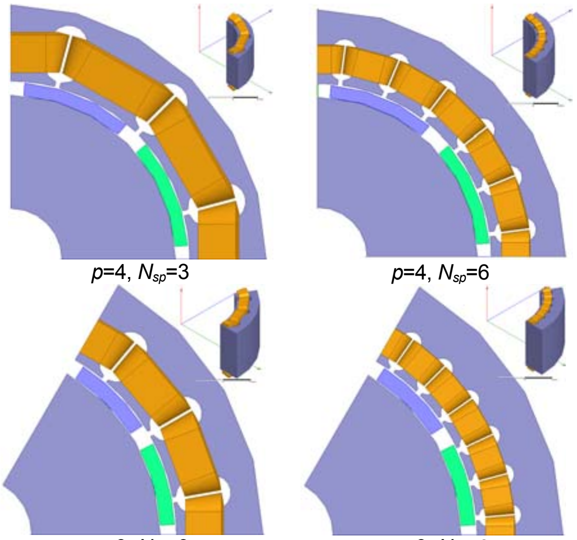

Fig.2. Configuration of different variants of the ECPS-machine

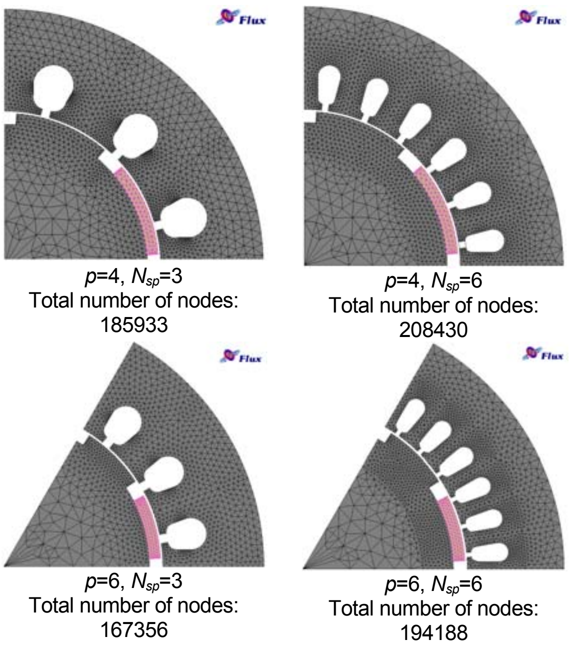

Fig.3. Cross-section of different models of ECPSM

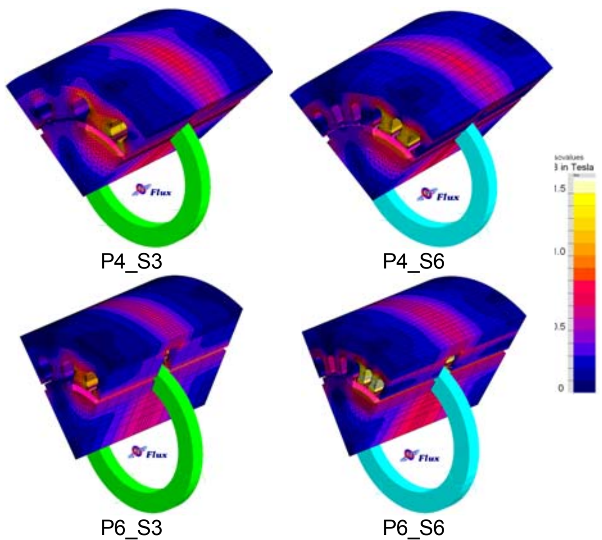

Fig.4. Magnetic field distribution within 3D models of ECPS-machine

For determination of distribution of electromagnetic fields inside considered structures of ECPS-machine four FEM models were prepared by using the 3D-calculation code via FLUX-3D. Cross sections of 3D models along with the finite element mesh and total number of nodes are shown in Fig.3.

Figure 4 shows the magnetic field distribution within all models called P4/6_S3/6, where *p* means the number of poles and *s* means the number of slots per pole.

The accurate determination of the magnetic field distribution in the air-gap of ECPS-machines is necessary to evaluate such the machine performances as electromagnetic torque, cogging torque or back electromotive force (emf). The presence of stator slots has a great influence on the motor performances as noise and vibrations due to radial forces, especially prominent at lower speeds.

Using the 3D-calculation model the magnetic field distribution and all secondary quantities (torque etc.) for different structures of ECPSM have been determined (summarized and shown in Table 1).

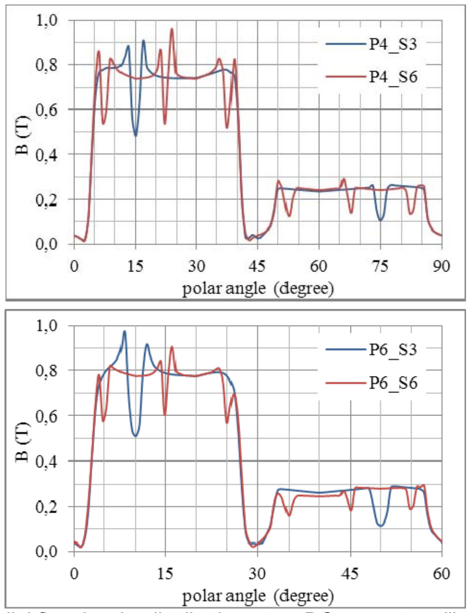

Fig.5. Radial flux density distribution at no-DC current auxiliary coil I_{aux} in the middle of air-gap

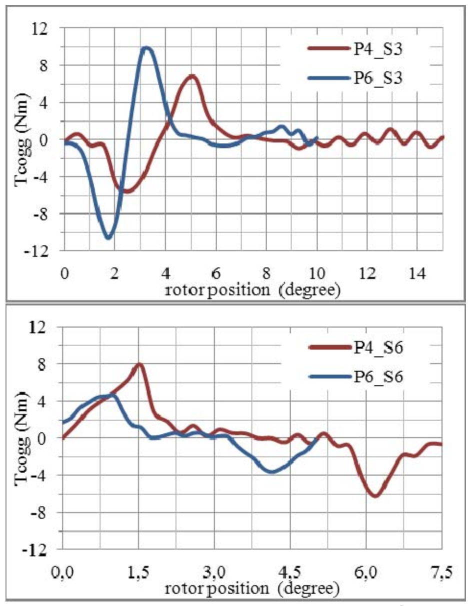

Fig.6. Cogging torque vs. rotor position without DC-currents of the auxiliary coil I_{aux} model P4_S3 and P6_S3 (top) P4_S_6 and P6_S6 (bottom)

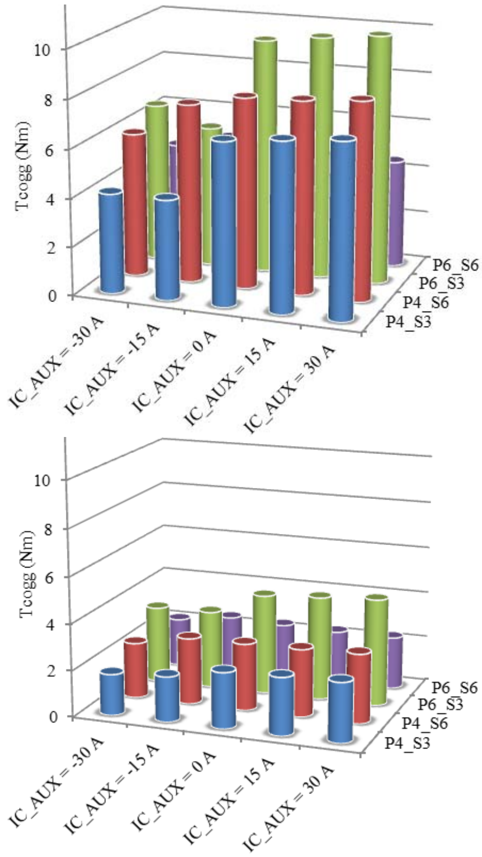

Fig.7. Maximal (top) and rms (bottom) values of cogging torque of ECPS-machines at different DC-currents of the auxiliary coil I_{aux}

Table 1. Data of different structures of ECPS-machines

	P4_S3	P4_S6	P6_S3	P6_S6
STATOR DATA				
Number of stator slots	12	24	18	36
Outer diameter of stator (mm)	200	200	200	200
Inner diameter of stator (mm)	140	140	140	140
Number of conductors per slot	46	30	22	20
Wire diameter (mm)	0,91	0,91	0,91	0,91
Slot area (mm^2)	300,63	152,41	179,00	100,32
MATERIAL CONSUMPTION				
Armature copper weight (kg)	3,49	2,95	4,48	2,73
Permanent magnet weight (kg)	0,87	0,87	0,87	0,87
Armature core steel weight (kg)	13,00	12,95	10,03	12,99
STEADY STATE PARAMETERS				
Stator winding factor	0,87	0,50	0,50	0,50
Armature phase resistance (ohm)	0,2656	0,3512	0,2370	0,3248
Torque (Nm/A)	0,32	0,48	0,45	0,64
NO-LOAD MAGNETIC DATA				
Stator-teeth flux density (T)	1,04	1,82	1,99	2,06
Maximal cogging torque (Nm)	6,7	7,8	9,7	4,6
FULL-LOAD DATA				
Average input current (A)	12,42	13,48	13,29	15,44
Armature current density (A/mm^2)	3,37	4,45	2,92	5,07
Total loss (W)	294,11	329,77	302,63	371,13
Output power (W)	4672,39	5062,64	5012,64	5806,56
Input power (W)	4966,50	5392,41	5315,27	6177,69
Efficiency (%)	94,08	93,88	94,31	93,99
Rated torque (Nm)	15,21	16,04	15,94	17,58
Estimated rotor moment of inertia (kg m^2)	0,04	0,04	0,04	0,04

The influence of the number of slots on the magnetic flux density in the middle of air-gap and the cogging torque, at no-current of the auxiliary coil I_{aux}, has been presented in Figs 5 and 6 respectively.

Figure 7 shows influence of different DC-currents of the auxiliary coil I_{aux} and type of ECPS-machine on the maximal and rms values of cogging torque of the machine.

As expected, the cogging torque much depends on the type of ECPS-machine in particular on number of poles and slots. The lowest values of cogging torque are achievable in the model P6_S6. Moreover, as shown in Fig.7, in this model there is a minimal influence of the values of cogging torque by a changing DC-current through the auxiliary coil and characterized by maximum starting torque capability. On the other hand, model P6_S6 generates largest magnetic and resistance losses.

Conclusions

Permanent-magnet motor with single teeth windings and a brushless auxiliary direct current control system for electric vehicle drives has been presented. On the basis of calculation of electromagnetic field (using the three-dimensional finite element method) a comparative analysis between different structures of ECPS-machine was able to define basic parameters of the machine (four configurations) such as magnetic flux density distribution in machine air-gap, efficiency, rated torque, material consumption, no-load magnetic data, full-load data, total losses and cogging torque at different current through auxiliary coil. The research results show that the fundamental structure of the machine must be modified according to additional requirements such as output power, rated torque, rated voltage, the range of field weakening capability or other requirements. Preliminary analysis and simulations of 5 kW machine have been demonstrated leading to best structures named P4_S3 and P6_S6 which should be further analyzed and optimized.

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