Basic structure and operational principles of double rotor permanent magnet synchronous machines used in HEV

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Abstract
Concerns over fluctuating gas prices and global climate change have sparked an explosion of interest in new automotive technology. The global car industry has already begun to show exactly where the future of cars is going and it seems that electric and hybrid cars are the right answer. Hybrid electric vehicles (HEVs) combine the internal combustion engine (ICE) of a conventional vehicle with an electric machine and battery, to improve the fuel economy and to reduce emissions of the whole traction system. Since there are different ways to combine the power from the electric machine and the ICE, there is still a lot of interest in research and development of new HEV operating principles.

The integration of the double rotor permanent magnet synchronous machine (DRPMSM) in HEV's presents one of the possible solutions and is attracting a lot of interest. The purpose of such an electromagnetic machine is to keep the ICE at maximum efficiency during all driving conditions. In other words, the idea is to enable the ICE to operate at its optimal operating point independent of the working point at the wheel. In this paper basic topologies and structure of DRPMSM are presented and some major modes of operation are explained. Furthermore, the proposed design of DRPMSM is shown where the finite element analyses are employed to determine the performance of the machine.

1. 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 DRPMSM commonly called as four quadrant transducer or dual mechanical port machine [1]-[4]. 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.

The DRPMSM is generally made of three active components of the machine as shown in Fig. 1: stationary part with winding – stator, rotating part with permanent magnets (PMs) – outer rotor and rotating part with winding – inner rotor.

1.1 DRPMSM integration in HEVs
The schematic diagram of the DRPMSM and its application in HEVs is presented in Fig. 2, where it is shown that the DRPMSM is inserted between the ICE and the reduction gear on the other side; this is then coupled to the HEV’s wheels.

As shown in Fig. 1 and Fig. 2 the DRPMSM is constructed from three main parts: an inner wound rotor, which is fed by one inverter via slip rings; an outer rotor with PMs; and a stator fed by the second inverter. The inner wound rotor is mechanically coupled to the ICE and enables the increase or decrease of the outer rotor speed produced by the ICE to the speed required at the reduction gear. The stator is a conventional stator with windings that interact with the outer rotor, which enables the...
increase (or decrease) of the outer rotor torque produced by the ICE to the torque level required at the reduction gear. Both, the inner rotor and stator are supposed to work as motor or generator. The most important advantage of this approach is that the outer rotor torque and speed can be controlled separately. Consequently, the ICE is able to operate at the optimal operation line as shown in Fig. 3.

Fig.3. ICE optimal operation line characteristic [1]

The ICE is supposed to work at any optimal operation point on operation line. The optimal operation point is the point at any given power where the ICE produces that power at the highest possible efficiency.

2. Operational principles of DRPMSM

As already described the most important feature of DRPMSM is that the outer rotor speed and torque can be controlled separately.

2.1 Outer rotor speed control

The inner rotor enables the change of outer rotor speed ($\omega_o$) over or under the ICE speed ($\omega_{ic}$). In either condition, there is a speed difference between the two rotors. To have meaningful torque interactions between the two rotors, inner rotor has to be compensated with excitation of speed difference, so that the two magnetic fields of the rotors are synchronized.

In case that we want the $\omega_o$ to be higher than $\omega_{ic}$, the inner rotor magnetic field caused by inner rotor currents must have the same rotation direction than the ICE. The $\omega_o$ (resultant speed of rotating magnetic field) is the consequence of the $\omega_{ic}$ and the speed of rotating magnetic field of inner rotor currents ($\omega_{curr}$). If the directions of $\omega_{ic}$ and $\omega_{curr}$ are the same, the $\omega_o$ is the sum of $\omega_{ic}$ and $\omega_{curr}$:

$$\omega_o > \omega_{ic} \rightarrow \omega_o = \omega_{ic} + \omega_{curr}. \quad (1)$$

In the other case, when we want the $\omega_o$ to be lower than $\omega_{ic}$, the inner rotor magnetic field caused by inner rotor currents must have the opposite rotation direction than the ICE:

$$\omega_o < \omega_{ic} \rightarrow \omega_o = \omega_{ic} - \omega_{curr}. \quad (2)$$

2.2 Outer rotor torque control

In a similar manner the outer rotor torque control is established. The stator can operate in motor or generator mode. When there is a need to increase the outer rotor torque produced by ICE to the higher level, the stator operates as a motor. In this case the stator currents magnetic field rotation direction has to be equal to the outer rotor rotation direction. Furthermore, the stator currents frequency has to be equal to the frequency of the outer rotor rotation. Contrarily, the stator operates as a generator, when there is a need to decrease the outer rotor torque produced by the ICE. In all cases the outer rotor PM position presents the reference for the whole control logic, including the outer rotor torque as well as the outer rotor speed control.

2.3 The most common modes of operation

Integration of DRPMSM in HEV offers many different modes of operation, bellow the most common ones are listed and described:

- Increase of outer rotor speed and torque: this mode is used when the vehicle is accelerating. Both, stator and inner rotor winding are operating as motors. During this mode the driving range is limited by the energy content of the battery.

- Decrease of outer rotor speed and torque: this mode is used when the regenerative braking is accomplished. The stator and inner rotor winding can both operate in generator mode, or only one of them.

- Simultaneous outer rotor speed decrease and torque increase: the outer rotor speed can be decreased in two different ways. We can simply decrease the ICE speed or we keep the ICE speed constant and decrease the outer rotor speed by inner rotor currents as described earlier. At the same time the stator winding is fed to increase the outer rotor torque.

- Simultaneous outer rotor speed increase and torque decrease: considering the fact that the ICE efficiency can be low at high speed [5], this mode of operation can be quite frequent as well. While the inner rotor currents increase the outer rotor speed, the stator operates as generator and charges the battery.

The vehicle could also be driven in pure electric
mode if no ICE is engaged.

3. Basic topologies of DRPMSM

One great advantage of the DRPMSM machine topology is that a high degree of integration can be achieved, since there are practically two electric machines integrated into one, both sharing the outer PM rotor. These two electric machines are often named as the stator machine (SM) and double rotor machine (DRM) [1]. The SM is formed by stator and PMs on the outer rotor and the DRM is composed by inner rotor and PMs on the outer rotor. According to different path directions of magnetic flux and structural arrangements, several topologies of DRPMSM are possible, as illustrated in the Fig. 5 [6].

![Fig.5. Different topologies of DRPMSM: a) radial-radial b) axial-axial c) axial-radial](image)

The axial/radial topology has the most complicated flux distribution and construction but has one advantage compared to the other ones. In axial-radial flux topology there is no magnetic coupling problem which can appear in other two topologies. Despite this advantage, the radial-radial and axial-axial topologies are still more promising in practice. The volume of the axial-axial topology is usually smaller than the one in radial-radial topology, but has much higher losses, mostly mechanical and iron losses [6].

However, different topologies have different characteristics, and the final choice of topology will greatly depend on the available space in the vehicle, the performance requirements and the cost of different arrangements.

3.1 Outer rotor construction in radial-radial flux topology

Since the radial-radial topology is gaining more and more attention by its simple structure, one important structure detail should be pointed out. The radial-radial machine could have different outer rotor structure configuration, as shown in Fig. 6.

![Fig.6. Outer rotor structure configuration: a) two PMs per pole b) one PM per pole](image)

When one PM per pole is used, the volume of used PMs is much lower than in the case of using two PMs per pole. Another advantage of using one PM per pole is that the magnets are interior and therefore the problems related to high centrifugal forces at higher speeds are avoided. Unfortunately this configuration (Fig. 6b) has a drawback as well. The magnetic coupling between the SM and DRM is much higher than in the case in Fig. 6a and by design the coupling cannot be totally avoided.

4. Finite element modeling

The analyzed electric machine is the radial-radial DRPMSM and can be regarded as a 36 stator slot – 8 pole outer rotor – 36 inner rotor slot combination. 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 M235-35A is taken into account using the single-value B-H characteristic. 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. The outer rotor design is made of laminated steel and interior PMs (one PM per pole).

![Fig. 7. No-load flux density distribution in DRPMSM](image)

In ideal case the flux will penetrate straight through the outer rotor with no leakage between the magnets. This is almost the case at no load condition (Fig. 7), where flux barriers prevent most of the flux to leak. Fig. 8 shows the flux density for both air-gaps.

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The DRM and SM are both supposed to work as motors and generators, therefore the back EMF (Fig. 9) is an important issue.

The electromagnetic torque of the DRPMSM in the Fig. 10 is the torque produced on the outer PM rotor as the result of the combined interaction of the stator currents with outer rotor and also the inner rotor currents with outer PM rotor. It is calculated at full load condition, at the constant current density and at the appropriate torque angle (torque angle is the angle between the stator or inner rotor MMF and the outer rotor direct axis respectively), where the maximum torque per ampere is achieved. The current density level for the stator winding has been set to 20 A/mm² (liquid cooled stator housing) and for the inner rotor winding to 7.5 A/mm².

4. Conclusion

This paper has presented a brief introduction of special DRPMSM used for HEVs. The use of this approach could improve the fuel consumption of conventional (series, parallel) hybrid vehicles. A basic structure of such a machine is shown and described. Different topologies of DRPMSM are presented and operational principles of such a machine are shortly discussed. At the end the FEM analysis is presented for the proposed radial-radial DRPMSM topology.

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Bibliography


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