Review of Electronic-continuously Variable Transmission Propulsion System for Full Hybrid Electric Vehicles

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Abstract
In this paper, the electronic-continuously variable transmission (E-CVT) propulsion system for full hybrid electric vehicles (HEVs) is reviewed. Firstly, the E-CVT propulsion systems are classified as two main groups, namely the gear E-CVT and the gearless E-CVT. Consequently, the development of E-CVT propulsion systems is discussed, with emphasis on their system architecture, principle of operation, merits and drawbacks. Finally, the development trend of E-CVT propulsion systems will be briefed.

Keywords
electric vehicle, electronic-continuously variable transmission, hybrid vehicle, full hybrid, gearless, planetary gear

1. INTRODUCTION
With ever-increasing concerns on energy shortage and environmental deterioration, hybrid electric vehicles (HEVs) or simply called hybrid vehicles have become globally attractive. They take the distinct advantages of higher fuel economy and lower exhaust emission than internal combustion engine vehicles (ICEVs), whereas much longer driving range and much easier refuel than battery electric vehicles (BEVs) [Chau and Chan, 2007].

Generally, the HEVs can be classified as micro, mild and full hybrid according to the level of electric power contribution in the total propulsion power. Among them, the full hybrid takes the definite advantage of possessing all hybrid features, namely electric launch, idle stop, full regenerative braking, engine downsizing and flexible recharging, hence further improving the fuel economy and suppressing the exhaust emission.

Before 1997, HEVs were unattractive and considered as an interim solution of BEVs, since they were clumsy and bulky, particularly their transmission systems on how to combine the electric driving force and engine driving force for propulsion. The resurrection of HEVs was due to the introduction of electronic- continuously variable transmission (E-CVT) by Toyota in 1997 [Sasaki, 1998]. Its prominent innovation is the adoption of planetary gearing to perform power splitting. In additional with the use of power electronics technology, electric driving force and engine driving force can be effectively split and combined. Subsequently, several E-CVT derivatives are developed successively, such as the Ford E-CVT system, the GM-Allison E-CVT system, the Timken E-CVT system, and the Renault E-CVT system [Miller et al., 2005]. However, the key element of these E-CVT systems is the planetary gear sets which inevitably suffer from the drawbacks of bulky size, mechanical wear-and-tear and audible noise.

In recent years, a new class of E-CVT propulsion systems have been proposed. They are free from using mechanical planetary gears, namely gearless. Basically, they are developed based on a double-rotor permanent magnet (PM) machine cascaded with another machine [Eriksson et al., 2002; Hoeijmakers et al., 2004].

In this paper, the E-CVT propulsion systems for the full HEVs will be reviewed. First, they are newly classified into two main groups: namely the gear E-CVT and the gearless E-CVT. Then, discussions will be focused on their system architecture, principle of operation as well as merits and drawbacks. In addition, the latest development trend of E-CVT systems will be revealed.

2. GEAR E-CVT PROPULSION SYSTEMS
The gear E-CVT system can be sorted into two categories, according to the power split manner performed by planetary gears [Miller, 2006]. The first category can be named as input power split, which is adopted by Toyota and Ford. And the second category can be called compound power split, which is adopted by GM-Allison.

2.1 Toyota E-CVT propulsion system
Figure 1 shows the basic configuration of the Toyota

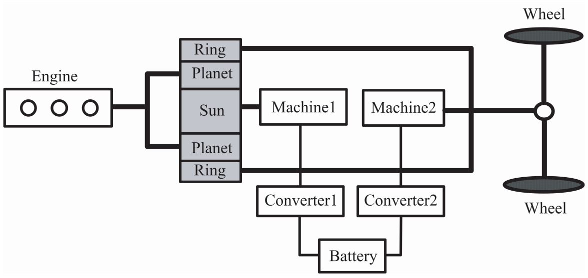

Fig. 1 Toyota gear E-CVT propulsion system

E-CVT propulsion system, which mainly consists of a planetary gear set, a battery pack, the Machine 1 (normally operating as a generator), the Converter 1 (normally operating as a controlled rectifier), the Machine 2 (normally operating as a motor), and the Converter 2 (normally operating as an inverter). In this system, the planetary gear set plays a key role to split the engine power into electric power flow and mechanical power flow. On the one hand, the mechanical power produced by the engine is transferred to the driveline via the ring gear. On the other hand, the sun gear is attached to the Machine 1, which converts a portion of the engine power to electric power so that it can be used to feed the Machine 2 to drive the driveline. The Converter 1 and Converter 2 work with the battery pack to buffer the electric power transfer between the Machine 1 and Machine 2. If the mechanical power transferred by the ring gear is less than the desired driving power, the battery releases electric power via Converter 2 and Machine 2; otherwise, the battery stores the electric power. The relationship between the engine torque and the driveline torque can be expressed as:

$$T_d = T_m + \left(\frac{1}{1+\rho}\right)T_e \quad (1)$$

$$\omega_d = (1+\rho)\omega_e - \rho\omega_g \quad (2)$$

$$\rho = \frac{N_s}{N_r} \quad (3)$$

where T_d is the driveline torque, T_m is the Machine 2 torque, T_e is the engine torque, ω_d is the driveline speed, ω_e is the engine speed, ω_g is the Machine 1 speed, ρ is the planetary gear ratio, N_s is the number of sun gear teeth, and N_r is the number of ring gear teeth. By proper controlling the power absorbed by the battery and then feeding back into the Machine 2, ω_e can be maintained constant while ω_d is varying. Hence, a continuously variable ratio between the engine speed and the wheel speed can be achieved.

2.2 Ford E-CVT propulsion system

As shown in Figure 2, the Ford E-CVT propulsion system possesses two planetary gears. The first planetary gear is attached to engine shaft, and is responsible for power split. The second planetary gear is in charge of coupling the driving torque. Compared with the Toyota E-CVT propulsion system, the Ford E-CVT system can distribute driving power more flexibly due to the adoption of the output planetary gear. The relationship between the engine torque and the driveline torque can be expressed as:

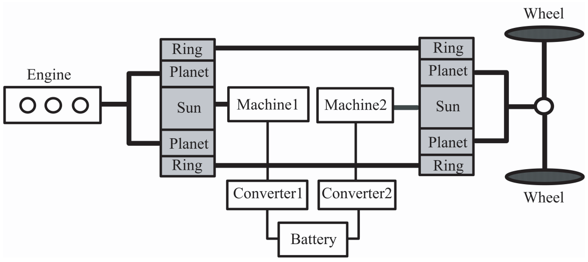

Fig. 2 Ford gear E-CVT propulsion system

$$T_d = \left(\frac{N_2}{N_1}\right)T_m + \left(\frac{1}{1+\rho}\right)\left(\frac{N_2}{N_3}\right)T_e \quad (4)$$

where N_1, N_2, N_3 are the numbers of teeth of the sun gear, planet gear and ring gear, respectively, of the output planetary gear.

2.3 GM-Allison E-CVT propulsion system

Rather than simply an input-split E-CVT system, the GM-Allison E-CVT propulsion system is a compound-split system as shown in Figure 3. This E-CVT system is mainly composed of three clutches, two planetary gears, two machines, two converters and a battery pack. By means of engaging or disengaging different clutch arrangements, the E-CVT propulsion system can alter its architecture so that the output torque can meet the road load demand.

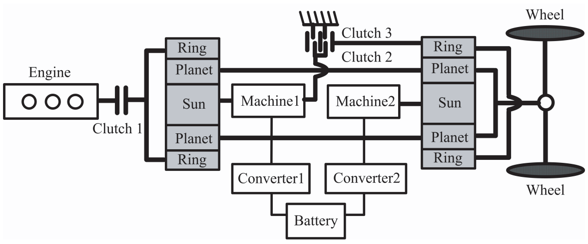

Fig. 3 GM-Allison gear E-CVT propulsion system

When vehicles operate at the city-driving mode, both the Clutch 1 and Clutch 3 are engaged while the Clutch 2 is disengaged. Thus, the planetary gear attached to the engine is responsible for input power split while the planetary gear coupled with the driveline is in charge of output torque coupling. The relationship between the engine torque and the driveline torque can be expressed as:

$$T_d = \left(1 + \frac{1}{\rho_1}\right) T_m + (1 + \rho_1) T_e \qquad (5)$$

where ρ_1 is the input planetary gear ratio.

If vehicles operate at the highway driving mode, both the Clutch 1 and Clutch 2 are engaged while the Clutch 3 is disengaged. This kind of operation mode is so-called compound split, in which the input and output planetary gears perform the function of power split together. The relationship between the engine torque and the driveline torque can be expressed as:

$$T_d = \left(\frac{\rho_2}{1 + \rho_2}\right) T_m - \left(\frac{\rho_1 \rho_2^2}{1 + \rho_2}\right) T_e \qquad (6)$$

where ρ_2 is the output planetary gear ratio.

Compared with those propulsion systems adopted by existing ICEVs, the distinct advantages of these E-CVT propulsion systems are summarized as follows.

(1) Because a continuously variable ratio between the engine speed and the wheel speed can be achieved, the engine can always operate at its most energy-efficient operating area, hence resulting in a considerable reduction of the fuel consumption.

(2) The E-CVT system can fully enable the idle stop feature and the electric launch feature. These features are particularly essential to improve the energy efficiency of the full hybrid.

3. GEARLESS E-CVT PROPULSION SYSTEMS

Borrowing the idea of input power split performed by using the planetary gear, a family of gearless E-CVT propulsion systems is being actively developed. The key is to make use of a double-rotor machine to split the engine power into electric power flow and mechanical power flow [Hoeijmakers et al., 2006]. Thus, the mechanical wear-and-tear and audible noise associated with the gear E-CVT propulsion systems can be eliminated.

As shown in Figure 4, this E-CVT propulsion system is mainly composed of a double-rotor induction machine, a cascaded induction machine, two power converters and a battery pack. The inner rotor of the double-rotor machine is attached to engine shaft while the outer rotor is coupled with the second machine in cascade. So, the engine power is split into the electric power which can be withdrawn via slip rings and the mechanical power which is coupled with the driveline. The slip power can be used to feed the cascaded machine via the two power converters or to charge the battery pack. When the direct-coupled mechanical power cannot fulfil the desired driving power, the battery can release power to top up the driving force. The relationship between the engine power and the driving power can be expressed as:

$$P_e = P_{mech} + P_{elec} \qquad (7)$$

$$P_{elec} = (\omega_e - \omega_d) T_e \qquad (8)$$

where P_e is the engine power, P_{mech} is the mechanical power transfer, P_{elec} is the electric power transfer, ω_e is the engine speed, ω_d is the driveline speed, and T_e is the engine torque. By controlling P_{elec}, ω_e can be maintained constant when ω_d is varying. Hence, the desired continuously variable ratio between the engine speed and the wheel speed can be attained.

Figure 5 shows the engine optimal operation line (OOL), where P_2 shows the speed and torque required at the driveline shaft, P_1 shows the speed and torque offered by the engine. If the primary shaft adopts speed control to regulate the speed change Δn between the engine and the driveline, while the second shaft adopted torque control to govern the torque change ΔT between the engine and the driveline shaft, the engine will operate along the OOL. Hence, the E-CVT propulsion system can keep the maximum efficiency during all driving conditions [Cheng et al., 2007].

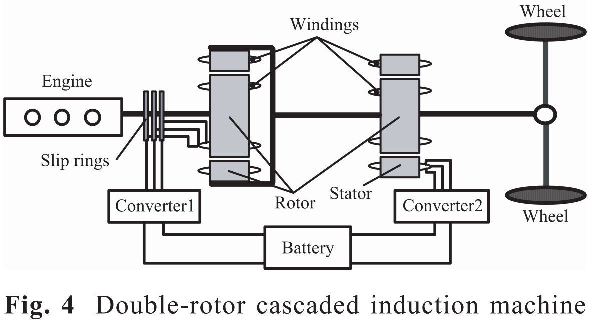

Fig. 4 Double-rotor cascaded induction machine gearless E-CVT propulsion system

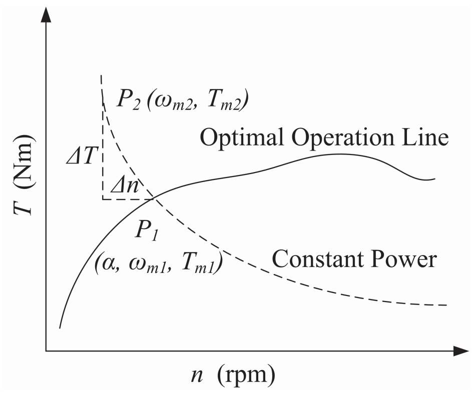

Fig. 5 Gearless E-CVT control strategy

In order to reduce the system weight and size, the two machines can be integrated into a single machine. The key is to share the outer rotor of the first machine with the rotor of the second machine so that the stator is

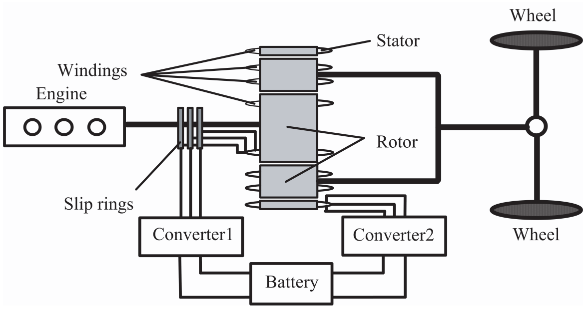

Fig. 6 Double-rotor integrated induction machine gearless E-CVT propulsion system

placed concentrically around the outer rotor. Figure 6 shows the configuration of the double-rotor integrated induction machine E-CVT propulsion system. The corresponding principle of operation is the same as that if the double-rotor induction machine cascaded with another induction machine.

For the purpose of improving the system efficiency, the two induction machines can be superseded by two PM brushless machines. So, the double-rotor integrated PM machine E-CVT propulsion system is shown in Figure 7. In case the space under the vehicle hood may not be able to accommodate this radial-field double-rotor integrated PM machine, it can be transformed into an axial-field version as shown Figure 8. The principle of operation is the same as the radial-field counterpart.

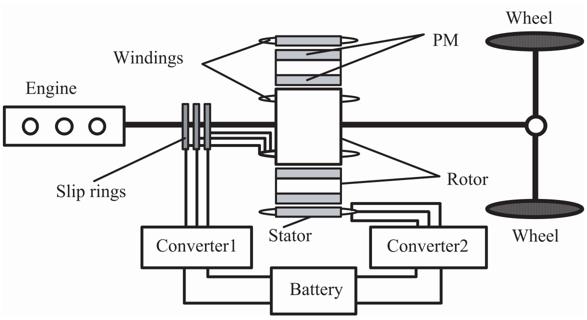

Fig. 7 Double-rotor integrated PM machine gearless E-CVT propulsion system

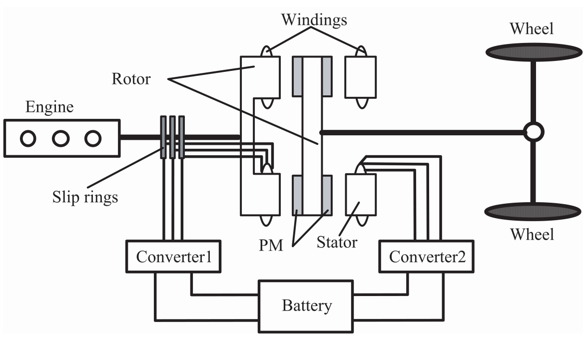

Fig. 8 Axial-field double-rotor integrated PM machine gearless E-CVT propulsion system

No matter the double-rotor integrated machine E-CVT propulsion system is based on induction or PM brushless machine, or based on radial-field morphology or axial-field morphology, the magnetic fields between different airgaps of the machine are coupled to certain extent. Such coupling will degrade the independency of two airgaps, and adversely affect the controllability of the E-CVT system. Recently, by employing the orthogonal nature of radial field and axial field, the decoupling double-rotor integrated PM machine gearless E-CVT propulsion system has been proposed as depicted in Figure 9. The key is to employ a double-rotor integrated PM machine which consists of an axial-field machine in the first stage and another radial-field machine in the second stage [Zhao et al., 2008]. Due to its decoupling nature between the first stage and second stage, this E-CVT propulsion system can provide better controllability.

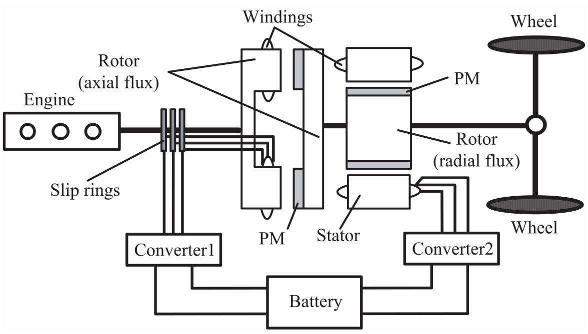

Fig. 9 Decoupling double-rotor integrated PM machine gearless E-CVT propulsion system

The advantages of the aforementioned gearless E-CVT propulsion systems are summarized as follows.

(1) Due to the absence of clutches, they can significantly improve the transmission efficiency and reduce the overall size.
(2) Because of the absence of planetary gear sets, the mechanical wear-and-tear and audible noise can be avoided. Also, they are mechanically simple, hence offering high reliability.

Nevertheless, they rely on the use of double-rotor machines in which slip rings and carbon brushes are inevitably employed to transmit power away from the rotating body. The use of slip rings and carbon brushes definitely violates the concept of maintenance-free operation, causes power loss, and involves bulky mechanism to ensure good contacts.

4. BRUSHLESS GEARLESS E-CVT PROPULSION SYSTEMS

As discussed before, the gearless E-CVT propulsion systems are preferred to the gear E-CVT propulsion systems, but still suffer from the use of slip rings and carbon brushes. So, the development trend of E-CVT propulsion systems is to invent a brushless gearless one.

Following the idea of using a double-rotor machine to perform power split, the double-stator machine [Niu et al., 2008; 2009] should be able to perform the same task. So, very recently, a double-stator PM brushless machine gearless E-CVT propulsion system has been proposed [Wang et al., 2008]. As shown in Figure 10, there are two regulated power flow paths from the engine to the wheels: namely, via the outer stator of the first stage machine, Converter 1, Converter 2 and the second stage machine; via the inner stator of the first stage machine, Converter 3, Converter 2 and the second stage machine. The first stage machine is a double-stator PM machine, whereas the second stage machine is a standard induction motor or PM brushless motor. Both power converters are standard 3-phase controlled rectifiers. The outer-stator path is responsible for the major power flow, whereas the inner-stator path performs power split control using the battery pack as a buffer.

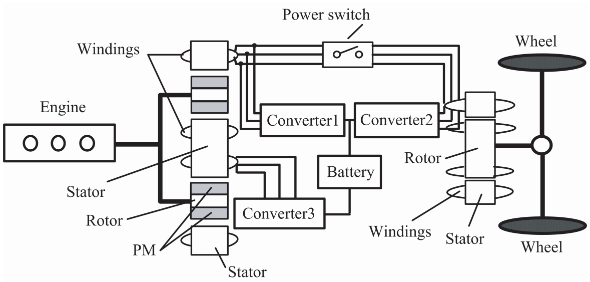

Fig. 10 Double-stator PM brushless machine gearless E-CVT propulsion system

By properly controlling the two controlled rectifiers, the engine can operate at constant speed while the wheel speed varies with the road load profile and driver's control, hence offering the merit of continuously variable gearing. When there is no need to perform power split, the system efficiency can be further improved by using a power switch to directly transfer power from the outer stator of the first stage machine to the second stage motor.

Compared with the double-rotor counterparts, this double-stator PM brushless machine gearless E-CVT propulsion system possesses the following merits.

(1) The system reliability is improved owing to the elimination of slip rings and carbon brushes.
(2) The inner stator winding not only provides power split of the engine power, but also functions to perform cranking for the engine.
(3) The bidirectional power switch can directly transmit the outer-stator output power of the first stage machine to the second stage machine during cruising, thus eliminating the unnecessary controlled rectifier and inverter losses.
(4) Since the first stage machine and the second stage machine are connected by electrical means, they can be separately mounted with the engine and the final driveline, thus eliminating the mechanical transmission which is clumsy and bulky.

5. CONCULUSION

In this paper, various E-CVT propulsion systems have been reviewed, which are essential for full HEVs. These E-CVT propulsion systems have been classified as the gear E-CVT and the gearless E-CVT. Both of their merits and drawbacks have been discussed. Consequently, the development trend has been identified, hence revealing the latest concept of brushless gearless E-CVT propulsion systems.

Acknowledgements

This work was supported and funded in part by a grant (Project No. 50729702) from the National Natural Science Foundation of China, a grant from the Chang Jiang Chair Professorship at Southeast University, Nanjing, and a grant (Project No. BE2008130) from the Key Technology R&D Program of Jiangsu Province, China.

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(Received August 22, 2009; accepted October 16, 2009)