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Hybrid Propulsion

Classification of HEVs

Two major classifications of HEVs, 潮流

- one is based on the power flow - more academic in nature and can provide more technical information
- another is based on the hybridization level - more straightforward and can be easily realized by general public
杂交

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机电动力的流动

Based on the flows of electrical and mechanical powers, HEVs used to have two basic configurations – the series hybrid and parallel hybrid.

Some HEVs offering the features of both the series and parallel hybrids, the classification has been extended to series-parallel.

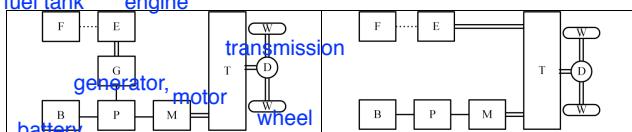
With the advent of some HEVs with dual-axle propulsion that cannot be represented by these three kinds, the basic configurations have been extended to complex hybrid.

series hybrid
parallel hybrid
series-parallel hybrid
complex hybrid

系列混合动力
并联混合动力
串并联混合
复杂的混合

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fuel tank engine

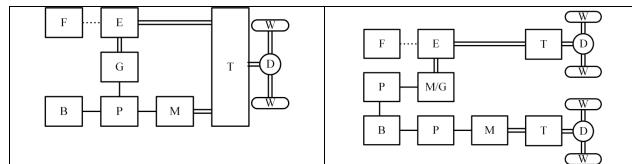


The key feature of the series hybrid is to couple the engine with the generator to produce electricity for pure electric propulsion

B is the battery, D is the differential, E is the engine, F is the fuel tank, G is the generator, M is the Motor, P is the power converter, T is the transmission, W is the wheel, the solid line represents the electrical link, the double line represents the mechanical link, and the dotted line represents the hydraulic link. Both the electrical and mechanical links are bidirectional in nature, and the hydraulic link is unidirectional.

串联式混合动力车的主要特点是将发动机和发电机耦合起来产生纯电力推进所需的电力

并联混合动力车的主要特点是将发动机和电动机与变速器结合起来推动驱动轮



The series-parallel hybrid combines the features of both the series and parallel hybrids

The complex hybrid further combines the features of pure electric propulsion and hybrid propulsion, can offer additional & versatile operating modes.

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Based on the operating features and power levels of HEVs, they are classified as:

- Micro hybrids
- Mild hybrids
- Full hybrids

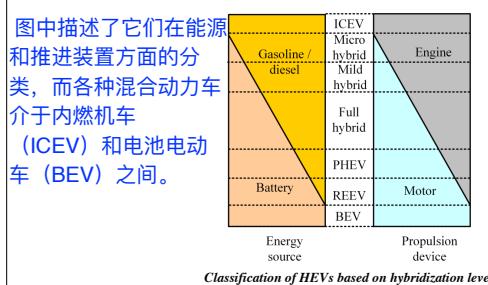
Micro hybrids
Mild hybrids
Full hybrids
Plug-in hybrid EV (PHEV)
Range-extended EV (REEV)

Recently, this classification has been further extended to include the latest types of HEVs:

- Plug-in hybrid EV (PHEV)
- Range-extended EV (REEV)

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Figure depicts their classification in terms of the energy source and propulsion device, whereas all kinds of hybrids lie between the internal combustion engine vehicle (ICEV) and the battery electric vehicle (BEV).



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它配备了一个集成起动发电机 (ISG)

For the micro hybrid, it is equipped with an integrated-starter-generator (ISG) which is typically 3-5 kW with the system voltage of 14-42 V. Instead of providing power assist to help the heat engine, it offers two important hybrid features: the idle stop-start which shuts down the heat engine whenever the vehicle is at rest so as to reduce the fuel consumption, and regenerative braking which recovers the braking energy during deceleration to regenerate electricity for battery charging. The Citroën C3 is a micro hybrid.



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怠速停止起动，在车辆静止时关闭热机，以降低油耗；
再生制动，在减速时回收制动能量，以再生电能供蓄电池充电。
雪铁龙C3是一款微型混合动力车。

For the **mild hybrid**, the ISG is increased to 7-15 kW with the system voltage of 100-150 V. It not only provides the hybrid features of **idle stop-start** and **regenerative braking**, but also **assists** the heat engine to **propel** the vehicle. Thus, it enables to **adopt a downsized engine**. The **Honda Insight** is a mild hybrid.

但也协助热机推动车辆。因此，它能够采用缩小的发动机。

本田Insight是一款温和的混合动力车
ELEC7402 Hybrid Propulsion - 9



For a **full hybrid**, it can offer **versatile operations** by using the **heat engine alone**, the **electric motor alone** or a **combination of both**. Instead of using the ISG, it adopts the **electric variable transmission (EVT)** or called **electronic-continuously variable transmission (ECVT)** system which is typically 50-60 kW with the system voltage of 500-600 V. Using EVT, it can

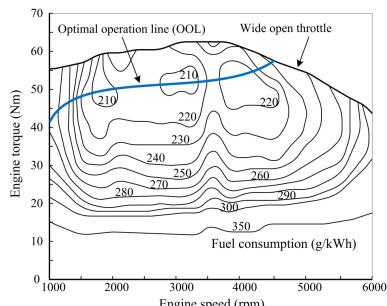


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offer **all hybrid features**, including the **electric launch**, **idle stop-start**, **regenerative braking**, and **power assist**.

Increasingly, the **full hybrid** can enable the **heat engine working at its optimal operation line (OOL)** to achieve efficiency optimization.

The Toyota Prius is a full hybrid.



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Meanwhile, a derivative of this full hybrid is the power hybrid. The only difference is that the power hybrid **does not have the feature of downsized engine**. It installs the **same size engine** as that of a conventional ICEV so that the resulting hybrid propulsion power can provide more torque and better acceleration performance than the ICEV. A representative of this power hybrid is the Lexus RX450h.



由此产生的混合动力可以提供比内燃机车更多的扭矩和更好的加速性能。
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For the **PHEV**, it provides **all features of the full hybrid**, while having an additional feature of **plug-in rechargeable**. In general, it is equipped with **more battery packs**



than the full hybrid, typically 4-5 kWh, so that it can offer a **decent electric range** at the **pure electric mode**. It normally operates at the **blended mode** in which the **electric motor and heat engine complement one another to maximize the fuel economy**.

它可以提供一个体面的纯电动模式的电动范围。它通常工作在混合模式中，其中电动机和热机彼此互补以最大化燃料经济性。
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Pros and Cons of PHEVs

- 😊 Can operate at all-electric mode or blended mode
- 😊 Long driving range, comparable with ICEVs
- 😊 More energy efficient than HEVs
- 😊 Better energy diversified than EVs
- 😢 Heavier than HEVs due to the use of more batteries
- 😢 Not zero local emissions when operating at blended mode

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Compared with the **PHEV**, the **REEV** usually installs a **smaller heat engine** but a **larger battery pack**. As reflected by its name, it prefers to work as a **BEV** until the **battery capacity** drops to a **predefined threshold**. Then, it works as a series hybrid so that the **heat engine drives the generator to charge the battery pack and provide power to the electric motor**. At higher speeds and loads, the **REEV** generally operates at the **blended mode** to maximize the fuel economy. In order



作为**一个BEV**工作，直到电池容量下降到预定的阈值。
在更高的速度和负载下，**REEV**通常在**混合模式**下运行以**最大化燃料经济性**。
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to provide the desired electric range, the battery requirement is typically over 16 kWh.

Pros and Cons of REEVs

- 😊 Normally operate at all-electric mode
- 😊 Long driving range, comparable with ICEVs
- 😊 More energy efficient than HEVs
- 😊 Better energy diversified than EVs
- 😢 Heavier than HEVs due to the use of more batteries
- 😢 More complex than EVs due to the additional engine and generator

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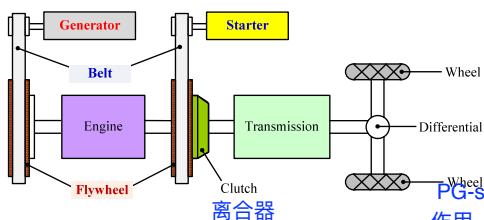
Hybrid features of HEVs

	Micro	Mild	Full	PHEV	REEV
Idle stop-start	✓	✓	✓	✓	✓
Regenerative braking	✓	✓	✓	✓	✓
Power assist		✓	✓	✓	✓
Electric launch			✓	✓	✓
Efficiency optimization			✓	✓	✓
Decent electric range				✓	✓

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Separated-Starter-Generator 起动马达为冷起动提供高起动转矩，发电机为蓄电池充电发电。由于这两台机器的利用率都很低，因此重量大，体积

The **starter motor** provides high starting torque for cold cranking, and the **generator** produces electricity for battery charging. It offers from poor utilization of both machines, hence heavy weight and bulky size.



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PG-set在将发动机功率分为机械和电气两种功率流方面起着关键作用。发动机产生的机械动力通过齿圈传输到动力传动系。

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太阳齿轮连接到机器上，机器1将发动机的一部分动力转换为电

力，以便它可以用来为机器2提供动力来驱动传动系统。

转换器1和转换器2与蓄电池组一起工作，以缓冲机器1/2之间的电

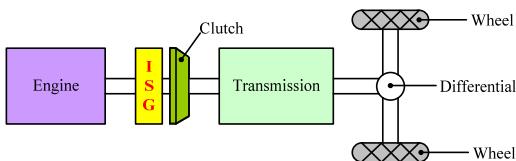
力传输。如果所需的车辆功率>发动机功率，蓄电池将释放电源

以补充发动机功率；否则，蓄电池将存储过量的发动机功率。

Integrated-Starter-Generator (ISG)

集成起动发电机(研究小组)

The **ISG** incorporates both starter motor and generator functions in a single unit, while eliminating the use of transmission belts and flywheels.



ISG将起动马达和发电机功能集成在一个单元中，同时传动带和飞轮的使用。

它应该为冷起动提供高起动扭矩

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它应该提供宽速度范围的发电

它应该提供高功率密度和高扭矩密度

它应该在很宽的速度范围内提供高效率

ISG Features:

- It should offer high starting torque for cold cranking
- It should offer wide-speed range power generation
- It should offer high power density and high torque density
- It should offer high efficiency over a wide speed range



Honda ISG

(http://en.wikipedia.org/wiki/File:Honda_Insight_IM_A.jpg)

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电子无级变速器 (ECVT)

电动变速器 (EVT)

Electronic Continuously Variable Transmission (ECVT) / Electric Variable Transmission (EVT)

- Combine engine and motor powers without using clutches
- Provide full hybrid features, including electric launch, idle stop, regenerative braking and downsized engine
- Enable engine operating at optimal operating line (OOL)

在不使用离合器的情况下合并发动机和马达功率

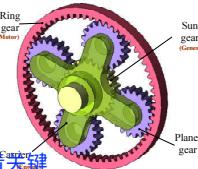
提供全混合动力功能，包括电动启动、怠速停止、再生制动和缩小发动机尺寸使发动机在最佳工作线（OOL）下工作

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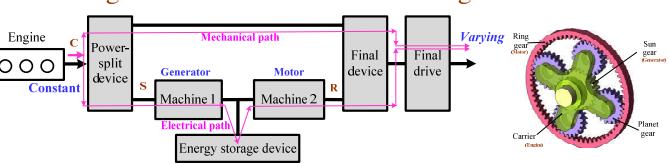
Basic EVT System

- A basic EVT system is composed of:

- a planetary gear (including a sun gear, a planet carrier which holds several planet gears meshed with the sun gear, and a ring gear with inward-facing teeth that mesh with the planet gears)
- a motor
- a generator



- The engine is attached to the planet carrier.
- The motor is coupled with ring gear which is connected to the driveline shaft.
- The generator is mounted to the sun gear.



The PG set plays a key role to split the engine power into 2 paths of power flow: mechanical and electrical. the mechanical power produced by the engine is transferred to the driveline via the ring gear.

the sun gear is attached to the machine 1, which converts a portion of the engine power to electrical 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 electrical power transfer between the machines 1/2. If the desired vehicle power > the engine power, the battery will release electrical power to supplement the engine power; otherwise, the battery will store the excessive engine power.

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Compare with the traditional parallel-axis gear, the planetary gear possesses the following advantages:

- Higher power density and higher torque density
- Higher power transmission efficiency
- Larger reduction ratio in a given volume
- Multiple kinematic combinations with coaxial shafting
- Better load distribution and greater stability

与传统的平行轴齿轮相比，行星齿轮具有以下优点：

更高的功率密度和扭矩密度

更高的功率传输效率

在给定体积下的较大压缩比

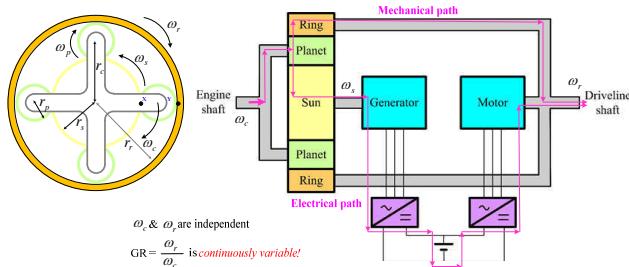
同轴轴系多运动组合

更好的负载分布和更大的稳定性

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通过控制发电机获取的功率，然后反馈到电机中，当传动系统转速变化时，发动机转速可以保持恒定。因此，可以实现连续可变的传动比。

By controlling the power taken by the generator and then feeding back into the motor, the engine speed can be maintained constant when the driveline speed is varying. Hence, a continuously-variable gear ratio can be achieved.



由于没有离合器、变矩器或变速器，可以显著提高传动效率，减小整体尺寸，从而提高能源效率和功率密度。此外，由于它的机械简单，它提供了高可靠性。

在发动机转速和车轮转速之间存在连续可变比的情况下，发动机始终可以在其最节能或最佳工作线（OOL）下工作，从而显著降低燃油消耗。

Merits of Planetary Gear EVT

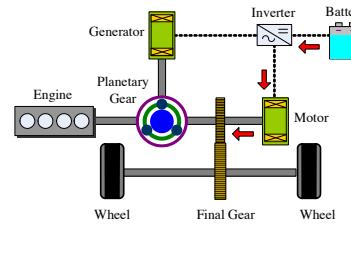
- Because of the absence of clutches, torque converters or shifting gears, it can significantly improve the transmission efficiency and reduce the overall size, hence increasing both the energy efficiency and power density. Also, since it is mechanically simple, it offers high reliability.
- In the presence of continuously-variable ratio between the engine speed and the wheel speed, the engine can always operate at its most energy-efficient or optimal operation line (OOL), hence resulting in a considerable reduction of the fuel consumption.

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普锐斯从停止加速使用电池和电机驱动车轮。它在发动机起动前加速到约60公里/小时，因此可以在较窄的转速范围内工作以获得最佳效率。

Starting (Electric launch)

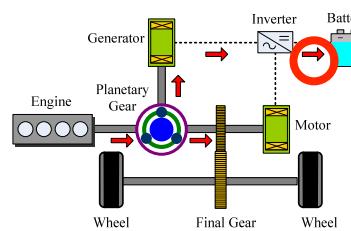
The Prius accelerates from a stop using the battery and electric motor to drive the wheels. It accelerates to about 60 km/h before the engine is started so it can operate within a narrow rpm band for optimum efficiency.



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Normal Driving

When cruising speed is reached, the engine is started to drive the wheels and the generator, the latter supplying electricity to charge the battery and power the electric motor as needed.



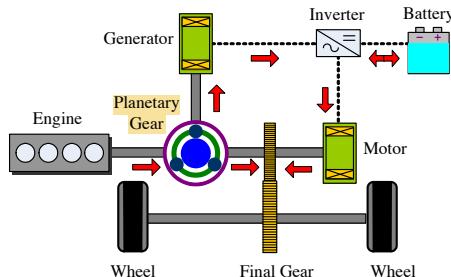
当达到巡航速度时，发动机启动驱动车轮和发电机，后者提供电力给电池充电，并根据需要为电机供电。

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➤ The system can fully enable the idle stop feature (the engine is completely shut down when the vehicle is stopped) and the electric launch feature (the motor provides all necessary torque required to put the vehicle in motion). These two features are particularly essential to improve the energy efficiency of the full hybrid.

➤ The system can fully enable regenerative braking when the vehicle is slowing or downhill coasting, and full-throttle acceleration where both the engine and electric motor operate simultaneously to provide the required power demand.
系统可以完全启用怠速停止功能（车辆停止时发动机完全关闭）和电动启动功能（电机提供使车辆启动所需的所有扭矩）。这两个特性对于提高全混合动力车的能效尤为重要。

ELEC7402 Hybrid Propulsion - 27
当车辆减速或下坡滑行时，该系统可完全启用再生制动，并在发动机和电机同时工作的情况下实现全油门加速，以提供所需的功率需求。
Prius EVT:

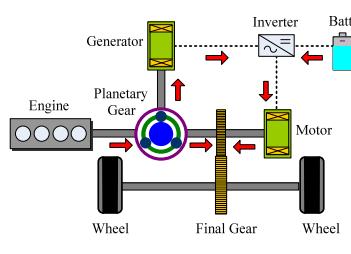


The turning point of HEV development was the advent of Toyota Prius in 1997, which introduced the first PG EVT system.

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Acceleration

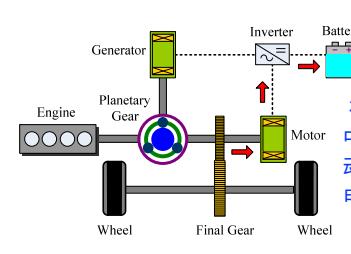
When extra power is needed for acceleration or hill climbing, electrical energy is supplied to the motor from the battery and generator.



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Deceleration

During braking or coasting, energy is recovered through regenerative braking to recharge the battery.



在制动或滑行过程中，能量通过再生制动回收，为电池充电。

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Stopping 发动机会关闭以节省燃料。

When the Prius comes to a stop, the engine is shut off to conserve fuel.

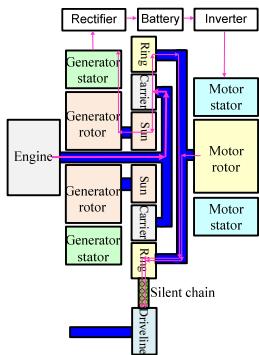
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gear and the final gear. The silent chain, or inverted-tooth chain, is a type of chain with teeth formed on its links to engage with the teeth in the sprockets. The links in a silent chain have little impact or sliding, hence producing less vibrations and noise than other chains.

需要一个无声链条来传递齿圈与主减速器之间的扭矩。无声链，或倒齿链，是一种链上的牙齿形成的链接，以啮合在链轮的牙齿。无声链中的链环几乎没有冲击或滑动，因此产生的振动和噪音比其他链小。

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Practical Arrangement of EVT in Prius



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Electric Machine Power Split

同心地

- The combination of two concentrically arranged machines can realize the power split.
- The 1st machine is a double-rotor one in which its inner rotor is coupled with the engine, whereas its outer rotor is coupled with the 2nd machine and the driveline shaft. The inner rotor of the 1st machine is connected to a converter via slip rings. The 2nd machine is fed by another converter.

两台同心排列的机器组合可实现功率分流。

第一台机器是双转子机器，其内转子与发动机耦合，而其外转子与第二台机器和传动轴耦合。第二台机器的内转子通过滑环连接到转换器。第二台机器由另一台转换器供电。

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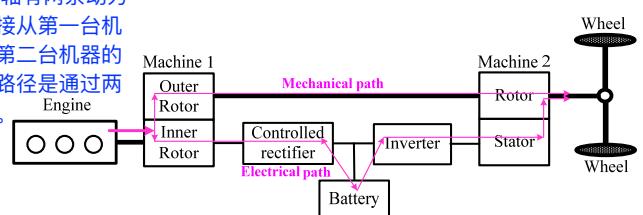
(http://en.wikipedia.org/wiki/File:Toyota_INZ-FXE_Engine_01.JPG)

ICE and the EVT

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从发动机轴到传动轴有两条动力流路径。一种是直接从第一台机器的外转子传递到第二台机器的机械功率。另一条路径是通过两个转换器的电力流。

- There are two paths of power flow from the engine shaft to the driveline shaft. One is the mechanical power directly passing from the outer rotor of the 1st machine to the 2nd machine. Another path is the electrical power flow through two converters.



ELEC7402 Hybrid Propulsion - 39

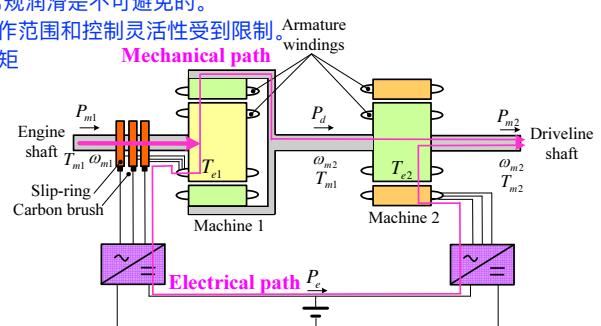
关键是对行星齿轮的依赖，这是一种机械装置，其中传递损失、齿轮噪声和常规润滑是不可避免的。

由于车辆速度/发电机转速和发动机转速都由一个方程来控制，所以EVT的工作范围和控制灵活性受到限制。整个电动汽车传动系统非常复杂，需要一个无声的链条来传递环与环之间的扭矩。

➤ The key is the reliance on the planetary gear which is a mechanical device in which transmission loss, gear noise and regular lubrication are inevitable.

➤ Since the vehicle speed, generator speed and engine speed are all governed by a single equation, the operating range and control flexibility of EVT are limited.

➤ The whole EVT system is very complicated which needs a silent chain to transmit torque between the ring



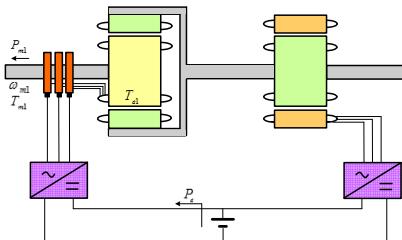
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Cranking Mode

In the cranking mode, only the double-rotor motor works. The primary machine works in torque control in order to make full use of the fast response of the current loop. Because of action and reaction, the direction of rotating field is opposite to the rotating direction of the inner rotor. When the ICE shaft speed reaches the critical starting speed judged by the ICE control unit, the ignition signal can be sent out.

在盘车模式下，只有双转子电机工作。为了充分利用电流环的快速响应，主机采用转矩控制。由于作用和反作用，旋转场的方向与内转子的旋转方向相反。当冰轴转速达到冰控单元判断的临界起动转速时，可以发出点火信号。

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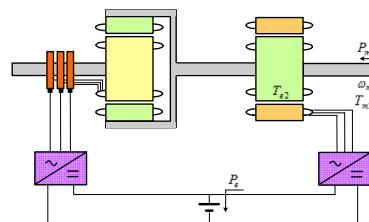


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Regenerative Braking Mode

在此模式下，机器2作为发电机工作，以回收制动能量。

In this mode, the machine 2 works as a generator to recover the braking energy.



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Double-Rotor EVT

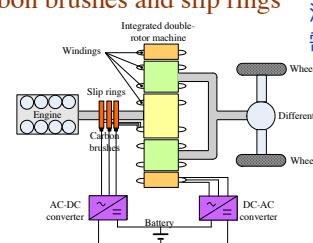
功率分流

➤ Use double-rotor machine to perform power split => Gearless

☺ Eliminate mechanical gear

⊗ Need carbon brushes and slip rings

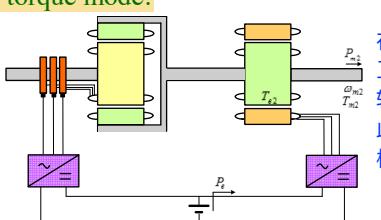
双转子电动汽车
用双转子机进行功率分流
消除机械齿轮
需要碳刷和滑环



ELEC7402 Hybrid Propulsion - 46

Electric Launch Mode

In the electric launch mode, the ICE does not work. To avoid the rotation of ICE, the primary machine does not work either. Hence, only the secondary machine is operating in torque mode.



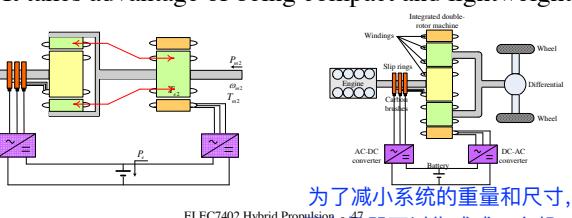
ELEC7402 Hybrid Propulsion - 43

电动发射方式
在电动发射模式下，ICE不工作。为了避免ICE的旋转，主机也不工作。因此，只有辅助机器在扭矩模式下工作。

Integrated Double-Rotor Induction EVT

➤ 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 1st machine with the rotor of the 2nd machine, and the stator is placed concentrically around the outer rotor.

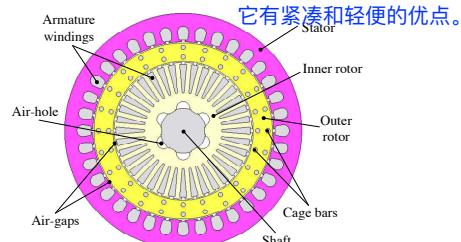
➤ It takes advantage of being compact and lightweight.



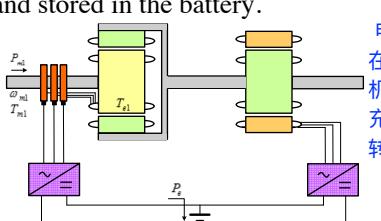
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为了减小系统的重量和尺寸，
两台机器可以集成成一台机
器。关键是1机外转子与2机转
子共用，定子围绕外转子同心
放置。

Induction DR machine:



电池充电模式
在这种模式下，当车辆停止时，
机器1的内转子会发电给蓄电池
充电。当时，发动机的动力完全
转化为电能，并储存在电池中。



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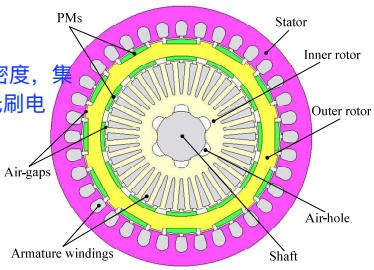
ELEC7402 Hybrid Propulsion - 48

Integrated Double-Rotor PM EVT

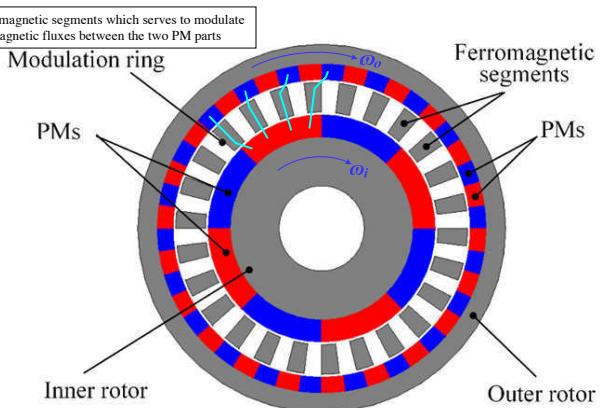
- In order to further improve the efficiency and power density, the integrated double-rotor machine can adopt the **PM brushless machines**.

PM DR machine:

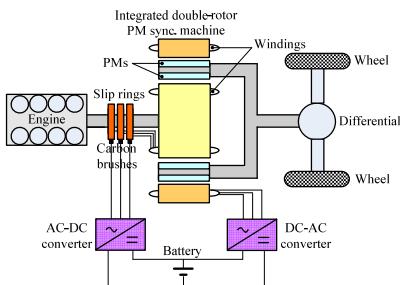
为了进一步提高效率和功率密度,集成双转子电机可以采用永磁无刷电机。



ELEC7402 Hybrid Propulsion - 49

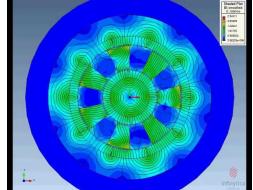
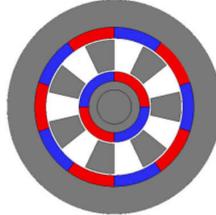


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ELEC7402 Hybrid Propulsion - 50

Field-modulated magnetic gears



$$N_s = p_i + p_o$$

$$G_r = -\frac{p_o}{p_i} = -\frac{\omega_i}{\omega_o}$$

N_s is the number of ferromagnetic segments (7 in the fig)
 p_i is the number of inner PM pole-pairs (2 in the fig)
 p_o is the number of outer PM pole-pairs (5 in the fig)
 $G_r = -2.5$

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Magnetic Gears

The double-rotor machine is a newly introduced gearless power-split device. However, it requires brushes and slip-rings which are less reliable and incur need of regular maintenance.

In order to overcome these drawbacks, a new class of magnetic-gear (MG) EVT systems has been developed based on contactless magnetic gears which can offer the definite advantage of brushless and pseudo-gearless power-split operation

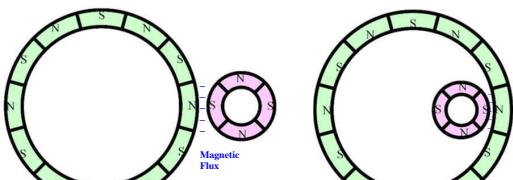
磁齿轮

双转子电机是一种新型的无齿轮功率分流装置。
然而,它需要的电刷和滑环不太可靠,需要定期维护。

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为了克服这些缺点,开发了一种新型的基于非接触磁性齿轮的永磁无齿轮EVT系统,该系统具有无刷和伪无齿轮分功率运行的明显优势

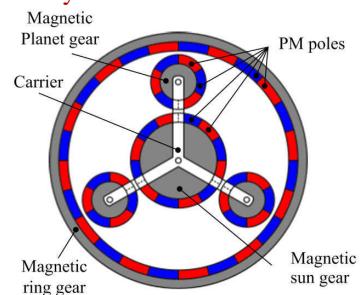
Converted magnetic gears



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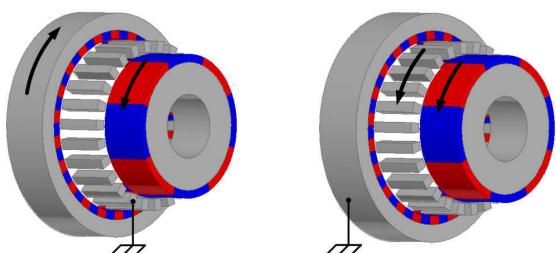
Magnetic Gear Power Split

Magnetic Planetary Gear:



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Magnetic Coaxial Gear:



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为了实现功率分流，将调制环设计为另一个转动体。因此，相应的速度关系由：

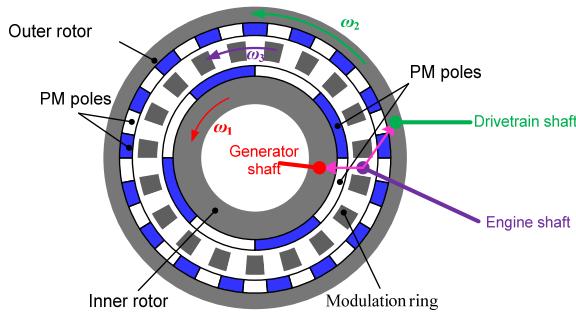
In order to achieve the power split, the modulating ring is designed as another rotational body. Thus, the corresponding speed relationship is governed by:

$$\omega_1 + G_r \omega_2 - (1 + G_r) \omega_3 = 0$$

where ω_1 , ω_2 , ω_3 are the rotational speeds of the outer rotor, inner rotor and modulating ring respectively, and G_r is the gear ratio between the inner rotor and the outer rotor (ω_1 / ω_2)

$\omega_1, \omega_2, \omega_3$ 外转子/内转子和调制环的旋转速度, G_r 是齿轮传动比之间的内转子和外转子之比(ω_1 / ω_2)

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使用磁性同轴齿轮进行功率分割

由于磁性齿轮可以提供非接触式的转矩传递，行星齿轮的缺点是传递效率低，机械摩擦大，噪音大

是可以克服的

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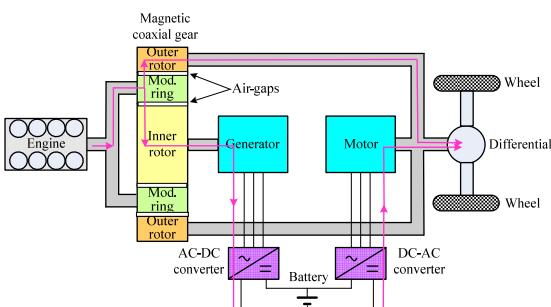
因为没有碳刷和滑动

消除了环的磨损和需要定期维护的缺点。

Magnetic Coaxial Geared EVT

- Use magnetic coaxial gear to perform power split
- Since the magnetic gear can offer non-contact torque transmission, the drawbacks of planetary gear such as low transmission efficiency, significant mechanical friction and annoying audible noise aroused from the can be overcome
- Because of the absence of carbon brushes and slip rings, the drawbacks of wear-and-tear and need of regular maintenance are eliminated.

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ELEC7402 Hybrid Propulsion - 60

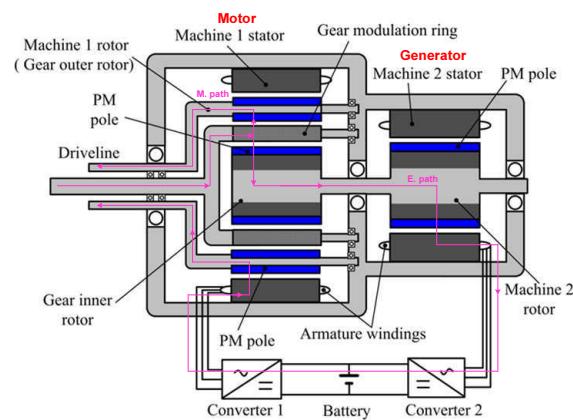
Integrated MCG EVT

- In order to improve the efficiency and power density, the two machines can be integrated into a single machine.
- In order to further improve the efficiency and power density, the PM brushless machines can be adopted.

为了提高效率和功率密度，可以将两台机器集成成为一台机器。

为了进一步提高效率和功率密度，可以采用永磁无刷电机。

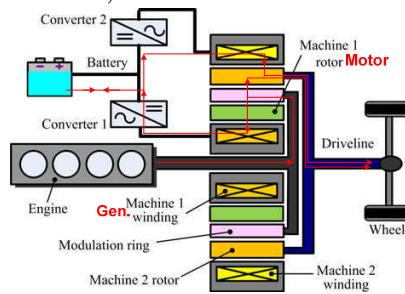
ELEC7402 Hybrid Propulsion - 61



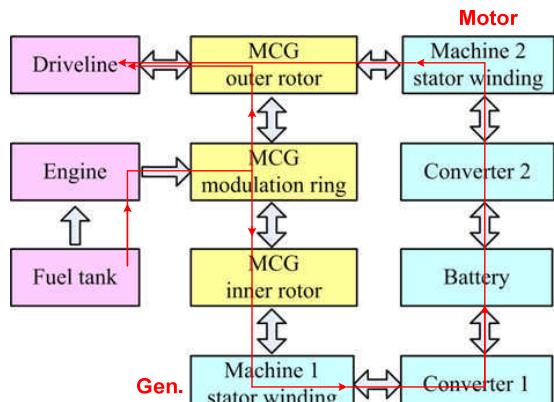
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Compact MCG EVT

- By further integrating the machine to enable the input shaft at the left-hand side and the output shaft at the right-hand side, the machine becomes a compact unit.



ELEC7402 Hybrid Propulsion - 63



ELEC7402 Hybrid Propulsion - 64