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Study of different types of continuous variable transmission for an electric hybrid vehicle

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Abstract-
Traction systems based on electric-driven continuously variable transmissions (e-CVTs) are widely used in complete hybrid power trains for passenger cars. This paper is written to help you understand this technology and its potential by explaining the operation principle and introducing a simple standard for electric transmission machines' specifications. In this paper, a continuously variable electronic transmission (E-CVT) drive system for a full hybrid is presented. Therefore, the E-CVT drive system's development is discussed focusing on the system architecture, functional principles, and advantages and disadvantages. Finally, the development trend of the E-CVT drive system is presented.

Keywords–*Power split, hybrid powertrain, epicyclical gearset*

Introduction

Concept of hybrid power train systems-

Each vehicle powertrain essentially has to:

a) Develop sufficient power to meet the vehicle's performance requirements.

b) Keep sufficient energy storage onboard to drive the vehicle within the specified range.

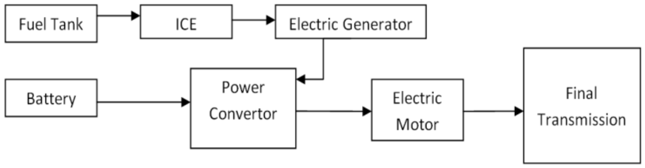
c) Have high efficiency;

d)Emission only a few environmental pollutants.

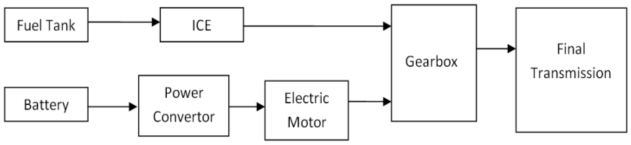
Typically, a vehicle may have more than one energy source and energy converters (energy source), such as a gasoline/diesel IC engine system, a fuel cell electric motor system with hydrogen, and a chemical battery electric motor system.

The hybrid electric vehicles are further classified in further 3 categories-

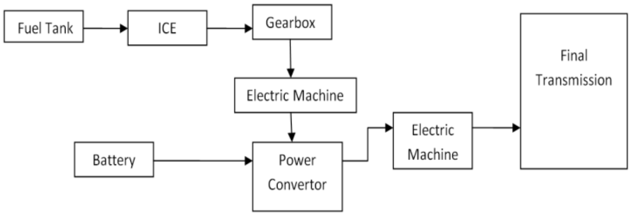
1) Series hybrid transmission



2) Parallel hybrid transmission



3) Series-parallel hybrid transmission



A hybrid vehicle transmission consists of two power sources. One is the primary power source, and the other is the secondary power source. To recover part of the braking energy, the hybrid transmission has at least one bidirectional energy source, generally an electrochemical storage system. At present, fossil fuel engines are the first choice for the primary power source.

Series/parallel Hybrid Drivetrains (power-split driveline)

With fully hybrid transmissions, today's power-sharing solutions are viewed as a compromise between the dimensioning of components (motor, electrical machines, and mechanical parts of the transmission) and performance. Regardless of the implementation, this solution requires two electrical machines with the motor and the differential. The best-known example is

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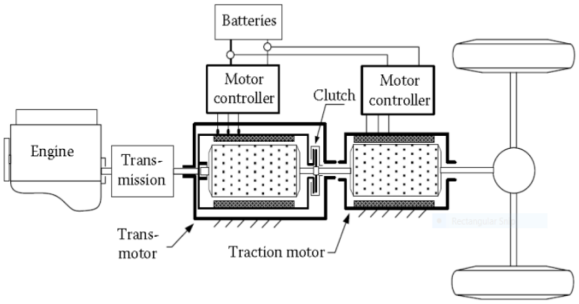
the system developed and implemented by the Toyota Motor Company (HSD, Hybrid Synergy Drive) in the Toyota Prius [6]. Another driveline system of the input power distribution type is the Ford Hybrid System (FHS) [7].

The engine power is divided into two parts: one part goes via the ring gear to the motor/generator and the other to the differential. This is how the transmission takes its name from the hybrid E-CVT transmission (continuously variable electrical transmission) with power distribution.

However, at high vehicle speed, the motor/generator can operate at a negative speed while keeping the motor speed below a certain speed to achieve high motor operating efficiency. We say turn in the opposite direction of the engine speed. In this case, the motor/generator delivers positive power to the planetary gear, i.e., H—the motorization. From the above analysis, it can be seen that the primary function of a motor/generator is to control the motor speed and, therefore, to decouple the motor speed from the wheel speed.

The traction motor increases the output torque of the planetary gear's ring gear with a torque coupling mode via the output pinion, with which the engine torque is decoupled from the vehicle load. This transmission works like a CVT. The power delivered electrically from one machine to another changes the ICE's torque-speed operating point without delivering or pulling power. Of course, the power ratio is not always zero, for example, when charging electrically and operating with a pure battery.

Another solution for obtaining a power distribution device is shown in the Figure. This transmission is functionally similar to the e-CVT transmission shown in the Figure and is referred to as variable electrical transmission (EVT).



Relationships regarding the speeds

Generally, the relationships governing the speed ratios in a planetary geartrain aredifferent from those valid for the ordinary gearbox. The fundamental parameter of theepicyclic gearbox is the geartrain fundamental ratio is defined as follows:

$$\tau = \frac{-R}{S}$$

Where:

R is the number of teeth of the ring;

S is the number of teeth of the sun;

Furthermore, since in general, all the flat epicyclical gears have the same module, the

Condition of matching of the axes of the sun and ring implies the following relation betweentheir teeth number and those of the satellites:

R= S+2P

Where:

P is the number of teeth of the satellites.

The kinematic of a planetary gear, namely the determination of its transmission ratio,

It's easy considering that its operation analysis is not affected by a change of reference frame,i.e., if the speeds are quantified concerning a moving reference frame rather than a fixedone. Choosing the carrier speed as the speed of the new reference system and referring thering and sun speeds to this one, the following relationship can be written as –

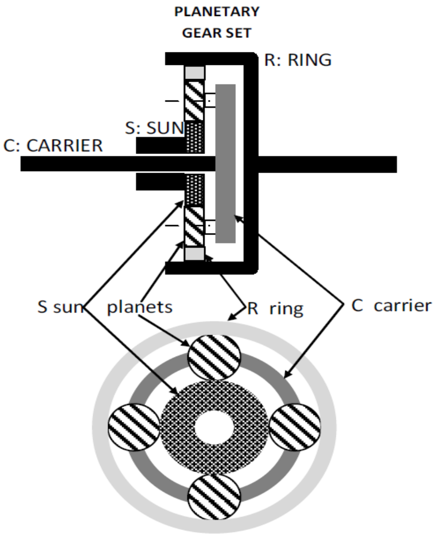
$$\tau = \frac{\omega \boldsymbol{sc}}{\omega \boldsymbol{rc}} = \frac{\omega \boldsymbol{s} - \omega \boldsymbol{c}}{\omega \boldsymbol{r} - \omega \boldsymbol{c}} = \frac{-R}{S}$$

Where:

- $\omega \mathbf{r}$ ring rotational speed;
- $\omega \mathbf{c}$ carrier rotational speed;
- $\omega \mathbf{s}$ sun rotational speed;

The fundamental speed ratio (τ) is a negative quantity and represents the sun/ringspeed ratio when the carrier is stopped and defines the relationship between the three wheelsspeeds. The Willis formula can be obtained by developing the

$\omega \mathbf{c} = \omega \mathbf{s}\left(\frac{1}{1-\tau}\right) - \omega \mathbf{r}\left(\frac{\tau}{1-\tau}\right)$



Charging of a hybrid car

This depends on the type of hybrid. Most, including series and plug-in hybrids, use the petrol engine to create electricity and charge the battery. Plug-in hybrids can also use mains electric sources too.

Parallel hybrids are different because they only charge the battery by capturing excess energy and converting it to electricity. Excess energy usually wasted when the car is idling or decelerating is instead stored in the battery for later use, for example, regenerative braking.

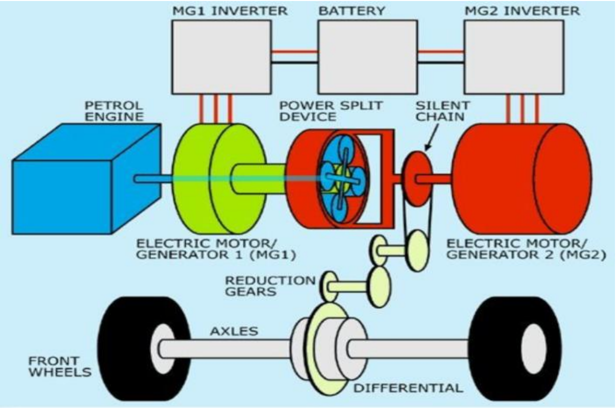
Regenerative braking in hybrid cars

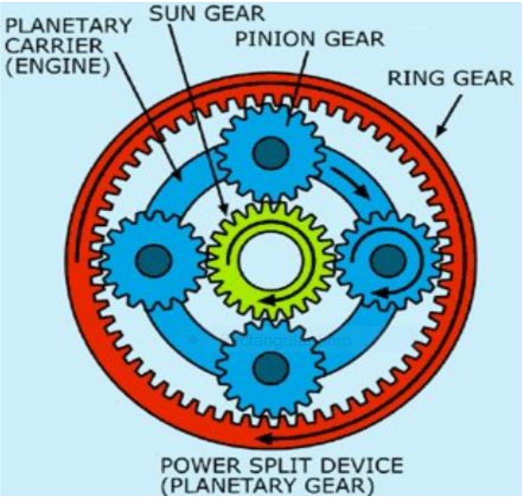
Regenerative braking is a method of recoupling the energy lost during braking and storing it as electricity in the battery. When you apply the brakes in your car, the kinetic energy used to drive the car is no longer required. It is usually given off as heat in the brake pads. But the regenerative braking technology in a hybrid car can convert it into electricity. Here's how it works: When you press the accelerator pedal, the battery can turn the motor that turns the wheels. If you take your foot off the accelerator or apply the brakes, the process is reversed. Electricity to the engine is cut off, and instead, the wheels transfer their kinetic energy to the engine, essentially transforming it into a generator to return electricity to the battery.

Hybrid Transmission

Planetary CVT

Most complete hybrid cars introduced by Toyota Prius (including Honda, Ford, and GM) use planetary CVT gearboxes to combine the two power sources and vary the gear ratio. It is a complicated but clever idea. The picture below shows the architecture of the Toyota Prius system. The drivetrain consists of a motor, an MG1 electric motor (which normally acts as a generator), an MG2 electric motor (which mainly works as a drive motor), and a planetary gear called the "Power Split Device.", Inverter and a battery.





The engine crankshaft is connected rigidly to the planetary carrier (blue part), which drives the pinion gears. The pinion gears drive the outer ring gear (red part) and the inner sun gear (green part) simultaneously. The ring gear is connected to the front wheels through some reduction gears. The sun gear is connected to MG1. Therefore, the engine's power is divided into two paths, one goes to the generator MG1, and another goes to the wheels. Meanwhile, the motor MG2 connects permanently to the ring gear (red) and directly drives the wheels. As a result, both the engine and MG2 can provide power.

How does it vary the transmission ratio to optimize the engine's rev and torque to match the wheel speed? The answer lies in the generator MG1. Assuming the green sun gear is fixed, the blue planetary gears run around the sun gear and drive the red ring gear, whose rotation is coupled to the wheels. In this case, the ratio between engine rev and wheel speed is fixed. If we let the green sun gear rotate in the same direction as the blue planetary carrier, the red ring gear will slow down. This means the wheel speed is reduced in relation to the engine rev. It virtually equals shifting to a lower gear.

Where does the excess power go? It is used to spin the generator MG1, which may use the electric power to recharge the battery or to drive the motor MG2, which contributes to the propulsion power. The faster the generator MG1 is allowed to spin, the more power it generates, and the MG2 provides more propulsion power. Interestingly, if the battery does not take or contribute power to the system (e.g., during extended cruising), all MG2 power comes from the engine. The more power the engine transfers to MG1 and then electrically to MG2, the less power the engine directly transfers to the wheels. By controlling the current flowing through the MG1 and MG2, you can alter the sun gear's speed, hence the transmission ratio and the proportion between engine/motor power. As the transmission ratio could be varied infinitely, the hybrid planetary gearbox is seen as a special kind of CVT (Continuous Variable Transmission).

GEAR E-CVT PROPULSION SYSTEMS

The gear E-CVT system can be sorted into two categories,according to planetary gear's power split manner. The first categorycan be named input power split, which is adoptedby Toyota and Ford. And the second category can becalled the compound power split, which is adopted by-Allison.

Toyota E-CVT propulsion system

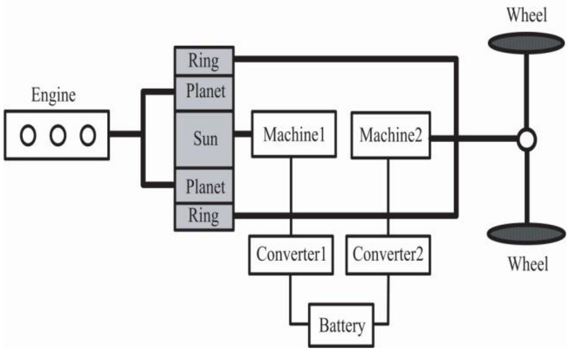
The Figure shows the basic configuration of the Toyota E-CVT drive system, which mainly consists of a set of planetary gears, a battery, machine 1 (usually used as a generator) and converter 1 (generally as a regulated rectifier), machine 2 (generally as a motor)) and converter 2 (generally as an inverter). In this system, the planetary gear assembly plays a crucial role in dividing engine power into electrical power flow and mechanical power flow. On the one hand, the engine's mechanical power is transferred to the transmission via the ring gear. On the other hand, the solar wheel is attached to machine 1, which converts part of the engine power into electrical energy, so that machine 2 can be driven to drive the transmission. Converter 1 and converter 2 cooperate with the battery to absorb electrical energy transmission between machine 1 and machine 2. If the mechanical power transmitted by the ring gear is less than the desired drive power, the battery releases electrical energy via converter 2 and machine 2; otherwise, the battery stores electrical energy. The relationship between engine torque and engine torque can be expressed as

$$T_d = T_m + \frac{1}{2+\rho} T_e$$

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

$$\rho = \frac{N_s}{N_r}$$

Where Td is the transmission torque, Tm is the torque of the machine 2; Te is the torque of the motor, ωd is the transmission speed, ωe is the engine speed, ωg is the speed of the machine 1, ρ is the planetary gear ratio, Ns is the number of solar gears, and Nr is the number of ring teeth. By correctly controlling the power consumed by the battery and then re-injecting it into machine 2, ωe can be kept constant while ωd varies. Therefore, a stepless ratio between engine speed and wheel speed can be achieved.



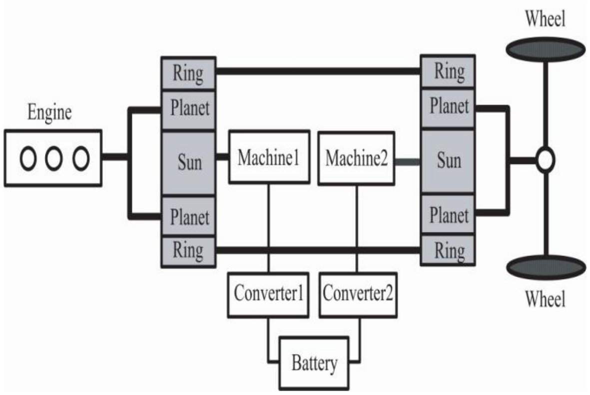
Toyota gear E-CVTpropulsion system

Ford E-CVT propulsion system

As Figure 2 shows, the Ford E-CVT drive system has two planet gears. The first planet gear is attached to the motor shaft and is responsible for the power distribution. The second planetary gearbox is responsible for coupling the engine torque. Compared to the Toyota E-CVT drive system, the Ford E-CVT system can distribute the drive power more flexibly thanks to the planetary gearbox. The relationship between engine torque and engine torque can be expressed as follows:

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

Where $N1$, $N2$, $N3$ are the numbers of teeth of the sungear, planet gear, and ring gear, respectively, of the planetary output gear.



Ford gear E-CVT propulsionsystem

GM-Allison E-CVT propulsion system

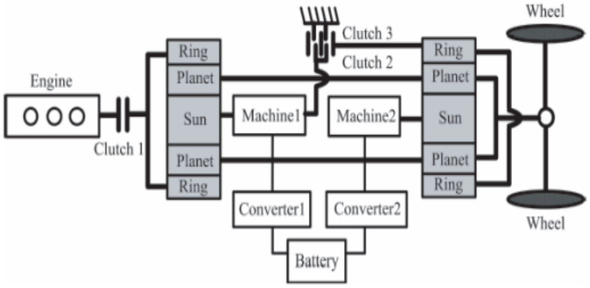
Rather than simply an input-split E-CVT system,the GM-Allison E-CVT propulsion system is a compound-split system, as shown in Figure 3. This E-CVTsystem comprises three clutches, twoplanetary gears, two machines, two converters, and abattery pack. By means of engaging or disengagingdifferent clutch arrangements, the E-CVT propulsionsystem can alter its architecture so that the outputtorque can meet the road load demand.When vehicles operate at the city-driving mode, bothClutch 1 and Clutch 3 are engaged while clutch 2 is disengaged. Thus, the planetary gear attachedto the engine is responsible for input powersplit while the planetary gear is coupled with the drivelineis in charge of output torque coupling. The relationshipbetween the engine torque and the drivelinetorque can be expressed as:

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

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

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

Where $\rho 2$ is the output planetary gear ratio, compared with those propulsion systems adopted byexisting ICEVs, the distinct advantages of these ECVTpropulsion systems are summarized as follows.(1) Because a continuously variable ratio betweenthe engine speed and the wheel speed can beachieved, the engine can always operate at itsmost energy-efficient operating area, resulting in a considerable reduction of the fuel consumption.(2) The E-CVT system can fully enable the idle stopfeature and the electric launch feature. Thesefeatures are particularly essential to improve theenergy efficiency of the full hybrid.



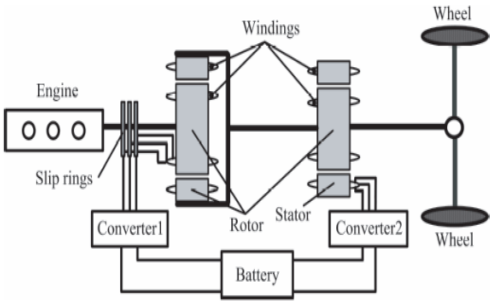
GEARLESS E-CVT PROPULSION SYSTEMS

A family of gearless E-CVT drive systems is developed based on distributing the input power to the planetary gear. The main thing is to use a twin-rotor machine to split the motor power into electrical and mechanical power flows. This eliminates mechanical wear and audible noise associated with E-CVT transmission drive systems. As Figure shows, this E-CVT drive system mainly consists of a double-rotor induction machine, a cascade induction machine, two power converters, and a battery. The double rotor machine's inner rotor is attached to the motor shaft, while the outer rotor is coupled to the second cascade machine. The motor's power is thus divided between the electrical power, which can be obtained via slip rings, and the mechanical power coupled with the gearbox. The glide performance can supply the machine in cascade via the two converters or charge the battery. If the directly coupled mechanical power cannot achieve the desired drive power, the battery can release energy to supplement the driving force. The relationship between engine power and drive power can be expressed as follows:

$$Pe = Pmech + Pelec$$
$$Pelec = (\omega e - \omega d)Te$$

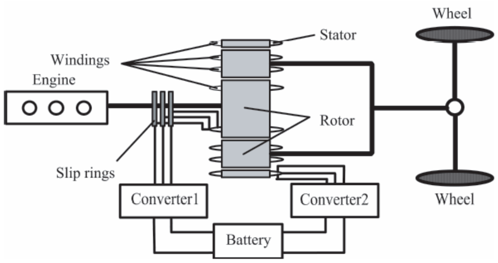
Where$Pe$is the engine power, $Pmech$is the mechanicalpower transfer, $Pelec$is the electric power transfer, $\omega e$is the engine speed, $\omega d$is the driveline speed, and $Th$is the engine torque. By controlling $Pelec$,

ωecan bemaintained constant when $\omega d$is varying. Hence, thedesired continuously variable ratio between the enginespeed and the wheel speed can be attained.Figure shows the engine optimal operation line(OOL), where $P2$ shows the speed and torque requiredat the driveline shaft.$P1$ shows the speed and torqueoffered by the engine. If the primary shaft adoptsspeed control to regulate the speed change Δnbetweenthe engine and the driveline, the second shaftadapted torque control governs the torque changeΔT between the engine the driveline shaft, the enginewould operate along the OOL. Hence, the E-CVTpropulsion system can keep maximum efficiencyduring all driving conditions.



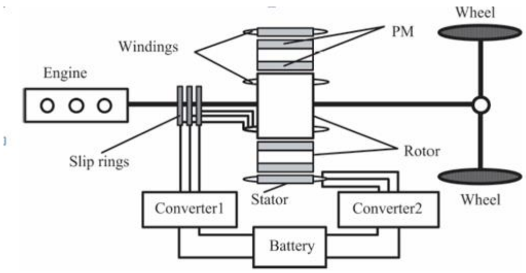
Double-rotor cascaded induction machine

The gearless E-CVT propulsion system



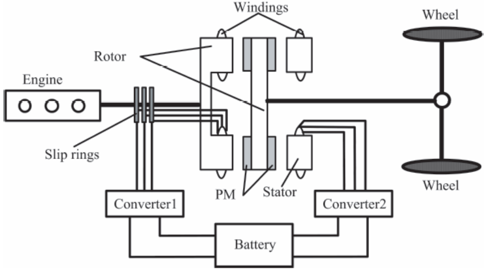
Double-rotor integrated induction machine gearless E-CVT propulsion system

To reduce the system's weight and size, the two machines can be integrated into a single machine. The key is to share the first machine's outer rotor with the rotor of the second machine so that the stator is concentric around the outer rotor. The Figure shows the configuration of the E-CVT drive system of the integrated double rotor induction machine. The corresponding functional principle is the same as that of the double rotor induction machine in cascade with another induction machine. To improve the system's efficiency, the two induction machines can be replaced by two brushless PM machines. The drive system E-CVT of the PM machine with a double integrated rotor is thus shown in Figure. Suppose the space under the vehicle's hood could not accommodate this PM machine with an integrated double rotor with a radial field. In that case, it can be converted into an axial field version, as shown in Figure. The principle of operation is the same as that of the radial field.



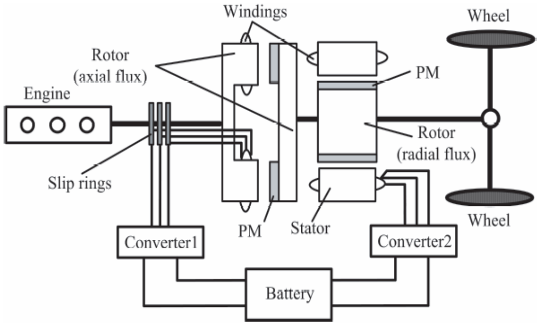
Double-rotor integrated PM machine gearless E-CVT propulsion system

It does not matter whether the E-CVT drive system of the integrated double rotor machine is based on a brushless induction or PM machine or based on the morphology of the radial field or the morphology of the axial field of the magnetic fields between the different air gaps of the machine coupled to some degree. Such a coupling worsens the independence of two air gaps and negatively affects the E-CVT system's controllability.



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

Recently, using the radial and axial fields' orthogonal nature, the gearless E-CVT drive system of the PM machine with an integrated double rotor has been proposed as shown. The key is using a double rotor integrated into the PM machine, which consists of an axial field machine in the first stage and another radial field machine in the second stage. Due to its decoupling type between the first and the second stage, this E-CVTdrive system can offer better controllability.



Decoupling double-rotor integrated PM machinegearless E-CVT propulsion system

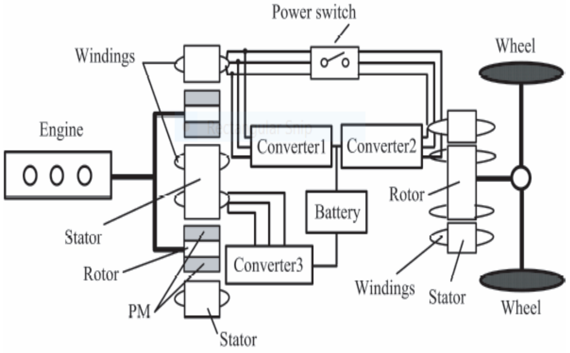
The advantages of those mentioned above gearless ECVTpropulsion systems are summarized as follows

(1) Due to the absence of clutches, they can significantlyimprove the transmission efficiency andreduce the overall size.
(2) Because of the absence of planetary gear sets, themechanical wear-and-tear and audible noise canbe avoided. Also, they are mechanically simple,hence offering high reliability.Nevertheless, they rely on double-rotormachines in which slip rings and carbon brushes are inevitably employed to transmit power away from therotating body. The use of slip rings and carbon brushes violates the concept of maintenance-free operation,causes power loss, and involves bulky mechanisms to ensure good contacts.

BRUSHLESS GEARLESS E-CVT PROPULSIONSYSTEMS

As previously discussed, gearless E-CVT drive systems are preferred overdriven E-CVT drives
Systems, however, still suffer from the use of slip rings and carbon brushes. The development trend of E-CVT drive systems is, therefore, to invent a brushless system without gear. After the idea of using a double rotor machine to perform a power distribution, the double stator machine should be able to perform the same task—a gearless PM-E-CVT drive system for a brushless machine with a double stator. As shown in Figure, there are two regulated power flow paths from the motor to the wheels: namely, via the external stator of the first stage machine, converter 1, converter two, and the second stage machine; via the internal stator of the first stage machine, converter 3, converter two and the second stage machine. The second stage machine is a PM double stator machine, while the second stage machine is a standard induction motor or a brushless PM motor. The two converters are standard three-phase controlled rectifiers. The external stator path is responsible for the main current flow, while the internal stator path performs current distribution control using the battery pack as a buffer. By properly controlling the two regulated rectifiers, the motor can be operated at a constant speed.
In contrast, the wheel speed varies depending on the load profile on the road and the driver's control. This offers the advantage of a continuously variable gear. If energy distribution is not required, the system's efficiency can be further improved by using a circuit breaker to transfer the energy directly from the outer stator of the first stage machine to the motor of the second floor. Compared to counterparts with a double rotor, this brushless E-CVT drive system with PM stator and double stator offers the following advantages.

(1) The reliability of the system is improved by eliminating slip rings and carbon brushes.
(2) The internal stator winding provides a power distribution of the engine power andstarts the engine.
(3) The bidirectional circuit breaker can transmit the output power while driving directly from the first stage machine's outer stator to the second stage machine, thereby avoiding unnecessary loss of regulated rectifiers and inverters.
(4) Since the first stage machine and the second stage machine are connected by electrical means, they can be mounted separately with the motor and the final gear, eliminating the cumbersome and bulky mechanical gear



Double-stator PM brushless machine gearless-CVT propulsion system

Conclusion

In this article, we discussed various E-CVT drive systems that are essential for complete HEVs. These E-CVT drive systems have been classified as Gear E-CVT and Gearless E-CVT. Their advantages and disadvantages were discussed. Therefore, the development trend was identified that reveals the latest concept of brushless gearless E-CVT drive systems.
In summary, the advantages of a power distribution CVT over an electrical CVT are given here:

1) The transmission efficiency is higher because most of the power is transferred to the mechanical branch, which consists of planet gears.
2) A lower maximum current flow through the electrical branch is required, resulting in smaller electrical machines.

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