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Performance comparison of double and single rotor permanent magnet machine

***Abstract**. This paper presents the performance comparison between a special double rotor permanent magnet synchronous machine and the adequate conventional single rotor permanent magnet machine. The here presented double rotor machine is primary meant for use in hybrid electric vehicles to improve the fuel economy and to reduce emissions of the whole traction system. Finite element analyses are employed to determine the performance of each machine, where special attention was paid to the iron loss and electromagnetic torque calculation.*

***Streszczenie.** W artykule zaprezentowano porównanie działanie maszyny synchronicznej z magnesem trwałym i specjalnym podwójnym wirnikem oraz konwencjonalnej maszyny z magnesem trwałym i jednym wirnikiem. Prezentowany tutaj silnik z podwójnym wirnikiem był pierwotnie pomyślany do wykorzystania w hybrydowych pojazdach elektrycznych w celu poprawienia gospodarki paliwami i redukcji emisyjności gazów z całego systemu trakcyjnego. Do opisu działania każdej z maszyn wykorzystano metodę elementów skończonych a specjalną uwagę skierowano na straty w żelazie i moment elektromagnetyczny. (**Porównanie działania maszyn z magnesem trwałym jedno- i dwuwirnikowych**)*

Keywords: double rotor electric machine, permanent magnets, finite element analysis, hybrid electric vehicles.
Słowa kluczowe: maszyna elektryczna dwuwirnikowa, magnesy trwałe, metoda elementów skończonych, elektryczny pojazd hybrydowy

Introduction

With ever increasing oil prices and concerns on natural environment, the hybrid electric vehicle (HEV) has become one of the most celebrated concepts for present and nearest future transportation. One of the key components of HEVs is a highly efficient traction system. One of the most interesting solutions for hybrid vehicles traction system presents the use of a double rotor permanent magnet synchronous machine (DRPMSM) commonly called as four quadrant transducer [1-3] or dual mechanical port machine [4-6]. Due to double rotor structure and double winding, it enables the vehicle's internal combustion engine to operate at optimal efficiency, thus improving fuel economy and reducing emissions of the whole traction system.

In the present paper one of the possible solutions of such a DRPMSM is presented and compared to a conventional single rotor permanent magnet (PM) machine structure. The purpose of this paper is to evaluate the performance of the DRPMSM which employs two moving parts in order to be directly connected on one side to the HEV's wheels and on the other side to the HEV's internal combustion engine. Furthermore, the performances of the DRPMSM are directly compared to the traditional PM machine characteristics which can be used only as a traditional motor/generator in the HEVs traction system. The here employed machines can be directly compared because they differ only in the moving parts design. They are made of equal materials.

Methods and compared machines topologies

Fig. 1 and Fig. 2 show cross sections of the two analyzed machine topologies. The machine on Fig. 1 is the so called DRPMSM and is built of three active parts; a stator, inner wound rotor and outer PM rotor between them. The machine topology on Fig. 2 has only one rotor and could be regarded as a conventional PM machine. It has the same stator, PM, flux barrier and stack dimensions as the DRPMSM. Since there is no inner wound rotor, the PM rotor is extended to the shaft.

All results presented in the paper are obtained from finite element (FE) analyses by employing the FE package Ansys. The nonlinearity of the magnetic material is taken into account using the single-value B-H characteristic as shown in Fig. 3, given by the manufacturer of electrical steel M235-35A (for the frequency of 200 Hz), which is used in both FE models investigated in this paper. All calculations are made considering constant PM rotor speed of 3000 rpm. Permanent magnets 33UH used in the FE models are considered to have the ideal radial magnetization direction and the remanence adequate to the PM temperature of 150°C.

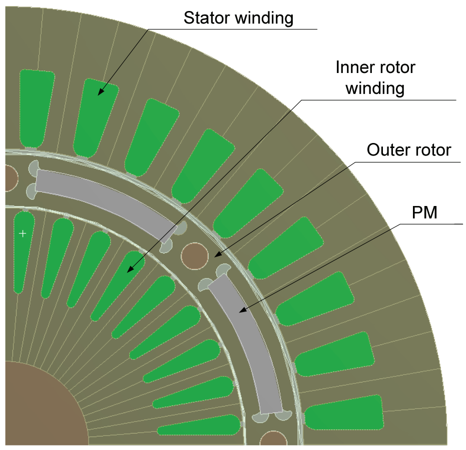

Fig. 1. Double rotor PM synchronous machine (DRPMSM)

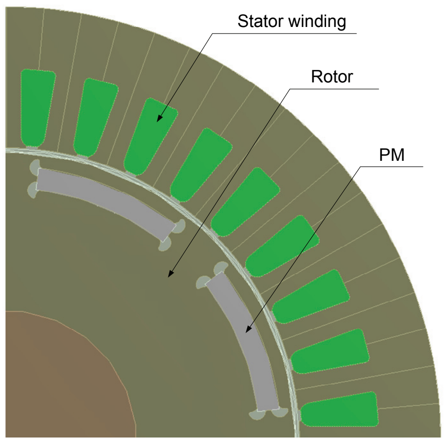

Fig. 2. Single rotor PM synchronous machine

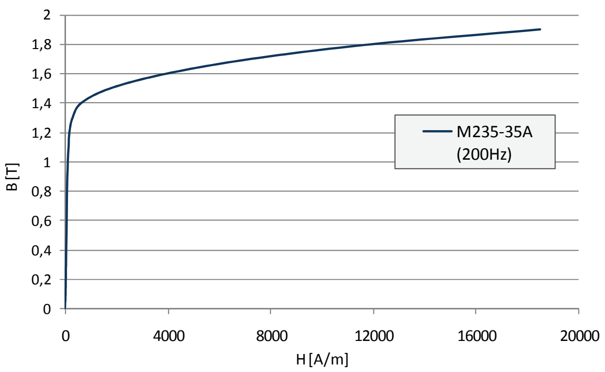

Fig. 3. B-H characteristic of electrical steel M235-35A given by the manufacturer for the frequency of 200 Hz

FE analysis results

FE computations for both machines are made using single mesh during rotor rotation. It means that the mesh of the whole FE model (Fig. 4) is generated only once. Since the mesh can stay unchanged, the remesh error is eliminated and besides, it is time saving. Another benefit, when single mesh is used, is obtained at iron loss calculation. Since each mesh element remains equal during rotation, the flux density characteristic over one electrical period can be obtained for each element. Furthermore the higher harmonic components of flux density can be calculated for each element separately, and for this reason the iron losses can be accurately determined. The iron losses in this paper have been calculated using the approach shown in [7] where improved Bertotti's iron loss model is proposed and coefficients for M235-35A steel grade are identified.

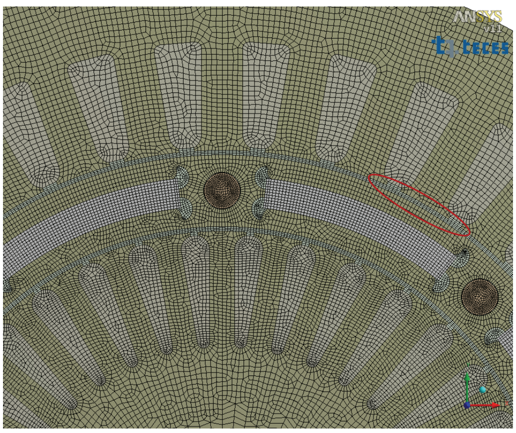

Fig. 4. Double rotor PMSM model mesh

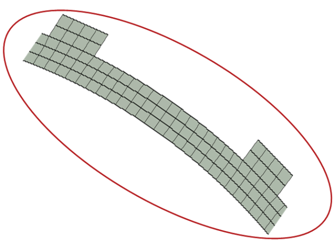

Fig. 5. Zoomed outer air-gap mesh divided in 3 layers and with slot openings

Fig. 6 through Fig. 9 present no-load conditions for both considered machines. It is clearly seen that the DRPMSM, due to inner rotor slots, contains less iron in the construction than the single rotor machine and therefore at equal PM excitation achieves significantly higher flux density values in the inner rotor region. Furthermore, higher flux density values in the inner rotor cause higher total iron losses of the DRPMSM in comparison to the total iron losses of the single rotor machine.

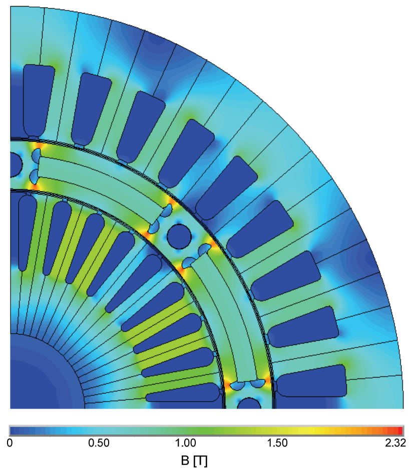

Fig. 6. No-load flux density distribution in DRPMSM

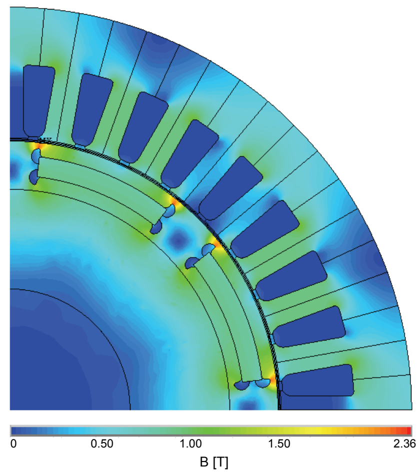

Fig. 7. No-load flux density distribution in single rotor PM machine

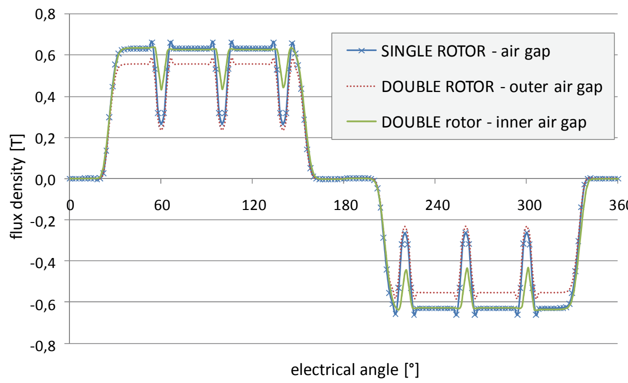

Fig. 8. Comparison of no-load air gap flux density

Since the DRPMSM has two air-gaps, the air-gap flux densities achieve lower values than the one in the case of single rotor machine with single air-gap as seen in Fig. 8. Consequently, the back-EMFs of DRMPSM have lower values as shown in Fig. 9.

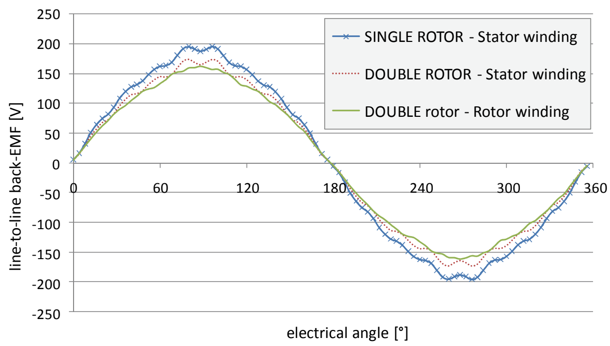

Fig. 9. Comparison of line-to-line back-EMF at speed of 3000 rpm

Because both of the stators have the same geometry and because the DRPMSM exhibits much smaller magnetic flux density value in the outer air-gap, its stator iron loss is smaller than the stator iron loss from the single rotor machine as is presented from the iron loss calculation results from Table 1.

Table 1. Comparison of iron losses at no-load condition (3000 rpm)

Machine topology	DRPMSM	Single rotor PMSM
Stator [W]	60	76
PM rotor [W]	58	55
Wound rotor [W]	35	/
Total iron losses [W]	153	131

Two load cases, stator half and stator full load, were additionaly investigated where the electromagnetic torque and iron losses have been compared. At full load condition the stator winding in both compared machines is supplied with current density of 20 A/mm^2 (adequate for a water cooled stator housing) and in case of DRPMSM with additional 7.5 A/mm^2 of current density in inner rotor winding. The electromagnetic torque is calculated using the Virtual Work method considering the supply currents as being perfectly sinusoidal. Moreover, the electromagnetic torque is calculated at the appropriate torque angle (torque angle is the angle between the stator/inner rotor magnetomotive force and the PM rotor direct axis), where the maximum torque per ampere is achieved.

The electromagnetic torque of the DRPMSM in the Fig. 10 and Fig. 11 is the torque produced on the outer PM rotor as the result of the combined interaction of the stator currents with outer PM rotor and also the inner rotor currents with outer PM rotor.

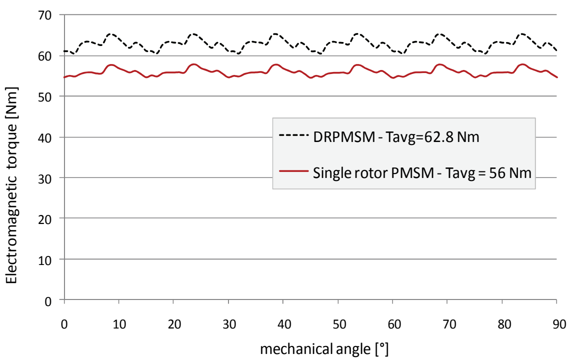

Fig. 10. Electromagnetic torque comparison at stator half load conditions; DRPMSM – stator current density of 10 A/mm^2, inner rotor current density of 7.5 A/mm^2; Single rotor PM machine – stator current density of 10 A/mm^2

Due to the additional currents in the inner rotor, the DRPMSM in case of stator half-load conditions achieves higher average torque value than the single rotor PM machine as shown in Fig. 10.

Table 2. Comparison of iron losses at stator half-load condition (3000 rpm)

Machine topology	DRPMSM	Single rotor PMSM
Stator [W]	173	228
PM rotor [W]	80	115
Wound rotor [W]	91	/
Total iron losses [W]	344	343

In case of stator full-load conditions (Fig. 11) it is clear that the single rotor PM machine reaches approximately the same average value of the electromagnetic torque than the DRPMSM. From the Fig. 10 and Fig. 11 and considering the fact that the DRPMSM has less iron material, we could conclude that the DRPMSM core gets obviously more saturated at the same stator current density levels of both machines and with additional inner rotor current.

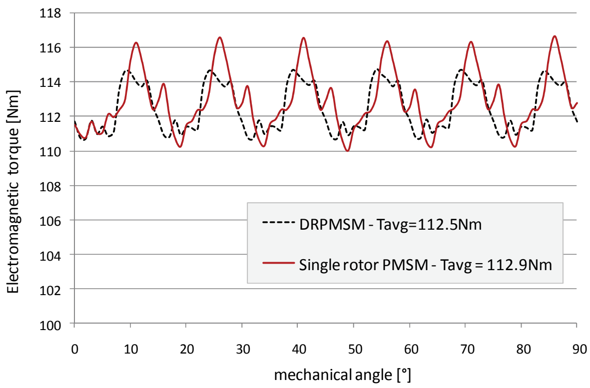

Fig. 11. Electromagnetic torque comparison at stator full load conditions; DRPMSM – stator current density of 20 A/mm^2, inner rotor current density of 7.5 A/mm^2; Single rotor PM machine – stator current density of 20 A/mm^2

As presented in Fig. 12, the single rotor PM machine achieves lower flux density values at full-load condition in rotor area and higher flux density values in stator where consequently produces higher iron losses as shown in Table 3 in comparison to DRPMSM.

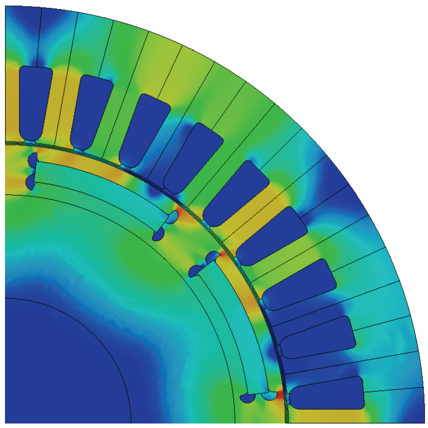

Fig. 12. Full-load flux density distribution in single rotor PM machine

Table 3. Comparison of iron losses at stator full-load condition (3000 rpm)

Machine topology	DRPMSM	Single rotor PMSM
Stator [W]	267	321
PM rotor [W]	98	152
Wound rotor [W]	103	/
Total iron losses [W]	468	473

Conclusion

In the paper a DRPMSM, primary used for specific application in HEVs, is presented and its performance is compared to a conventional single rotor PM machine. Due to less complex construction and on the basis of the presented results, the single rotor PM machine is still preferable in applications, where double rotor construction is not needed.

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