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Modified concept of permanent magnet excited synchronous machines with improved high-speed features*

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Abstract: Permanent magnet (PM) excited synchronous machines used in modern drives for electro-mobiles suffer in high speed regions from the limited battery-voltage. The field weakening requires designing machines with reduced power conversion properties or increasing the size of the power converter. A new concept of such a machine features PM excitation, single-tooth winding and an additional circumferential excitation coil fixed on the stator in the axial center of the machine. By the appropriate feeding of this coil, the amplitude of the voltage effective excitation field can be varied from zero to values above those of the conventional PM-machines. The capability of reducing the excitation field to zero is an important safety aspect in case of failing of the feeding convertor.

Key words: electric vehicles, permanent magnet excited synchronous machines, field weakening, optimal feeding

1. Introduction

The maximal travelling distance of electric vehicles is limited by the type of battery, as well as its maximal energy capacity. When it comes to the design of such vehicles, certain limits of the feeding voltage and current for the electrical machine unit should not be exceeded. The driving unit has to be sized with respect to these limits in such a way that the requirements of the different standardized driving cycle can be satisfied optimally. It means that the machine should be characterized by minimal volumetric and gravimetric values, and the optimal energy conversion should be within high rpm-ranges. In such applications the

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properties of the permanent magnet synchronous motor, such as high torque, high power, high efficiency and low noise are of the highest importance. There are many studies and publications regarding permanent magnet excited synchronous machines [1-6]. To achieve the utmost efficiency of energy conversion within the lower speed range, the dimensions of permanent magnets are oversized, exciting an increased no-load flux density. The required torque values are achieved by minimizing stator currents resulting in reduced losses. This advantage of machines with high flux density values within the low speed range is inherently connected to the challenges encountered in the high speed operation range, where, due to the limited voltage values, the force creating current cannot be driven into the machine coil. Thus, to cope with a wide speed range, an optimal drive design for electro-mobiles should offer a field weakening capability of 1:4 or even 1:5. The common technique for field weakening is based on shifting the stator current in such a way, that it partly counteracts – weakens – the excitation field. This requires an unfavorable over-sizing of the machine and the current convertor. Other designs are based on embedded excitation magnets or constructions with mechanical displacements within the excitation arrangement. While in [7] an axial displacement of the stator-structure compared to the rotor is proposed, in [8] by skewing of axial separated rotor rings (excitation) against each other the induced voltage can be varied in a wide range. Moreover the same features can be achieved by twisting or displacing the excitation magnets [9, 10].

This paper presents a machine topology, in which field weakening is enabled with a simple stator fixed DC-coil (**E**lectric **C**ontrolled **P**ermanent Magnet Excited **S**ynchronous **M**achine: **ECPSM**). To control the field in the range from zero up to maximal values, which offers wide speed variations, this coil has to be fed by a simple DC-chopper. This kind of machine, possessing a conventional stator of a three phase machine, has already been analyzed in [13-15]. This paper describes the features of a modified ECPSM structure with single-tooth windings. This solution additionally offers the shortest possible machine construction, especially when compared to machines with drum type windings.

2. Operation modes of the ECPSM

As seen in Figure 1 the uniqueness of the **ECPSM** lies in the stator-fixed auxiliary control coil, which is placed in the axial center of the machine, between the pole structures of the rotor.

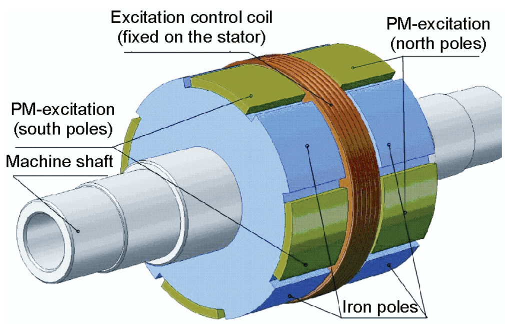

Fig. 1. Rotor of the **ECPSM** with the stator-fixed control coil integrated between the pole structures

On the one side of the rotor, an alternating arrangement is formed by permanent magnets exhibiting one polarity together with iron poles. On the other side of the intersecting control coil, the same arrangement is positioned with permanent magnets of inverse polarity. As the control coil can be mounted in the center-trench of the stator iron core, it can be fed by a 2Q-DC-chopper via stator-fixed terminals in such a way, that the effective excitation field can be varied, producing induced voltages in the armature winding between zero and the maximum value, which is limited only by the saturation of the iron core. The entire machine has been depicted in Figure 2.

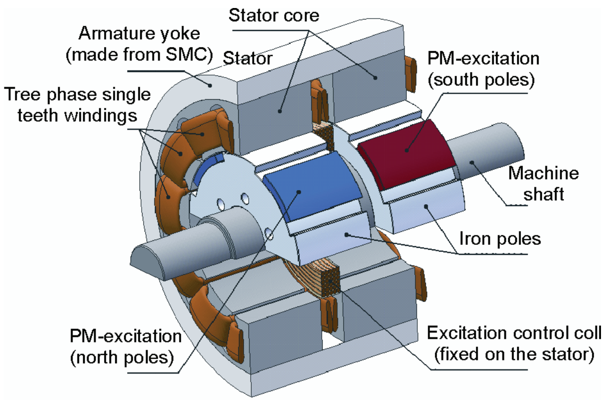

Fig. 2. **ECPSM** with the surface-mounted PM rotor and three phase single-tooth windings stator structure with fixed excitation control auxiliary coil

The main data of the analyzed **ECPSM** is given in Table 1.

Table 1.

$2p$: number of poles	8
r_{ostat}: outer radius of the stator	164.3 mm
r_{istat}: inner radius of the stator	80 mm
l_{as}: axial length one part of the stator	50 mm
w_{oslot}: width of the slot opening	4 mm
ns: number of slots	12.0
m: number of phases	3
h_{slot}: height of the slot	51.3 mm
w_t: width of the tooth	30.0 mm
r_{ip}: ratio iron pitch/angle pole	0.8
t_m: thickness of magnets ($NdFeB$, B_r = 1.2 T)	7.5 mm
n_1: number of turns in the single coil winding	30
n_2: number of turns in the auxiliary coil	200

The calculation of the magnetic field distribution within the **ECPSM** machine has been performed using the 3D-calculation code via FLUX-3D (Finite Element Electromagnetism module). Due to the periodicity of the model, the periodical cycling boundary conditions have been used. The exemplary field plot has been shown in Figure 3.

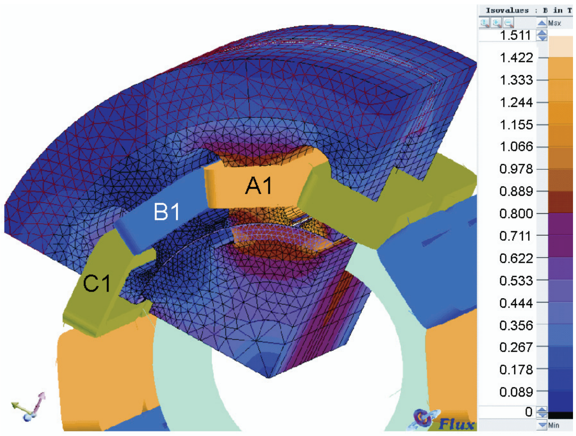

Fig. 3. Magnetic field distribution within the **ECPSM** (Transient Magnetic 3D application, Flux-3D Version 10.2.1). Total number of nodes of 2nd order mesh discretization was equal to 124444

The most important investigations of the **ECPSM** design deal with the over-speed capability based on the extensive use of auxiliary field winding. Figure 4 shows the magnetic field distribution on a 2D grid in an air-gap, axial center cut-plane and flow of magnetic flux in all volume regions of **ECPSM** for different DC-currents of the auxiliary coil i_{aux}.

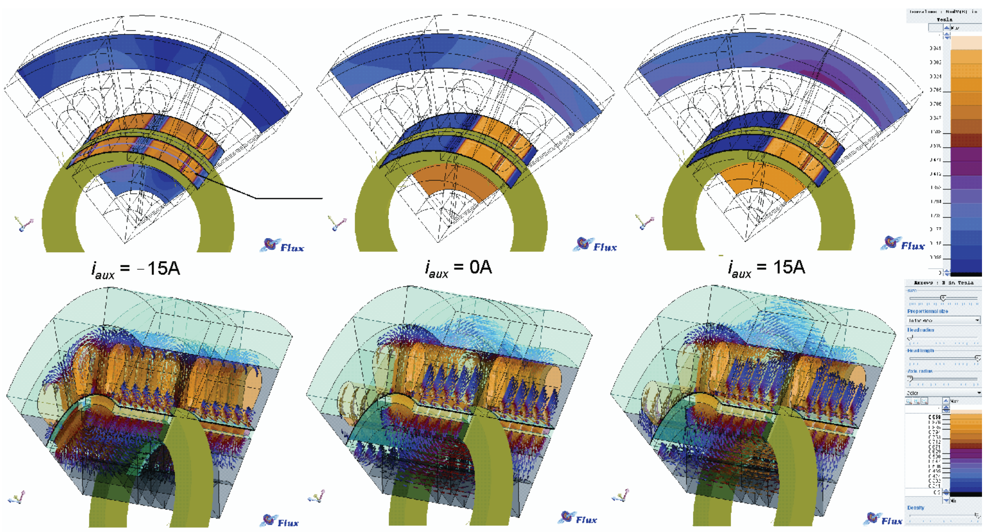

Fig. 4. Field distribution for different DC-currents of the auxiliary coil i_{aux}

The result of a negative direction of the current flow (i_{aux}) in the auxiliary coil is an increase of the magnetic field value in the air gap under the iron pole, as well as a slight weakening of magnetic field under the permanent magnet. On the other hand, the positive direction of the current flow reduces the magnetic field under the iron pole and slightly increases the magnetic field under the magnet pole. Thus, it is only possible to adjust the magnetic field range from zero to a maximum value in the iron pole air-gap. The effects of varied auxiliary field excitation currents at the air gap field values are exhibited in Figure 5.

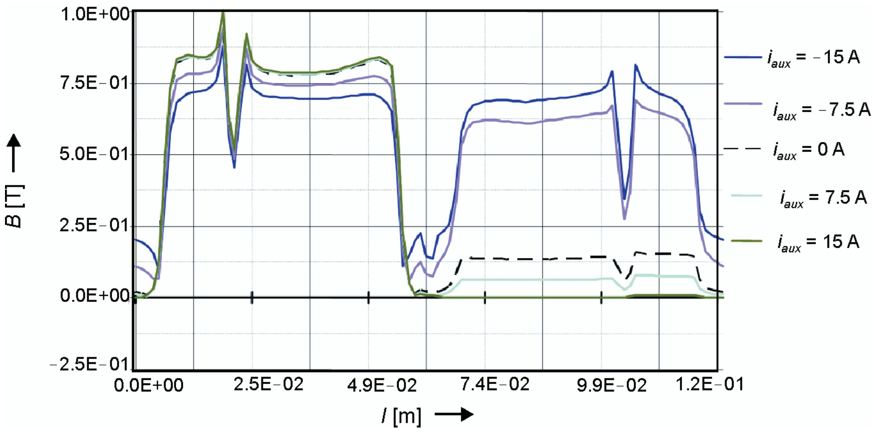

Fig. 5. Magnetic flux density (along the path 1 from Fig. 4) for varied DC-currents of the auxiliary coil i_{aux}

As can be seen, depending on the value and direction of the auxiliary current i_{aux} it is possible to obtain considerably varied field values within the machine. The next figure illustrates the influence of DC-currents of the auxiliary coil i_{aux} on the magnetic flux density value in the air gap of **ECPSM** (calculated for the samples along path 1 for radial direction of magnetic flux density).

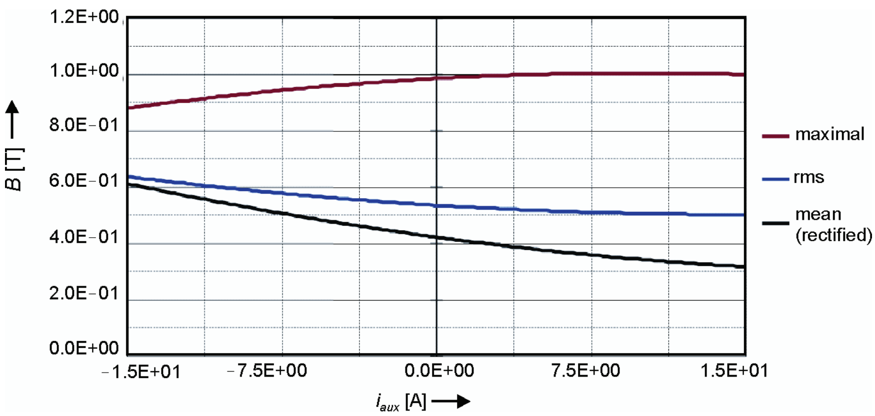

Fig. 6. Values of magnetic flux density vs. different DC-currents of the auxiliary coil i_{aux}

As can be seen in Figure 6, the positive current in the auxiliary coil i_{aux} causes non-uniformity in the magnetic field distribution in the air gap.

3. Influence of the auxiliary currents on induced voltages

The possibility of reducing magnetic field values within the machine leads directly to the possibility of influencing the induced voltages on the machine terminals, which can be successfully used for electromotive drives. In the low speed range, the **ECPSM** can operate at maximal field values (very high torque), while on the other hand the maximal speed is practically not limited by the voltage of the power converter, but only by the mechanical stresses. Figure 7 shows the induced voltage of phase 1 for the rotor speed of 10000 rpm for different DC-currents of the auxiliary coil i_{aux}. Changing the current i_{aux} from – 15 to 15 A results in the reduction (57%) of inducted voltage e_{s1} from 420 to 240 V.

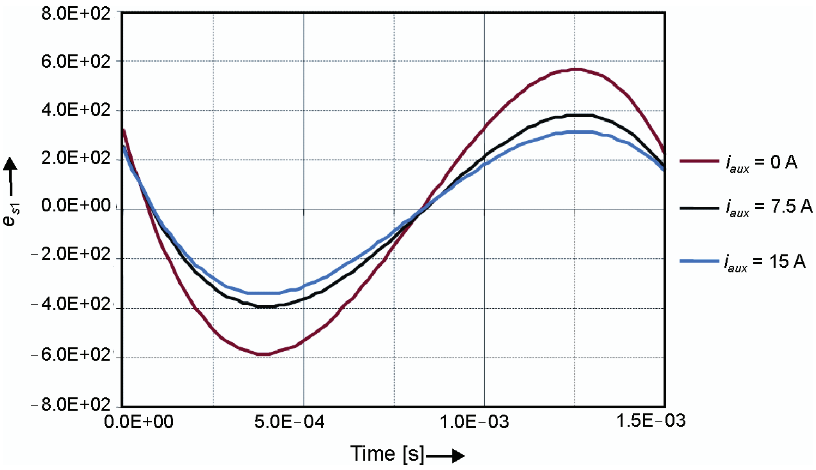

Fig. 7. Induced emf in phase 1 vs. time for a rotor speed of 10000 rpm for different DC-currents of the auxiliary coil i_{aux}

To demonstrate the principal advantages of **ECPSM** in comparison with conventional PM excited synchronous machines, the converter feeding should be simulated by solving the appropriate voltage equations. If the **ECPSM** is represented by an equivalent circuit model, with lumped parameters representing the magnetic state (currents i, inductances L and M) and electric state (voltages V and resistances R), the common voltage equation of phase ν of a machine with in total n stator and m rotor phases can be written as ([11]):

$$V_\nu = R_\nu \cdot i_\nu + \sum_{\mu=1}^{n+m} \left(M_{\nu,\mu} \frac{\partial i_\mu}{\partial t} + \frac{\partial M_{\nu,\mu}}{\partial x} \frac{d\,x}{d\,t} \cdot i_\mu \right) \tag{1}$$

with: $M_{\nu,\mu} = L_\nu$, if $\nu = \mu$.

Based on Eq. 1, the voltage equation at the terminal of phase 1 for an **ECPSM** with three stator phases (Fig. 8), a PM excitation phase with a constant "current" i_4 and an auxiliary excitation phase with an adjustable "constant" current i_5 is given by:

$$V_1 = R_1 \cdot i_1 + L_1 \frac{\partial i_1}{\partial t} + \frac{dL_1}{dt} \cdot i_1 + M_{1,2} \frac{\partial i_2}{\partial t} + \frac{dM_{1,2}}{dt} \cdot i_2 + M_{1,3} \frac{\partial i_3}{\partial t} + \frac{dM_{1,3}}{dt} \cdot i_3 + \overbrace{\frac{dM_{1,4}}{dt} \cdot i_4}^{Term\,4} + \overbrace{\frac{dM_{1,5}}{dt} \cdot i_5}^{Term\,5}. \tag{2}$$

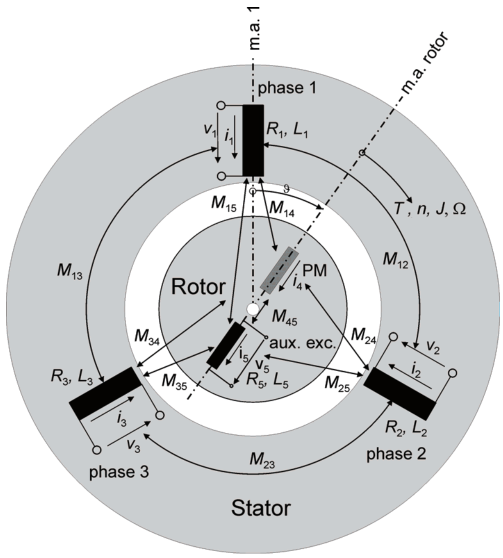

Fig. 8. Equivalent circuit of an **ECPSM** with three stator phases, excitation by permanent magnets (PM) and an auxiliary field winding (aux. exc.) The individual magnetic axes are labeled by m.a.

It can be derived from Eq. 2 that at high speeds the detrimental influence of an increasing back emf of Term 5 (moving magnet) on the current build up can be partially, or even fully, compensated by an appropriate value of the auxiliary current i_4 of Term 4. The final set of voltage equations for all phases composes the set of differential equations, which should be solved by dynamic simulations. This approach gives all information about the dynamical properties of the **ECPSM** machine and will be subject to future investigations.

For the proper functioning of the machine, the knowledge of the cogging torque is of great importance. Figure 9 shows the cogging torque vs. rotor position for different DC-currents of the auxiliary coil i_{aux}. This cogging torque was calculated by increasing the total number of nodes (201500).

Figure 10 shows the influence of DC-currents of the auxiliary coil i_{aux} on the value of the cogging torque. Changes of the current i_{aux} from −15 to 15 A do not have any significant impact on rms and mean values of cogging torque.

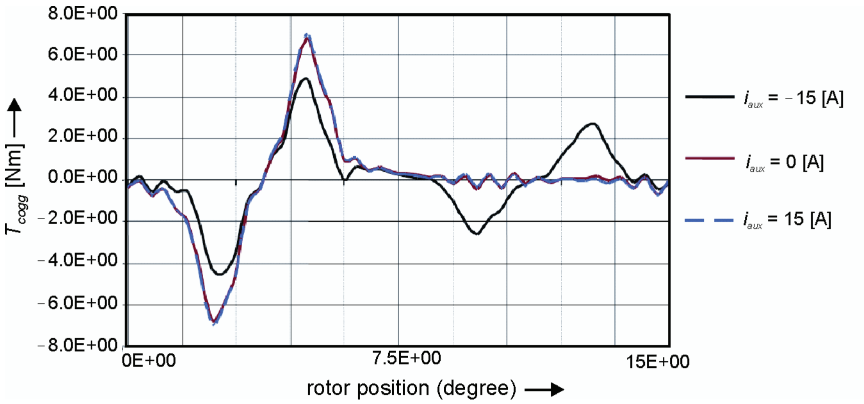

Fig. 9. Cogging torque vs. rotor position for different DC-currents of the auxiliary coil i_{aux}

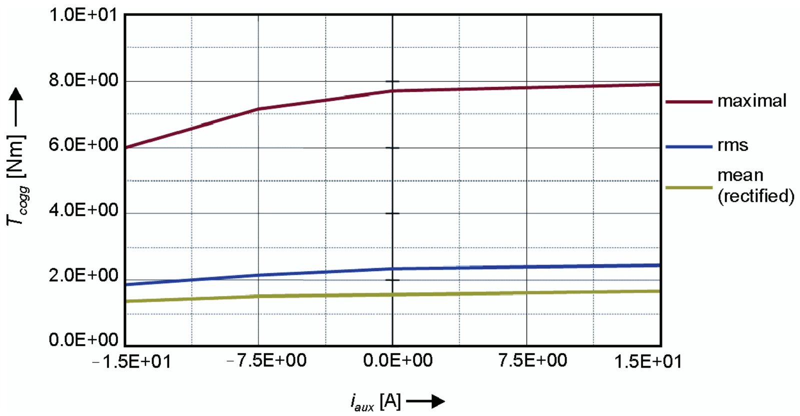

Fig. 10. Values of cogging torque vs. different DC-currents of the auxiliary coil i_{aux}

4. First measurements on a test-machine

For the buildup of a test machine a conventional stator of a three phase machine was used with the auxiliary excitation coil glued in the axial machine center. The rotor was composed by two individual parts, each carrying the ECPSM typical structure of uni-polar permanent magnets and iron poles (Fig. 11). The rotor parts can be skewed in such a way, that both models: one proposed in [12] and the new machine of this paper could be examined.

The test bench, which consists of a dynamometer, 3-phase power converter (H-bridges), H-bridge for the auxiliary coil and electrical loads, enabled an operation of the machine in a generator mode (**ECPSM** driven by the dynamometer) and motor mode (mechanically loaded by the dynamometer).

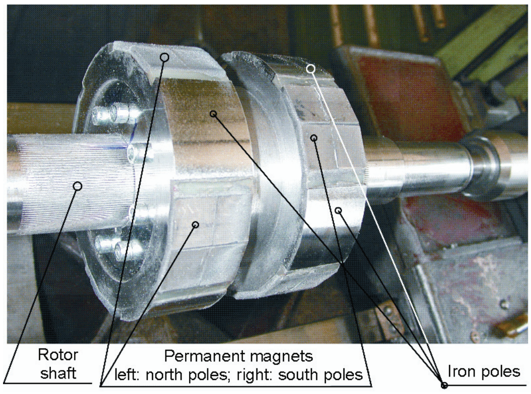

Fig. 11. Photo of the rotor of the test **ECPSM**. The photo exhibits the alternating arranged iron and permanent magnet poles on both sides of the axial center and the circumferential trench-space for the auxiliary field coil

The most important influence of the auxiliary field excitation currents has been measured and compared with this shown in Figure 7 showing good agreement in a very wide speed range [13].

5. Conclusions

The field weakening capability of the proposed machine design offers a nearly unlimited extension of the speed range, restricted only by mechanical stresses. The machine concept proposed in this paper features properties especially needed for hybrid driven or battery driven vehicles as high torque at low speed operation, extremely high speed operation and reduction of induced voltage in case of failing of the feeding convertor. As a result of this new machine concept with only axially displaced magnet and iron poles the iron structure can be composed by high permeable iron sheets instead of soft magnetic compounds (SMC) with reduced permeability. In summation, it can be stated that for the same torque and speed range, the apparent power necessary to feed the conventional PM machine has to be over twice the value of the equivalent power needed for the new **ECPSM**. For automotive applications, the apparent power is not only a matter of costs and volume of the inverters, but also of the intensified battery consumption. The presented structure of the permanent magnet machine has the capacity to influence a limited change in the magnetic parameters. Hence, further optimization work is required.

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