Research on the Radial-Radial Magnetic Field Modulated Brushless Compound-Structure Permanent-Magnet Synchronous Machine

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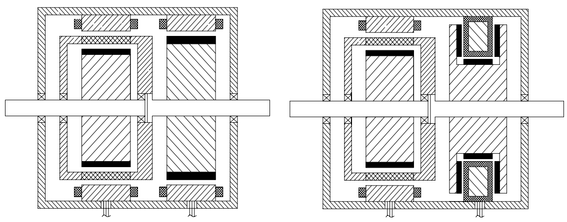
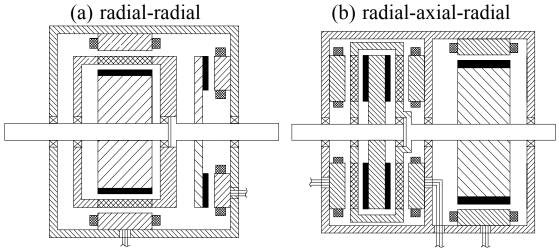
Abstract —A novel brushless compound-structure permanent-magnet synchronous machine (CS-PMSM) utilizing magnetic field modulation method is proposed. In addition to different flux topologies, this paper focuses on the operating principle of the radial-radial magnetic field modulated brushless CS-PMSM by analytical method. The validity of the operating principle is proved by the finite-element method (FEM) simulation and the harmonic analysis of the magnetic flux density of the air gap.

I. Introduction

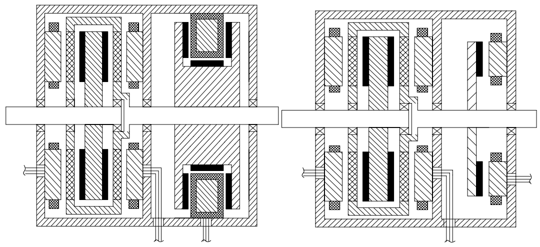
The compound-structure permanent-magnet synchronous machine (CS-PMSM) is a new power-splitting concept for hybrid electric vehicles (HEVs). Compared with hybrid electric systems with planetary gear unit, the CS-PMSM has advantages such as the compact structure, low noise and high efficiency [1]-[3]. However, the current CS-PMSM has two major problems. Firstly, the rotating winding needs brushes and slip rings, which may cause the problems such as maintenance, friction loss and so on. Secondly, the windings of the inner rotor are easily superheated [4]. To solve the above problems, a brushless CS-PMSM is proposed, based on the principle of the magnetic field modulation. There are six different flux topologies for the magnetic field modulated brushless CS-PMSM, i.e. the radial-radial, radial-axial, radial-axial-radial, axial-radial, axial-axial and axial-axial-radial structures, as shown in Fig. 1 respectively.



(a) radial-radial (b) radial-axial-radial



(c) radial-axial (d) axial-radial



(e) axial-axial-radial (f) axial-axial

Fig. 1. The different topological structures of the magnetic field modulated brushless CS-PMSM

II. The Operating Principle of the Radial-Radial Magnetic Field Modulated Brushless CS-PMSM

It is assumed that the pole pairs of the first PM rotor is n and the pole pairs of the rotary magnetic field of the first stator is p when the windings of the first stator are fed with m-phase AC current. Meanwhile, it is supposed that the number of the magnetic block and the insulating block is q, respectively. The relation of n, p and q is given by the equation:

$$p = \left| h * n + k * q \right| \tag{1}$$

where h is the positive odd number and k is the integral number.

In the HEV, the PM-rotor output shaft is connected with the internal-combustion engine (ICE) and the output shaft of the modulating ring rotor is connected with the load, as shown in Fig. 2. When the ICE drive the first PM rotor in the counter-clockwise direction, meanwhile, it is assumed that the driving torque is T and the rotary speed of the first PM rotor is Ω_1, as shown in Fig. 3. To keep the balance of the driving torque of the first PM rotor, the $2p$ pole pairs of the stator rotary magnetic field is built in the outer air gap of the radial magnetic field modulated brushless double rotor machine, when the windings of the first stator are flowing m-phase AC current. And it is supposed that the speed of the rotary magnetic field is Ω_2. The stator rotary magnetic field would produce the same pole pairs rotary magnetic field to the first PM rotor with the modulating action of the modulating ring rotor in the inner air gap of the radial magnetic field modulated brushless double rotor machine. The inner modulating torque would act on the first PM rotor in the clockwise direction, with the mutual effect of magnetic field in the inner air gap. And the value of the inner modulating torque is T_1.

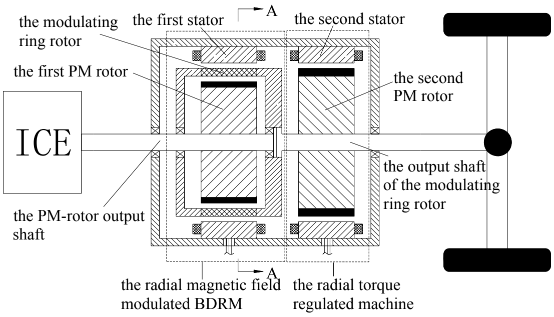


Fig. 2. The magnetic field modulated brushless CS-PMSM system

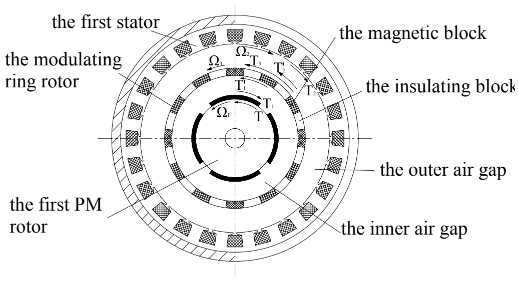


Fig. 3. the transverse section diagram of the radial magnetic field modulated BDRM

According to the equilibrium principle of the torque, the relation of T and T_1 is given by

$$T_1 = -T \tag{2}$$

According to the principle of the action torque and the reaction torque, the torque (T_1'), with the same value and the opposite direction to T_1, would act on the modulating ring rotor.

Meanwhile, the magnetic field of the first PM rotor would produce the same pole pairs rotary magnetic field to the first stator with the modulating action of the modulating ring rotor in the outer air gap of the radial magnetic field modulated brushless double rotor machine. The outer modulating torque would act on the first stator in the clockwise direction, with the mutual effect of magnetic field in the outer air gap. And the value of the outer modulating torque is T_2.

According to the principle of the action torque and the reaction torque, the torque (T_2'), with the same value and the opposite direction to T_2, would act on the modulating ring rotor.

Therefore, the output torque (T_3) of the modulating ring rotor is

$$T_3 = T_1' + T_2' = -(T_1 + T_2) \tag{3}$$

And it is assumed that the speed of the modulating ring rotor is Ω_3. From the above-mentioned analysis, the output shaft of the modulating ring rotor would drive the load with the torque (T_3) in the anticlockwise direction.

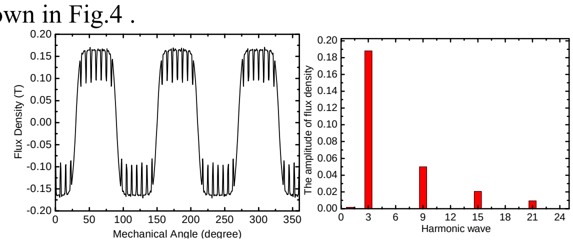
According to the magnetic field modulated principle [5], the relation of Ω_1, Ω_2 and Ω_3 is given by

$$\Omega_2 = \frac{h*n}{|h*n+k*q|}\Omega_1 + \frac{k*q}{|h*n+k*q|}\Omega_3 \tag{4}$$

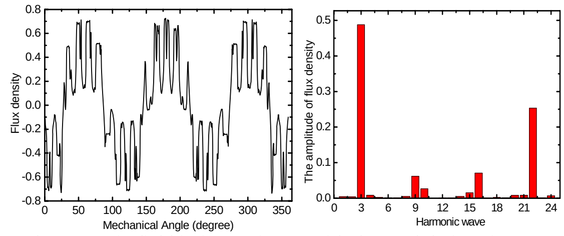
In the HEV, the speed of the first PM rotor (Ω_1) is known by the speed of the ICE, so the speed of the modulating ring rotor (Ω_3) is dependent on the speed of the first stator magnetic field. Thereby, the speed of the load can change infinitely variably with the connection to the output shaft of the modulating ring rotor.

III. Magnetic Field Analysis in the Air Gap

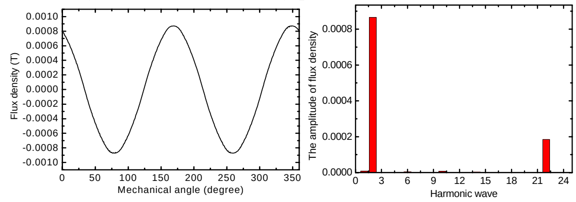
The magnetic field of the inner and outer air gap is analyzed with the modulating ring rotor of without it, as shown in Fig.4 .



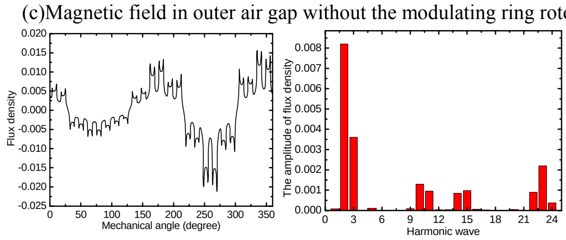
(a)Magnetic field in inner air gap without the modulating ring rotor



(b)Magnetic field in inner air gap with the modulating ring rotor



(c)Magnetic field in outer air gap without the modulating ring rotor



(d)Magnetic field in outer air gap with the modulating ring rotor

Fig.4. Magnetic field in inner and outer air gap

IV. References

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