A Novel Hybrid-Excited Flux-Modulated Memory Machine for Electrical Continuously Variable Transmission System

Mao Y[1] Niu S. X[2]

Abstract–This paper proposed a hybrid-excited double rotor double stator permanent magnetic machine applied in electrical continuously variable transmission (E-CVT) system which incorporates with the flux modulation and flux-memorizable concept. This machine can produce relative large torque in low speed region owing to flux modulation effect. Besides, this E-CVT system can achieve high speed operation in flux weakening mode which is realized by applying a short current pulse to demagnetize aluminum-nickel-cobalt (AlNiCo) magnets in this machine. There is no need to introduce a permanent excitation current in winding for this machine which results in avoiding inducing additional excitation losses. The configuration and operation principles of the proposed hybrid-excited flux-modulated memory (HEFMM) machine are presented. Electromagnetic characteristics of the proposed machine are analyzed using the time-stepping finite element method (TS-FEM).

Keywords–Electrical continuously variable transmission system, finite element method, flux modulation, memory machine

I. INTRODUCTION

With continuous growth in the number of hybrid electric vehicles (HEV), the request to improve its fuel economy and energy efficiency is increasing accordingly. Electrical continuously variable transmission (E-CVT) system is a desired technology to fulfill these requirements which can realize combination and separation of the power provided by both internal combustion engine (ICE) and the energy storage system [1]-[5].

The Toyota Prius E-CVT system which consists of a planetary gear power slit system and two electric machines with associated power inverters is a milestone in the development of HEVs [6]. In this E-CVT system, there is a planet gear connected with ICE, of which the sun gear is connected with the electric machine and the ring gear is connected to the other electric machine. This design effectively provides a fully integrated power supply system to realize acquisition, storage and conversion of energy. However, this E-CVT system integrated with mechanical planetary gearbox system suffers from relatively low reliability and low efficiency. Therefore, gearless E-CVT systems adopt permanent magnetic (PM) gears are gradually developed to replace conventional E-CVT systems employed mechanical gears [7]–[11]. Among these designs, permanent magnetic (PM) machines as well as induction machines with double rotor constructions can nicely split and combine power without plagued by mechanical problems such as frictional loss, high maintenance and audible noise various. In[9] a double stator double rotor brushless ECVT system is proposed. The core component of this E-CVT system includes a double-stator double-rotor flux-modulated machine and an energy storage system combined with several inverters . The schematic diagram of this E-CVT system is plotted as shown in Fig.1. The two rotors in this E-CVT system are coupled due to flux modulation effect. Compared to other designs, this kind of E-CVT system has many merits such as high torque density, high efficiency, integrated structure and low mutual effect between each winding [12-13]. But since the drive’s output voltage is limited by its dc bus, this E-CVT system may not realize the requirement in driving speed. Due to the fixed magnetic field of PM excitation, it is difficult for this machine to regulate magnetic flux so that not easy to accommodate HEV to different drive mode. So in this paper, a novel hybrid-excited flux-modulated memory (HEFMM) machine for E-CVT system is proposed to address these problems. The configuration of the core component of the proposed E-CVT system is shown in Fig. 2. Operation principles of the proposed E-CVT system are described in section II and performance of the HEFMM machine based on time-stepping finite element method (TS-FEM) are reported in section III.

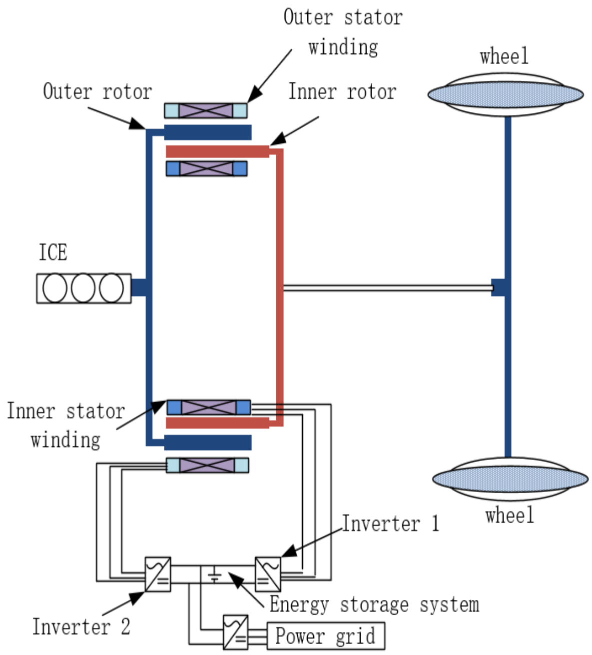

Fig. 1: Schematic diagram of the double rotor double stator ECVT system

II. CONFIGURATION AND OPERATION PRINCIPLE OF THE HYBRID-EXCITATION MACHINE

The cross section configuration of the machine part of the E-CVT system is shown in Fig.2. This machine is

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[1] Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong
E-mail: yuan.my.mao@polyu.connect.hk
[2] Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong
E-mail: eesxniu@polyu.edu.hk

composed of two stators, two rotors and three sets of windings. Both the inner stator and the outer stator are housed with a set of armature winding. In addition, another set of windings is introduced to the inner stator which is used to bear excitation current pulse. In this design, the aluminum-nickel-cobalt (AlNiCo) magnet segments and ferrite segments are attached to each tooth of the inner stator one by one. The magnetization coils are wound around the teeth behind the AlNiCo pieces. By applying a temporary current pulse to each coils, the AlNiCo magnets can be either magnetized or demagnetized [14-15]. With this design, the level of air gap flux density can be effectively regulated. The inner rotor and outer rotor in this machine both adopt surface mounted structure with the arrangement of one-PM-one-ferrite. The rotor PM material is NdFeB which is magnetized in radically outward direction in both two rotors.

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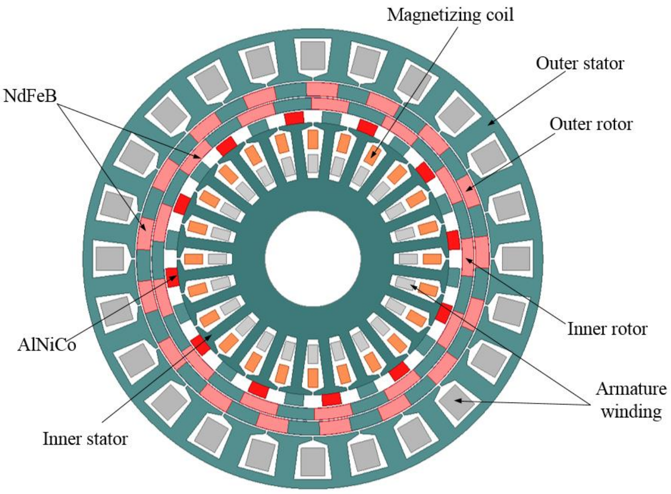
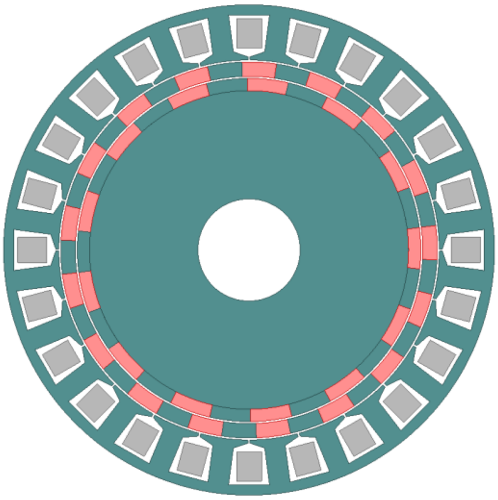
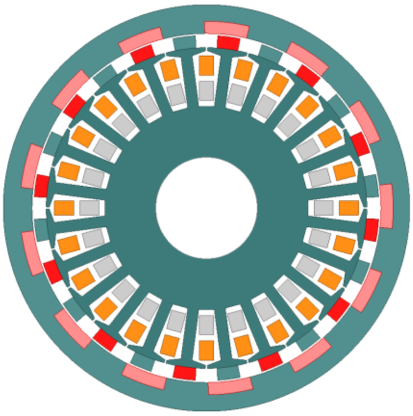


Fig. 2: Configuration of the hybrid-excited flux-modulated memory (HEFMM) machine for E-CVT system.



(a)



(b)

Fig. 3: The cross section configuration of equivalent part of the proposed HEFMM machine for E-CVT system: (a) MGM (b) MFMMM .

The structure of the proposed HEFMM machine can be seen as an integration of a magnetic gear machine (MGM) and a flux-modulated mnemonic machine (FMMM). As shown in Fig.3(a), the inner rotor, outer rotor and outer stator compose the MGM. Fig.3 (b) exhibits the configuration of FMMM which consists of the inner stator with AlNiCo flux modulator and the inner rotor.

The outer stator winding of the MGM in this design will interact with both inner and outer rotor. The operation principle of the MGM is based on the “magnetic gearing effect” which is governed by the following equation [16]:

$$P_{so}=N_{ro}-N_{ri} \tag{1}$$

where; N_{ri} and N_{ro} is the number of PM poles of the inner rotor and outer rotor respectively. P_{so} is the pole-pair number of the armature winding of outer stator. In this design, N_{ri}, N_{ro} and P_{so} are designed as 13, 17 and 4 respectively. Assuming the rotating speed of inner rotor and outer rotor are ω_{ri} and ω_{ro} respectively, the rotating speed of the outer stator winding field is ω_{so}, the rotational speeds and pole-pair number of two rotors and outer stator winding should satisfy the following equation:

$$-N_{ri}\omega_{ri}+N_{ro}\omega_{ro}+P_{so}\omega_{so}=0 \tag{2}$$

From (1) and (2) the rotating speed of armature winding field in outer stator can be expressed as:

$$\omega_{so}=\frac{N_{ri}\omega_{ri}-N_{ro}\omega_{ro}}{N_{ri}-N_{ro}}=\frac{N_{ri}\omega_{ri}-N_{ro}\omega_{ro}}{P_{so}} \tag{3}$$

So the frequency of armature current of outer stator winding is:

$$f_{so}=\frac{N_{ri}\omega_{ri}-N_{ro}\omega_{ro}}{60} \tag{4}$$

The FMMM part of the proposed HEFMM machine includes the inner stator and the mnemonic magnet modulator which can nicely interact with the inner rotor. The pole pair number of the inner rotor N_{ri}, the pole pair number of the modulator N_m and the pole pair number of the armature winding field of inner stator P_{si} also satisfy the principle of magnetic gear effect and governed by the equation[16]:

$$P_{si}=N_{ri}-N_m \tag{5}$$

In order to couple with design of the MGM part, N_m and P_{si} are set as 12 and 1 respectively. In the same way, the rotating speed of armature winding field in inner stator match the following formula:

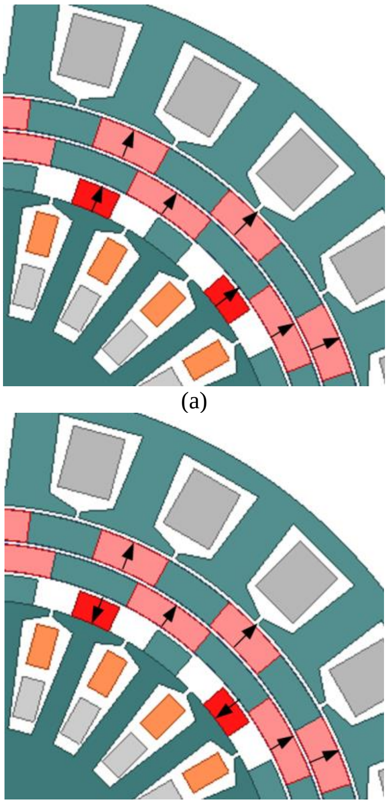
$$\omega_{si}=\frac{N_{ri}\omega_{ri}}{N_{ri}-N_m}=\frac{N_{ri}\omega_{ri}}{P_{si}} \tag{6}$$

Accordingly, the frequency of inner stator armature winding can be given as:

$$f_{si}=\frac{N_{ri}\omega_{ri}}{60} \tag{7}$$

Only when rotating speed of inner rotor and outer rotor match the frequency of armature winding field of inner stator and outer stator, the machine can work well to transmit steady torque. The specifications of the double rotor double stator hybrid-excitation machine in E-CVT system are listed in Table I. Due to flux modulation effect, when the inner rotor rotates at certain speed, field harmonics in the airgap are generated. Thus the rotors and the stator armature winding can interact with each other via common harmonics components. More specially, for the proposed MFMM in this paper, the 1-pole-pair main flux with the 13-pole-pair harmonic component exists in the inner airgap. On the other hand, in the outer airgap, there is the 13-pole-pair main flux with the 1-pole-pair harmonic component. The inner stator teeth employed with AlNiCo magnet and ferromagnetic poles work as a modulator to transform pole pairs between inner and outer airgaps. The 13-pole-pair flux excited by NdFeB magnet sets becomes 1-pole-pair in the inner airgap due to the modulation effect of the AlNiCo magnet or ferromagnetic pole-pieces.

As shown in Fig.4, the NdFeB magnet pieces embedded in inner rotor and outer rotor are all magnetized radially outwards. Since AlNiCo magnet material has intrinsically low coercivity and high remanence, its magnetization level can be adjusted by applying a temporary current pulse to the magnetizing coil housed in the inner stator. On the other hand, the coercivity of NdFeB magnet material is too high to be changed by this small current pulse. When the AlNiCo magnet pieces are magnetized to the same magnetization direction with the NdFeB magnet pieces, the magnetic fluxes are enforced. When the AlNiCo magnet pieces are demagnetized to the opposite magnetization direction, the magnetic flux with the NdFeB magnet pieces will produce a flux leakage loop via the AlNiCo magnet pieces and not link with the inner stator armature winding [17].


(a)

(b)

Fig. 4: Schematic diagram of the magnetization direction under (a) magnetization level (b) demagnetization level of the HEFMM machine.

Table 1: Specifications of the Double Rotor Double Stator Hybrid-excitation Machine In ECVT System

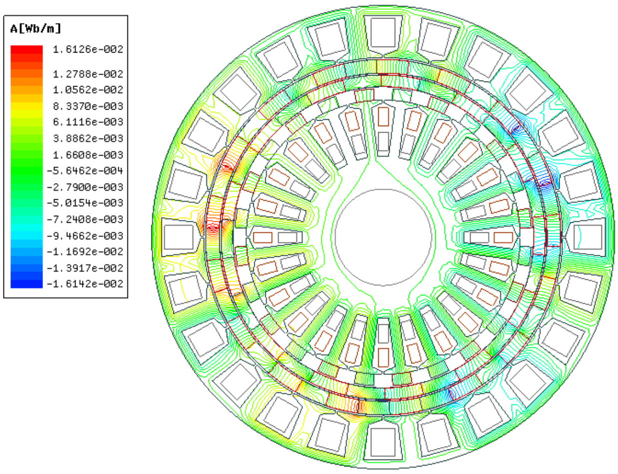
Symbol	Description	Unit	Value
D	Outer diameter	mm	240
l	Stack length	mm	65
h_{ri}	thickness of inner rotor	mm	6
h_{ro}	thickness of outer rotor	mm	7
h_m	thickness of AlNiCo pieces	mm	6
P_{so}	pole pair number of outer stator armature winding	N/A	4
P_{si}	pole pair number of outer stator armature winding	N/A	1
N_{ro}	pole pair number of outer rotor	N/A	17
N_{ri}	pole pair number of inner rotor	N/A	13
ω_{ro}	rotating speed of outer rotor	rpm	-150
ω_{ri}	rotating speed of inner rotor	rpm	300
a	air gap length	mm	1
$N1$	coil turns of outer stator winding	N/A	50
$N2$	coil turns of inner stator winding	N/A	50
Z	phase number	N/A	3

III. APPLICATION APPROACH AND PERFORMANCE ANALYSIS

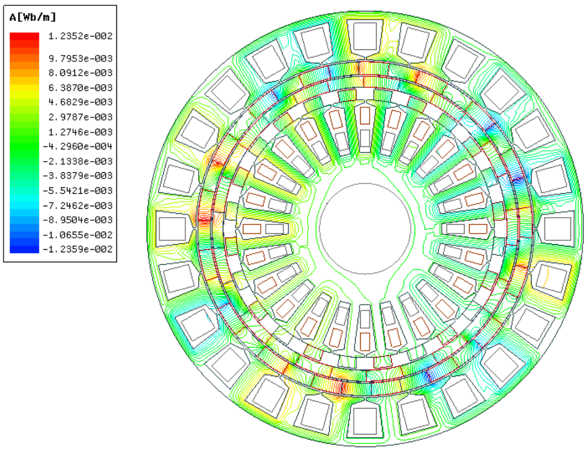
In contrast to fuel vehicles and battery electric vehicles (BEVs), HEVs should adapt to different drive mode by means of E-CVT systems [18]. In this design the inner

MFMMM serve as the primary motor with its rotor connected to the drive line while the outer DVPM machine serve as an auxiliary motor that connected to the internal combustion engine (ICE). When the HEV needs more power in climbing or starting up mode, the ICE will run and drive the auxiliary motor. On the other hand, when the HEV is driven at regenerative braking, idling time or downhills, the redundant energy provided by the wheels can be transformed into electrical energy and stored in the battery or ultracapacitor. By controlling the DC current pulse in the magnetization winding, the back emf can be reduced which allows more extensive speed range of the drive line. In a word, this E-CVT system can keep the HEV driven in a smooth and wide range speed under different drive mode.

The electromagnetic characteristics of the proposed machine are analyzed using TS-FEM. Compared with ac vector control in a traditional PM machine, the flux control of the proposed MFMMM is much simple. Only the direction of the DC current pulse in magnetization coils need to be controlled to demagnetize or magnetize AlNiCo magnet. Fig. 5 expresses the no-load magnetic field distribution of the proposed HEFMM machine under different magnetization level. It can be seen that magnetic field intensity of the proposed machine in magnetization level are much higher than that in demagnetization level. Corresponding back emf waveforms of inner stator winding and outer stator winding are shown in Fig.6. It clearly demonstrates that the amplitude of back emf of inner stator winding decreases from 50V to 30V after demagnetization. While, the outer stator winding’s emf waveforms stay unchanged after magnetize and demagnetize process of AlNiCo magnet modulator. The torque waveforms of inner rotor and outer rotor are shown in Fig.7. The report shows that inner rotor torque can be regulated.

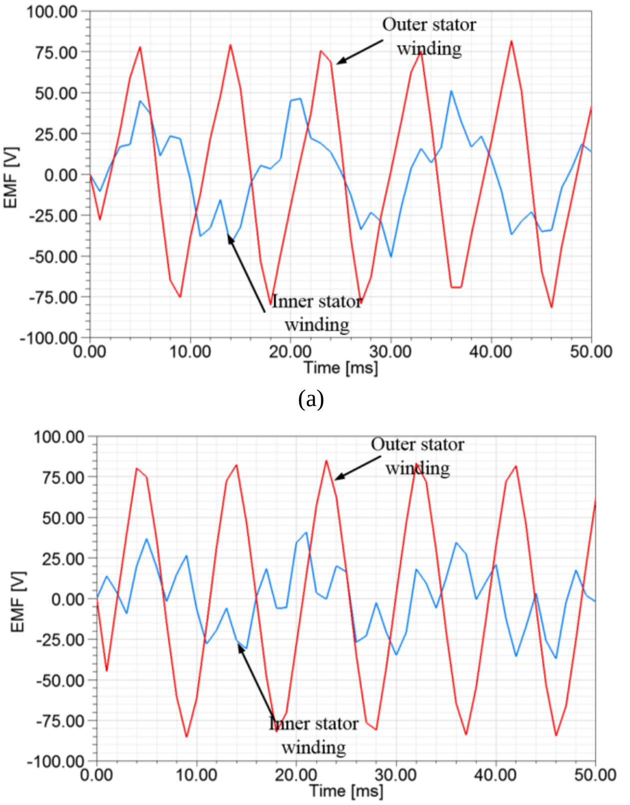


(a)



(b)

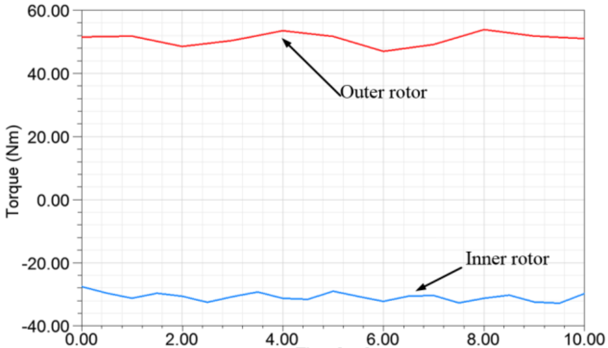
Fig. 5: No-load magnetic field distribution of the proposed HEFMM machine under (a) magnetization level (b) demagnetization level.



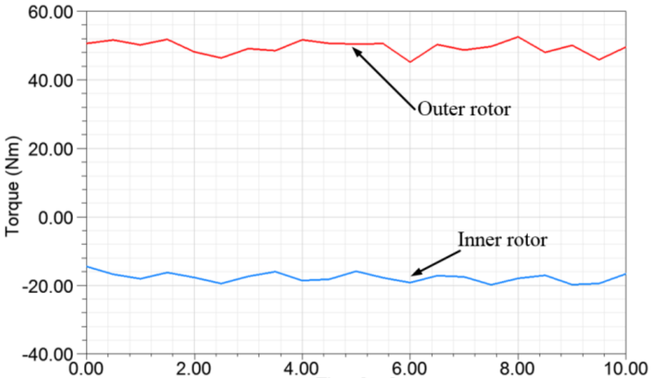
(a)

(b)

Fig. 6: No-load back emf waveforms of inner stator and outer stator of the proposed double rotor double stator machine under (a) magnetization level (b) demagnetization level.



(a)



(b)

Fig. 7: Torque waveforms of the poposed HEFMM machine under (a) magnetization level (b) demagnetization level.

IV. CONCLUSION

In a HEV, the E-CVT system is the core technology that converts the kinetic energy to the electric energy, and vise versa. A gearless E-CVT system which offer higher torque density, better stability and lower friction loss usually includes a PM machine, some inverters and a battery or ultracapacitor. But due to the drive's output voltage is limited by its dc bus, the E-CVT system may not realize the requirement in driving speed. To solve these problems, this paper proposed a novel double rotor double stator hybrid-excitation machine employing flux-modulated mnemonic design. Analysis based on TS-FEM has been conducted and the results are reported The simulation results validate the effectiveness of the proposed HEFMM machine.

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