A Novel Axial Flux Spoke-Array Magnetic-Field-Modulated Machine for Hybrid Electric Vehicle

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This paper proposes a novel axial flux spoke-array magnetic-field-modulated dual-mechanical-port (AFSA-MFM-DMP) machine, which is the key component of an electrical variable transmission (EVT) device. By cooperating spoke-array rotor and dual modulating ring rotors structure, power factor of the proposed machine is much higher than conventional magnetic-field-modulated dual-mechanical-port machines. Firstly, the machine structure and its operation principles are introduced. Based on the proposed machine, a HEV system is constructed. The machine torque transmission capability is verified by quasi-3D FEA and the results show that the AFSA-MFM-DMP machine has high power factor, viz. 0.75.

***Index Terms*—Axial flux, magnetic-field-modulated, dual-mechanical-port, high power factor**

I. Introduction

Due to the increasing oil prices and the concerns about environmental pollution, hybrid electrical vehicles (HEVs) are recognized as a suitable alternative for daily transportation. As the HEVs have two power sources, they are often designed to have a power-split structure. Toyota Prius for instance, the first and most successful commercial HEVs, adopts planetary gear to constitute the powertrain THS-II. Its THS-II includes two machines and a planetary gear. Even though this electrical variable transmission (EVT) system is mature and widely used in business, mechanical connection devices such as planetary gear have several issues such as inherent mechanical energy loss, regular maintenance, lubrication and gear noise [1] and can be improved.

Over the past decade, dual-mechanical-port electrical machines [1]-[5] are regard as a feasible replacement for traditional mechanical power transmission devices. In [1], an EVT device is brought up to combine two induction machines. The concept of dual mechanical port electric (DMP) machines is proposed in [2]. By cooperating magnetic gear with PM machines, a novel DMP machine topology is proposed [3]. Due to the so-called magnetic gearing effect, magnetic-field-modulated (MFM) machines is proved to have natural dual mechanical port characteristic and a few topologies are proposed [4]-[5]. All of them have successfully achieved power split while the multi air-gap and large leakage flux contribute these machine having low power factor.

In this paper, a novel axial flux spoke-array magnetic-field-modulated dual-mechanical-port(AFSA-MFM-DMP) machine is proposed to improve the power factor of magnetic-field-modulated dual-mechanical-port machines. The proposed machine configuration is shown in Fig.1. Fig.2 shows the HEV system based on the proposed machine and a regular permanent magnet (PM) machine. As the input and output shafts of the proposed machine are connected to ICE and PM machine respectively, the proposed machine is able to achieve the function of one machine and plenary gear in THS-II to provide speed different from ICE. The addition of the PM machine is to realize torque decoupling. The machine structure and operation principles are introduced. After that, the result of quasi-3D FEA is provided and discussed. The result shows proposed machine has high power factor, viz.0.75.

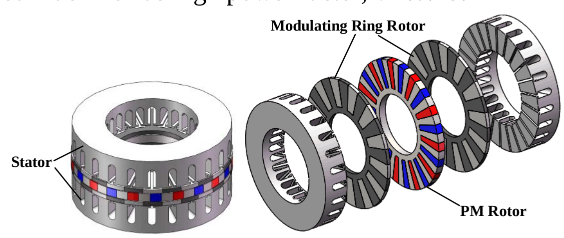

Fig. 1. Structure of proposed machine

II. Structure and Operation Principle

As shown in Fig.1 the AFSA-MFM-DMP machine consists of two stators, two modulating ring rotors and a PM rotor. Two stators and two modulating ring rotors have similar structure respectively. The PMs are arranged as spoke-array which can increase the air-gap flux density. The rotor core is separated into several segments and the magnets are attached to those segments. The modulating ring rotors consist of appropriate number of ferromagnetic modulator. There is half pole pitch shift between two modulating ring rotors, which is design to create a new main flux path to reduce flux leakage and main flux reluctance.

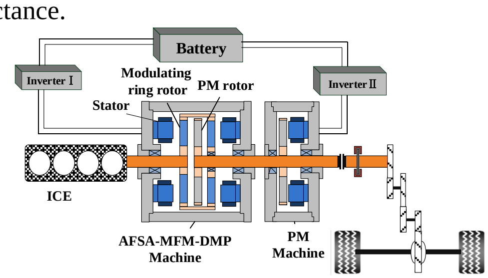

Fig. 2. The HEV system based on proposed machine and PM machine

Due to the so-called magnetic gearing effect, rotation speed of the PM rotor and the modulating ring rotor are independent, which implies that the proposed machine is capable of decoupling speed. The relationship of pole pair, speed and torque are characterized as follow [5]:

$$P_m = P_r + P_s \quad (1)$$

$$\Omega_3 = \frac{P_s\Omega_1 - P_m\Omega_2}{P_s - P_m} \quad (2)$$

$$T_3 = -(T_1 + T_2) \quad (3)$$

$$T_1 = -\frac{P_s}{P_m}T_2 \quad (4)$$

P_m is the number of the ferromagnetic modulator and P_r, P_s are the pole pair number of PM rotor and stator I respectively. Ω is the rotational velocity and T means torque while 1, 2, 3 means stator, modulator and PM rotor respectively. It can be seen the output Torque of proposed machine depends on input torque, so the PM machine is necessary to add extra torque.

III. Electromagnetic performance

As axial flux machines have inherent 3D flux path, the most accurate way to simulate the model is 3D FEA. Since the 3D time-stepping FEM is time-consuming, a Quasi-3D FEM approximation based on a 2D plane is preferred for performance evaluation to reduce complexity in the modeling and decrease computation time [6]

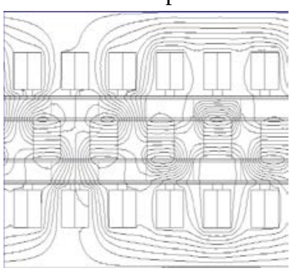

Fig. 3. No-load flux line

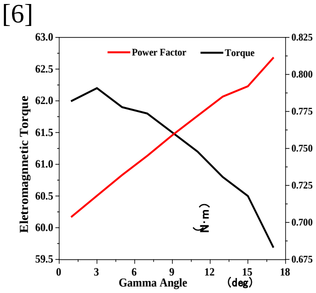

Fig. 4. Variation of torque and power factor vs gamma angle

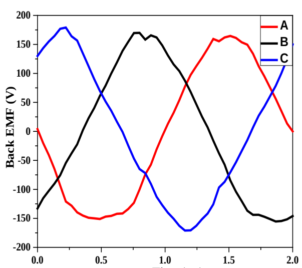

Fig. 3. Back EMF wave

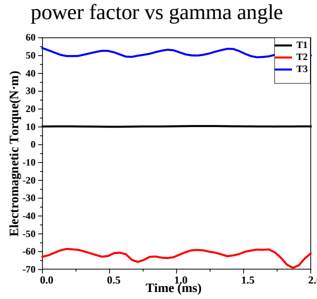

Fig. 4. Electromagnetic torque wave

To verify the fundamental operating principle of the topology, a model with gear ratio 2:10 is selected and Fig.3 shows the no-load flux line of unit machine. It can be seen the 5-pole magnetic field of PM rotor is modulated into 1-pole in stators. Fig.4 shows the variation of torque and power factor with gamma angle. With the increasing of gamma angle, the power factor increases and reaches 0.82, while torque decreases. In order to obain higher power factor without scarifying too much torque, the operation point is selected as gamma = 9°.

The waves of back EMF and Torque are shown in Fig.5 and Fig.6 respectively. The results of simulation and the structure parameters of model are listed in TABLE I. It can be seen the relationship of average torques accord with equation(3)(4). Where gamma angle is 9, the power factor of proposed machine is 0.75 which is much higher than that of traditional magnetic-field-modulated dual-mechanical-port machine. It can be seen the torque ripple of the machine is not small, but it can be smooth by optimizing gear ratio [5]. With the structure optimization, the power factor and torque density should be higher.

TABLE I
Types Sizes For Camera-Ready Papers

Parameters	Unit	Value
Rotor pole pairs	-	2
Stator pole pairs	-	10
Number of modulator	-	12
Outside radius of Stator	mm	220
Axial length	mm	82
T1	N·m	10.2
T2	N·m	-61.3
T3	N·m	51.0
Back EMF RMS	V	151
Phase current RMS	A	11
Torque Density	N·m/litre	18.2
Power Factor	-	0.75

IV. Conclusion

In this paper, a AFSA-MFM-DMP machine is proposed to enhance power factor as well as achieving speed decoupling of ICE and vehicle load.

Firstly, the structure and operating principle of proposed machine are presented. The performance of the proposed machine is shown lately and the FEA result prove that power factor of the AFSA-MFM-DMP machine can reach 0.75 without specific optimization. Moreover, the characteristic of speed decoupling is discussed. Based on the proposed machine, a HEV system is present to decuple both speed and torque between the ICE and vehicle load and perfectly replace the THS-II. Although the topology presented in this study exhibited high torque ripple, it can be solved by optimizing the gear ratio and structure parameter. The Topology is potential to reach higher power factor and torque density. The optimization procedure and results will be presented in full paper.

References

[1] M. J. Hoeijakers and J. A. Ferreira, "The electric variable transmission." in IEEE Trans. Ind. Appl, vol. 42, no. 4, pp. 1092-1100, July-Aug. 2006.

[2] L. Xu, "A new breed of electric machines - basic analysis and applications of dual mechanical port electric machines." in International Conference on Electrical Machines and Systems, 2005, pp. 24-31 Vol. 1.

[3] J. Wang, K. Atallah, and S. D. Carvley. "A Magnetic Continuously Variable Transmission Device." IEEE Trans Magn, vol. 47, no. 10, pp. 2815-2818, Oct. 2011.

[4] C. Tong, Z. Song, P. Zheng, J. Bai and Q. Zhao, "An axial magnetic-field-modulated brushless double-rotor machine for hybrid electric vehicles,"2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific, Beijing, 2014, pp. 1-5.

[5] J. Lai and J. Li, "A Novel Axial Flux Magnetic-Field-Modulated Dual-Mechanical-Port Dual-Electrical-Port Machine for Hybrid Electric Vehicle," 2016 IEEE Vehicle Power and Propulsion Conference, Hangzhou, China, 2016, pp. 1-6.

[6] F. Zhao, T. A. Lipo and B. I. Kwon, "A Novel Dual-Stator Axial-Flux Spoke-Type Permanent Magnet Vernier Machine for Direct-Drive Applications," in IEEE Trans Magn, vol. 50, no. 11, pp. 1-4, Nov. 2014.