

High Efficiency Electromagnetic Torque Converter for Hybrid Electric Vehicles

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ABSTRACT

A new concept of an electromagnetic torque converter for hybrid electric vehicles is proposed. The electromagnetic torque converter, which is an electric system comprised of a set of double rotors and a stator, works as a high-efficiency transmission in the driving conditions of low gear ratio including a vehicle moving-off and as a starting device for an internal combustion engine. Moreover, it can be used for an electric vehicle driving as well as for a regenerative braking. In this concept, a high-efficiency drivetrain system for hybrid electric vehicles is constructed by replacing a fluid-type torque converter with the electromagnetic torque converter in the automatic transmission of a conventional vehicle. In this paper, we present the newly developed electromagnetic torque converter with a compact structure that enables mounting on a vehicle, and we evaluate its transmission efficiency by experiment. Furthermore, using the experimental results and finite element analysis of the electric machine, we clarify the system loss of the electromagnetic torque converter.

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INTRODUCTION

With growing concerns about global warming, depleting fossil fuels, and air pollution, the importance of eco-friendly vehicles with low CO₂ emissions and exhaust free of environment pollutants is increasing. A hybrid electric vehicle (HEV) is one of the most practical options for eco-friendly vehicles. In order to satisfy the demands of automotive consumers, further improvement in the fuel economy of HEVs is required. Hence, the improvement of system efficiency for hybrid powertrains is still a main area of development.

Electric motor driving during low road-load driving conditions and vehicle energy recuperation using the electric motor during braking conditions are major gain factors for fuel economy improvement in hybrid powertrains. In addition to these factors, an improvement in transmission efficiency also contributes to improved fuel economy. In order to improve the transmission efficiency, the losses in the transmission system need to be reduced. Depending on the hybrid powertrain configuration, the total amount of loss as well as its generation mechanism differs. Hence, it is important to investigate the optimal configuration considering the new drivetrain components that improve the system efficiency of the hybrid system.

Hybrid powertrain configurations can be categorized into three types: parallel hybrid systems, series hybrid systems, and series-parallel hybrid systems. In a parallel hybrid system, an electric motor is attached to the

conventional mechanical transmission, enabling electric motor driving and regenerative braking [1,2]. One of the advantages of the parallel hybrid systems is good transmission efficiency at high speeds, especially for large vehicles. On the other hand, in order to complete other functions such as vehicle moving-off and engine starting, conventional devices such as torque converters or frictional clutches and engine starters are individually required, respectively. These devices are inevitable for conventional vehicles. However, for HEVs in which at least one electric motor is installed, these conventional devices are not necessarily efficient for improved fuel economy.

In both series hybrids [3,4] and series-parallel hybrids [5], which are called two-motor hybrid systems, two independent electric motors allow the realization of multiple functions such as vehicle moving-off, engine starting, engine driving, electric motor driving, and regenerative braking. Due to these multiple functionalities, no other mechanism is required for the vehicle. On the other hand, electric motors are large, and the transmission loss increases as the transmitting power increases in series hybrid systems. In series-parallel hybrid systems, the improvement in transmission efficiency at a high gear ratio is an essential research topic.

In this paper, we present a new hybrid system that takes the advantages of both the parallel hybrid systems and the two-motor hybrid systems. In order to downsize the system with two motors

while maintaining the multi-functionality of the two-motor hybrid system, a compound structure motor that consists of two rotors and one stator is considered.

In previous research, the same motor structure has been studied. In [6, 7, 8], the electromagnetic field coupling of the compound structure motor is analyzed. Then, the torque characteristics of the two motors, which compose the compound structure motor, are investigated. In [9,10], the control issue of field decoupling between the two motors is studied. The main focuses of these studies are on the characteristics of each motor consisting of a compound structure. In [11,12], the system characteristics of a continuously variable transmission (CVT), which is sometimes called an electrically variable transmission, are studied. However, neither the transmission efficiency nor system losses in the drivetrain system using the compound structure motor has been clarified.

In this paper, we focus on an analysis of the transmission efficiency of the hybrid system using the compound structure motor as a CVT. Based on this analysis, a new hybrid system using the compound structure motor and a portion of a conventional automatic transmission without a fluid-type torque converter is presented. Hereafter, we call this compound structure motor an electromagnetic torque converter (eMAT). In an eMAT, a slip ring system that enables the exchange of electric power between one of the rotors and the inverter circuit is installed inside the rotors. From the vehicle moving-off, the eMAT is capable of transmitting torque from an internal combustion engine (ICE) to the driveshaft while maintaining the rotational speed of the ICE at the optimal condition for the powertrain system. On the other hand, the automatic transmission is used to change the rotational speed of the ICE when the loss of the eMAT increases. In order to validate the eMAT, a prototype eMAT with a compact structure that enables mounting on a vehicle is developed, and the transmission loss of the eMAT is analyzed. Using this result, it is shown that the transmission efficiency of the eMAT is much higher than that of a conventional torque converter.

SYSTEM ARCHITECTURE AND CONCEPT

Electromagnetic Torque Converter

A schematic of the eMAT is shown in Figure 1. The eMAT is composed of an electromagnetic coupling (EMC), which is capable of transmitting torque between an input rotor and an output rotor bidirectionally, and a traction motor (TM), which is capable of exchanging electric power and mechanical power between the stator and an output rotor. In this structure, by sharing the function of the output rotor between the EMC and TM, one of the output rotors of the EMC or TM can be removed. A slip ring system, which is composed of a three-phase slip ring and brushes, is attached to the input rotor realized with a winding rotor in order to supply current to the winding coils. By using the slip ring system, electric power is bidirectionally transferred between the EMC and an inverter.

Figure 2 shows the power flows of the fluid-type torque converter and the eMAT in a low gear ratio or moving-off mode where the input speed is higher than the output speed. In both converters, the input power is transferred by splitting into two paths: a direct path where

the input torque is directly transmitted, and a derivative path where the power is generated in proportion to the relative speed of the input rotor and the output rotor. In a fluid-type torque converter, power is transferred by an oil medium, and no other controlling devices are required. In an eMAT, power is transferred by electromagnetic force and electricity. Although an eMAT requires inverters, it enables the control of the transmitting torque, thereby controlling the input speed such that the ICE is operated at its optimal condition. Furthermore, its drivable condition can be extended to the overdrive range, where the output speed is higher than the input speed. Additionally, due to the controllability of the inverters, the eMAT is capable of ICE cranking and EV driving as well as regenerative braking.

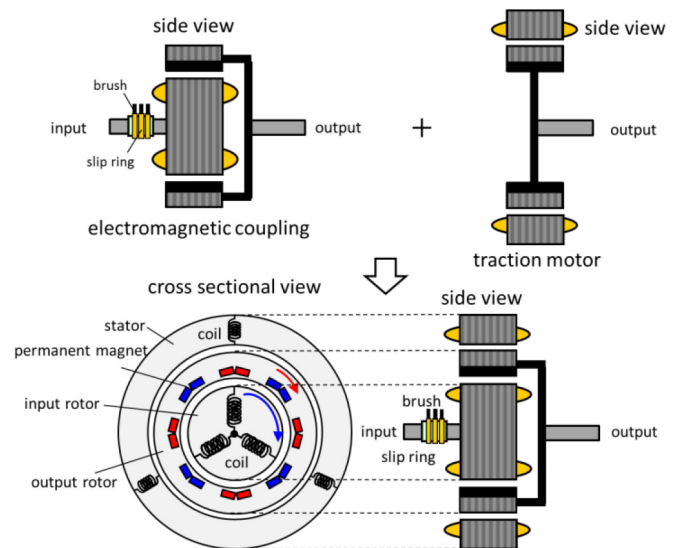


Figure 1. Schematic of the electromagnetic torque converter structure.

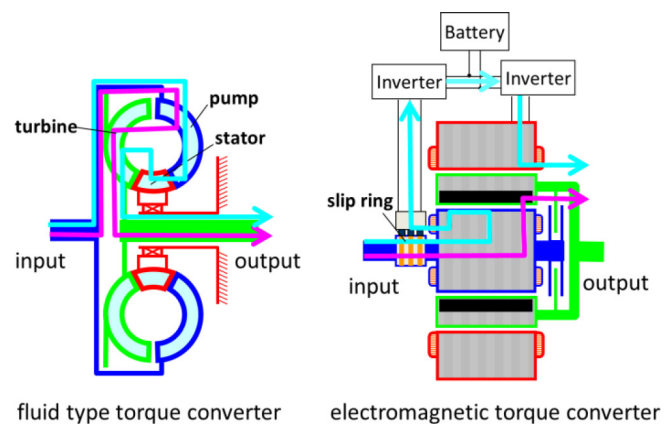


Figure 2. Power flows of a fluid-type torque converter and the electromagnetic torque converter (eMAT) in a vehicle during the moving-off mode.

System Concept

Figure 3 shows the entire eMAT system, including the inverters and the battery. As can be seen, the hybrid system configuration that we present in this paper is composed of the eMAT and a mechanical transmission. In this system, the eMAT is an advanced substitute for a conventional fluid-type torque converter that is typically used with an automatic transmission. Compared with conventional moving-off devices such as fluid-type torque converters and friction clutches, an eMAT basically has three advantages:

- An eMAT has a lower loss characteristic compared with conventional moving-off devices. Hence, the transmission efficiency of the resultant hybrid system is higher compared with hybrid systems in which conventional devices are used.
- An eMAT can change the engine speed continuously during engine driving conditions including vehicle moving-off. Consequently, this provides us with the effect of a CVT such as an improvement in system efficiency and ICE noise as well as vibration reduction due to an adequate change in the operating point of the ICE.
- An eMAT possesses multiple functionalities, i.e., a CVT function, an engine starting function, and an electric motor driving plus regenerative braking function.

Due to these advantages, by utilizing an eMAT with a conventional transmission, a high-efficiency hybrid system can be constructed without attaching a traction motor or an engine starter. Additionally, an eMAT can transmit smooth torque to the output shaft even if the input torque is subject to fluctuations caused by the ICE. This topic will be presented in another paper submitted for SAE 2016.

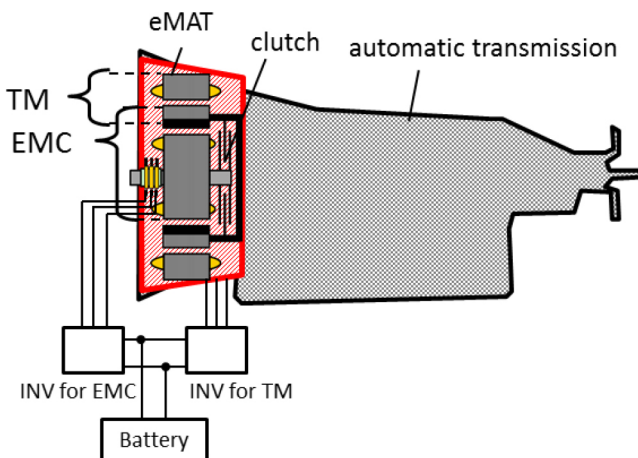


Figure 3. System structure of the presented hybrid system.

Basic Operating Modes and Characteristics

The presented hybrid system using an eMAT consists of three operating modes: a power transmitting mode, an engine starting mode, and an electric motor driving mode including regenerative braking.

Power Transmitting Mode

In the power transmitting mode, the engine torque is transmitted to the output shaft while adding motor torque from the electric power generated in the EMC to the output shaft when the input speed N_{in} is higher than the output speed N_{out} . Conversely, when the output speed is higher than the input speed, part of the transferred engine torque from the output shaft is used to generate electric power to simultaneously operate the EMC to transmit the engine torque. Figure 4 shows power flow schematics for the power transmitting mode. Since this mode is valid from vehicle moving-off to the overdrive condition, the function in this mode is a substitute for a CVT transmission accompanied by a torque converter.

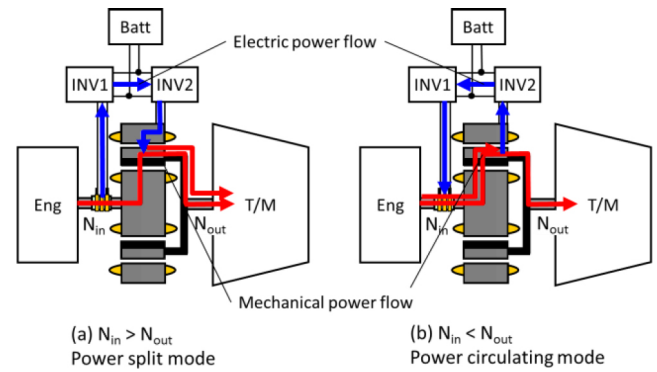


Figure 4. Power flows in the power transmitting mode.

Engine Starting Mode

In the engine starting mode, the input rotor is driven by the output rotor while simultaneously taking the reaction torque from the stator, thereby enabling engine cranking. This operation is available while the vehicle is stopping as well as in electric motor driving.

Electric Motor Driving and Regenerative Braking Mode

In the electric motor driving mode, the traction motor drives the output rotor connected to a drive shaft. Since the input rotor is decoupled from the output rotor, this mode is available regardless of whether the engine is on or off.

Operation in Cooperation with Transmission

In the presented hybrid system, the eMAT works in cooperation with the mechanical transmission such that the system efficiency of the hybrid system is maximized. In principle, the eMAT is a CVT; therefore, no other transmission is required for changing a speed rate of the system. However, the transmission efficiency of the eMAT deteriorates when the speed rate of the output rotor to the input rotor exceeds 1, where the loss of electricity increases. This can be confirmed by the following elementary formula for the transmission efficiency:

$$\eta = \begin{cases} \left\{ \frac{\eta_{emc}\eta_{tm}}{10^4} + \left(1 - \frac{\eta_{emc}\eta_{tm}}{10^4} \right) e \right\} \eta_{base}, & \text{if } e \leq 1, \\ \left\{ \frac{10^4}{\eta_{emc}\eta_{tm}} - \left(\frac{10^4}{\eta_{emc}\eta_{tm}} - 1 \right) e \right\} \eta_{base}, & \text{if } e > 1, \end{cases} \quad (1)$$

where the speed rate e is defined by $e = N_{out}/N_{in}$. The efficiencies of the EMC and TM components are denoted by η_{emc} and η_{tm} respectively. The transmission efficiency at $e = 1$ is denoted by η_{base} , and we call this the base efficiency. In Figure 5, the transmission efficiency calculated using Equation (1) is plotted, where both η_{emc} and η_{tm} are assumed to be 90%. The change rates of the efficiency with respect to the speed rate $|\partial\eta/\partial e|$ are plotted in Figure 6. It can be confirmed that the change rate of the efficiency with $e > 1$, i.e. overdrive range, is higher than that with $e \leq 1$, and both of them increase as the average efficiencies of the EMC and TM decrease or the speed rate e leaves from 1.