A Novel Electrical Continuously Variable Transmission System and its Numerical Model

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Abstract—A novel structure of electrical continuously variable transmission (E-CVT) system is presented. The core of the novel design is a double-stator double-rotor permanent magnet (PM) machine. The machine is brushless and compact in structure with improved torque density and reduced copper loss. Time-stepping finite element method (TS-FEM) is used to analyze the performances of the machine in both static and transient states. The merits of the proposed machine are validated using the TS-FEM results.

***Index terms*—Electrical continuously variable transmission, electric machine, finite element method.**

I. Introduction

During the past half century, energy crisis and environmental deterioration have drawn more and more attentions all over the world. As vehicles are important fuel consumers, hybrid electric vehicles (HEVs) are developed to reduce the consumption of fuel and reduce the emission of CO_2. The HEVs combine an internal combustion engine (ICE) and one or several electric machines (EM) to provide the traction power. An electrical continuously variable transmission (E-CVT) system is used in HEV for power splitting and transmission in order to reduce the power loss and improve the efficiency of the whole system [1].

Hitherto, various kinds of E-CVT systems have been developed. The Toyota Prius is a well-known E-CVT system which adopts a hybrid system consisting of an ICE and a pair of electric motor/generators (M/Gs). In Prius, a mechanical planetary gear is used to split the power from the ICE into a mechanical path and an electrical path [2]. However, due to the use of planetary gear, some mechanical problems such as frictional loss, maintenance and noise are unavoidable. To overcome these problems, many gearless E-CVT designs, in which the power splitting is realized by a combination of two electric machines, have been proposed. However, these designs still use carbon brushes and slip rings, which also cause mechanical problems. To avoid using carbon brushes, a gearless double-stator brushless PM machine E-CVT system is proposed [3]. As an additional induction machine is required for power splitting, such system is rather bulky. Recently, a magnetic-geared E-CVT system is proposed [4]. That design uses a magnetic gear to transmit torque without mechanical contact and it is also very compact structurally. There are also three rotational parts in the design. The complex structure makes it hard to manufacture.

A novel structure of brushless magnetic-geared E-CVT system is presented in this paper. The mechanical problems are alleviated and the structure is compact, which brings high torque density. The proposed machine has only two rotational parts, making it relatively easy to manufacture. The structure and working principle of the proposed design are described and time-stepping finite element method (TS-FEM) is used to analyze and validate its performance.

II. Proposed Structure and Working Principle

A. E-CVT System

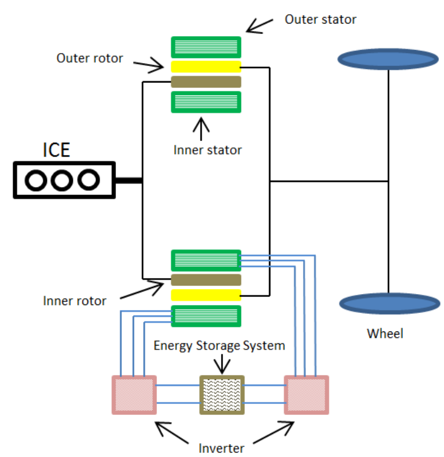


Fig. 1. The proposed E-CVT structure

The structure of the proposed E-CVT system in a HEV is shown in Fig. 1. The core device of the system is a brushless double-stator double-rotor PM machine and an energy storage system (ESS) with two inverters. The torque from the ICE is sent to the inner rotor and then output to the wheel of the HEV through the outer rotor. The ESS is connected to the two stators through the inverters.

The ICE operates with the highest efficiency at mid-range speed. When the HEV needs to brake or go downhill and the power from the ICE is more than needed, the outer stator and the outer rotor work as a generator and store the extra energy in the ESS. On the contrary, when the HEV needs to accelerate or go uphill and the power from the ICE cannot satisfy the demand, the inner stator and the two rotors work as a motor and the ESS is discharged to provide additional power to the wheel. The HEV can also operate in pure electric mode for launching to save fuel when the traffic is busy with many stops at short distance.

B. The Machine Structure and Working Principle

Fig. 2 shows the structure of the proposed double-stator double-rotor machine which is a combination of a double-

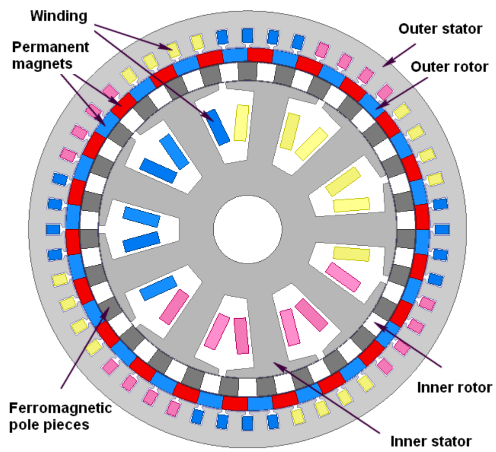


Fig. 2. The proposed machine structure

rotor Vernier PM (DVPM) machine and a multi-pole fractional-slot PM (MFPM) machine. The DVPM consists of the inner stator and the two rotors, whereas the MFPM consists of the outer stator and the outer rotor. The outer rotor is actually shared by the two machines. The outer rotor has 44 PMs which are arranged with magnetization directions changing between radially outward and inward from one to the other. The inner rotor consists of 27 ferromagnetic pole pieces for flux modulation.

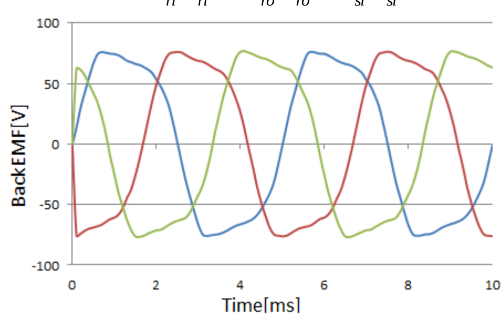
With the inner stator providing the inner rotating magnetic field, the operating principle of the DVPM is almost the same as that of a magnetic gear [5]. The basic rule is,

$$N_{ro} = \left(N_{ri} - P_{si}\right) \tag{1}$$

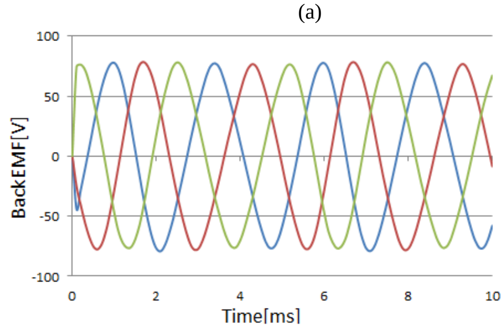
where N_{ro} is the number of PM pairs in the outer rotor, N_{ri} is the number of ferromagnetic pole pieces in the inner rotor and P_{si} is the pole-pair number of the inner stator winding.

The rotational speeds are governed by,

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



(a)



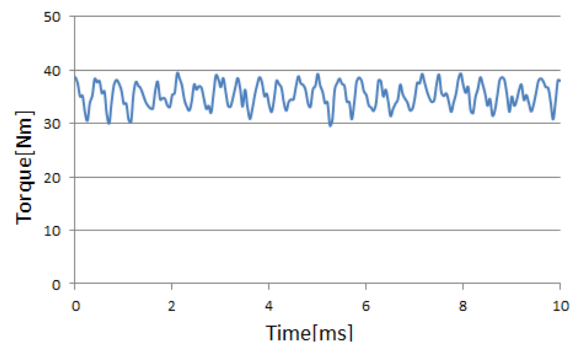
(b)

Fig. 3. Back EMF in (a) outer stator (b) inner stator

III. Performance Analysis Using FEM

The performance of the proposed machine is analyzed using 2-D TS-FEM. Fig. 3 shows the induced back EMF in the windings of the two stators when the outer rotor rotates at 545.5 rpm while the inner rotor is rotating at -444.4 rpm.

As mentioned in Section Ⅱ, the E-CVT can operate at three modes, namely pure electric mode, hybrid mode and battery charging mode. The output torque of the machine in pure electric mode and hybrid mode is shown in Fig. 4. It can be seen that the output torque in pure electric mode is around 35 Nm and around 43 Nm in hybrid mode while the input torque from ICE is around 10 Nm. However, the cogging torque of the machine is also relatively large. It may be reduced by skewing the slots.



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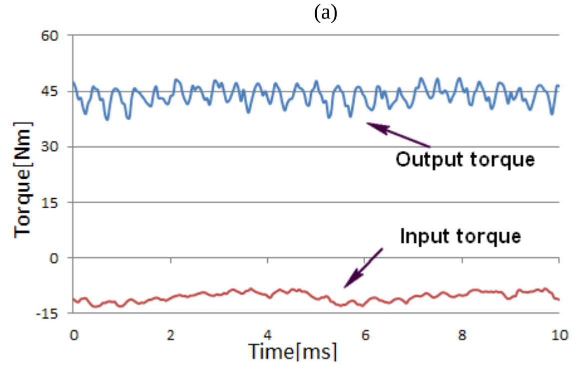

(b)

Fig. 4. Output torque in (a) pure electric mode (b) hybrid mode

IV. References

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