Overview of Power Networks in Hybrid Electric Vehicles

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Abstract

In hybrid electric vehicles (HEVs), the power network takes an ever-important role, which functions to adjust the engine operating region for less emissions, to incorporate the electric machine for higher overall efficiency, and to feed the increasing demand of electric loads with different voltage levels. Furthermore, more and more mechanically, pneumatically or hydraulically driven systems are gradually superseded by electrically driven systems. In this paper, the key issues, the main components, the powertrain arrangements and the voltage levels of the power network in HEVs are discussed.

Keywords

hybrid electric vehicle, power network, DC microgrid, powertrain, voltage level

1. INTRODUCTION

Although electric vehicles (EVs) have the advantages of zero emissions, high energy efficiency and quiet operation, their process of commercialization has been hindered due to some limitations, such as the short driving range, the lack of charging infrastructure, the time-consuming recharge and the high initial cost [Chan, 1993].

Rather than simply an interim solution, the hybrid electric vehicles (HEVs) form an individual family of EVs and exhibit strong competence in the auto market. The HEVs incorporate an internal combustion engine (ICE) and electric machine to ensure the ICE operating in its efficient mode. Hence, they have even longer driving range than ICE vehicles. By refuelling the gasoline from the existing gas station, the HEVs are well accepted by general publics [Chan and Chau, 2001].

Generally, the HEVs are classified into four kinds: the series hybrid, parallel hybrid, series-parallel hybrid, and complex hybrid, based on the powertrain arrangement [Chau and Wong, 2002]. Recently, another way to categorize the HEVs has also been accepted, namely the micro hybrid, mild hybrid and full hybrid, based on the operating features and power level of HEVs [Ebron and Cregar, 2005; Yu et al., 2008]. Additionally, in order to further improve the energy diversification and energy efficiency of HEVs, two gridable HEVs, namely the plug-in HEV (PHEV) and the extended-range EV (E-REV), have also been developed [Van Wieringen and Pop-Iliev, 2010]. For all kinds of HEVs, the power network is one of their key technologies, which governs their operations and performances.

In this paper, an overview of power networks in HEVs is presented. In section 2, the important issues of the power network will be discussed. In section 3, the main components of the power network, including the energy source, the power distribution part, the energy storage device and the load, will be described. Section 4 will be devoted to describing the powertrain arrangement of different HEVs. In Section 5, the voltage level of the power network will be discussed. Finally, a conclusion will be drawn in Section 6.

2. IMPORTANT ISSUES

2.1 Overall efficiency

In a conventional ICE vehicle, only 15-20 % of the consumed energy is utilized to propel the vehicles. In the hybrid version, the drivetrain efficiency can potentially be improved to about 30-40% [Emadi et al., 2005].

Compared with the ICE vehicle, the HEVs can improve the overall efficiency from various aspects [Lai and Nelson, 2007]. Firstly, the power network of HEVs can offer the functions to capture the wasted energy in the ICE vehicle, including the regenerative energy during braking or driving downhill and the engine output energy in the idle mode. Secondly, the energy management control of the power network can manipulate the engine operating at the optimal engine region. Thirdly, by combining the energy storage device with the energy source, the stored energy can downsize the peak power rating of the energy source, leading to higher efficiency of the energy source at partial load. Fourthly, more mechanical, pneumatic or hydraulic equipments are replaced by their electrical counterparts with higher efficiency [Eki et al., 2007]. Finally, the emerging energy-efficient power sources, such as the thermoelectric generator (TEG) [Eakburanawat and Boonyaroonate, 2006], and the hybridization of multiple sources [Chau and Wong, 2001] can also help to improve the overall efficiency.

2.2 Energy management control

The energy management control is definitely a multi-objective optimization problem since the power networks have multiple energy sources, power distribution parts, and storage devices with different considerations [Van Mierlo, 2000]. The supervisory control strategies and the top-down control method are studied [Pisu and Rizzoni, 2007; Rosario and Luk, 2007].

Generally, the operating points of the engine can be shifted by balancing the power distribution between energy sources, storage devices and loads. In order to avoid operating in the low efficiency and high emission region of the engine, the minimum engine speed control, the minimum engine turn-on time scheme, and the optimal operating region algorithm are investigated widely. As for the battery, the proper state-of-charge needs to be kept at a proper level within the safety voltage, current and temperature. Moreover, the output power and HEV mode changeover can be adjusted according to the geographical information from the navigation device.

3. MAIN COMPONENTS

3.1 Energy sources

The energy sources of the power network in HEVs have the engine for all HEVs, the power grid for the PHEV and E-REV, and new on-board energy sources, such as the TEG and fuel cell stack.

In a typical energy flow path of the ICEV, about 40 % of the fuel combustion energy is wasted in the form of waste heat of exhaust gas [Rowe, 1999]. Benefited from the Seebeck effect, the TEG can directly convert the heat energy to electrical energy. Consequently, the research on waste heat energy recovery of the exhaust gas in HEVs has been actively conducted in recent years [Yu and Chau, 2009]. The TEG has unique advantages of being maintenance free, silent in operation, independent of weather or geography, and involving no moving and complex mechanical parts [Zhang et al., 2008]. However, since the TEG is a non-linear device and its output power characteristics heavily depend on the external physical factors, the maximum power point needs to be tracked in practice [Zhang et al., 2009].

The fuel cell stack can produce power from hydrogen-rich gas without any emissions. Very similar with the TEG, the output characteristics of the fuel cell also depend on the load. So the maximum power point tracking is very essential for fuel cell application. The output voltage generated by a fuel cell stack varies widely and is low in magnitude (< 60 V for a 5-10 kW system, < 350 V for a 300 kW system) [Todorovic et al., 2004].

3.2 Electric machines

The electric machines in HEV drivetrain will act as the energy source in the generator mode, and as the electric load in the motor mode. For a micro hybrid or mild hybrid, the electric machine normally is used as an integrated starter-generator (ISG) instead of a flywheel mounted on the crankshaft between the ICE and transmission. The development of ISG system has been taking an accelerated pace [Walker et al., 2004].

For a micro hybrid, the belt-driven ISG is typically 3-5 kW with the idle stop and some regenerative baking feature. For a mild hybrid, the ISG is typically 7-12 kW with the additional feature of engine downsizing. For the full hybrid, the electric machine is typically 30-50 kW with all hybrid features, including the electric launch feature [Chau and Chan, 2007].

From the selection of electric machines for those commercial HEVs, the Japanese automakers prefer the permanent magnet machine, while the US automakers more like the induction motor [Xu, 1999]. Except the conventional ones, some newly designed motors have also been proposed [Chau et al., 2008].

3.3 Power distribution parts

With a continuously variable transmission (CVT), the ICE can be operated at the optimal efficient operating region at given torque and speed conditions [Delprat et al., 2004]. The CVTs have three categories, namely, mechanical CVT, hydraulic CVT, and electric CVT [Miller et al., 2005]. By exploiting a multi-port power transmission device, the most attractive technology of electronic-CVT (e-CVT) can incorporate the engine and a pair of motors/generators to achieve the optimal engine efficiency and minimum exhaust emissions [Miller, 2006]. Very recently, an e-CVT based on coaxial magnetic gearing has been developed which uses the modulation effect of permanent magnet fields to provide non-contact torque transmission and speed variation [Jian and Chau, 2009].

Power converters are the critical power distribution parts, serving for the motor drive, battery management system and voltage level conversion [Chau et al., 1998]. The bidirectional DC-DC converter and the multi-input converter are the two key technologies [Lai and Nelson, 2007; Liu and Chen, 2007; Solero et al., 2005].

3.4 Energy storage devices

Several energy storage technologies have been developed for HEVs, like flywheels, superconducting energy storage systems and the compressed air systems. Nevertheless, the battery and the ultracapacitor (UC) are commonly incorporated in HEVs due to their compensating characteristics.

Although many types of batteries are commercially available [Rydh and Sanden, 2004], only the lead-acid battery, nickel-metal hydride battery and lithium-ion battery are commonly used in HEVs [Tremblay et al. 2007]. Currently, the battery still needs significantly improvements for higher power density, better temperature performance, larger charge/discharge cycle number, longer lifetime, and lower cost as well. Technically, the modeling, fast charging and state-of-charge estimation are difficult problems [Pascoe and Anbuky, 2003; Piller et al., 2001]. Generally, the power network usually maintains the battery state-of-charge around 65-75 % [Wouk, 1995].

Unlike the battery, the UC has very high power density and almost unlimited charge/discharge cycles, but the energy density is very low. So the UC in the power network plays an auxiliary role. The UC normally provides the desired voltage level by connecting many cells with the 2.5-3.0 V range in series [Shah et al., 2008].

3.5 Loads

The power network in HEVs has to supply different kinds of loads [Krein et al., 1994].

(1) the lighting: the head light, the external light, the internal light, and etc;
(2) the pump and the electromechanical valve control: the water pump, the fuel pump, the oil pump, and etc;
(3) the vehicular control and safety electronics: the anti-lock braking, the electronic stability program, the electrical control unit, and etc;
(4) the drivetrain load: the electric four-wheel drive, the electric power steering, the active suspension, the electrically controlled brake, the throttle actuation, and etc;
(5) the passenger service load: the air-conditioning equipment, the media player, the navigation device, and the small power motors for wipers, windows, sunroof, seats, and etc.

The power demand of the main loads is listed in Table 1 [Chen et al., 2002].

Table 1 Power demand of loads

Loads	Power (W)	
	Initial peak	Average
Headlight	328.8	180.0
External light	645.6	372.0
Internal light	123.6	25.2
Air-conditioning	307.2	141.6
Power steering	590.4	300.0
Other electronics	505.2	240.0
Total	2500.8	1258.8

4. POWERTRAIN ARRANGEMENTS

The power network of HEVs have similar load, but the main powertrains handling with the energy from ICE, battery, and braking regeneration are very different due to different types of HEVs, as shown in Figure 1.

In the ISG based HEV, namely the micro or mild hybrid HEV, the ISG is connected between the ICE and transmission. The ISG will function as the starter when the battery drives the ISG, and as the generator when the ISG charges the battery.

In the PHEV or E-REV, the battery acting as the primary energy source will drive the electric machine denoted 'M/G' and the wheel in short driving range mode. While driving in the long range mode, the ICE will provide the needed power through the generator denoted 'G' to the battery.

In the series HEV, the electric energy is converted from the mechanical movement of the ICE first, and then, is used to propel the wheel.

In the parallel HEV, the engine and the battery can drive the wheel simultaneously. So the torque coupler is needed to connect them to the driveshaft.

In the series-parallel HEV, the mechanical energy can be distributed within the ICE and two electric machines with the power split device like the planetary gear. So, the series-parallel HEV has the features of both the series HEV and the parallel HEV.

In the complex HEV, it can provide the dual axle propulsion and the axle balancing control. The complex HEV has the front-hybrid rear-electric type and the rear-hybrid front-electric type, which show different control performances.

5. VOLTAGE LEVELS

In the 1920s, the earliest power network in automobiles adopts 6 V voltage level, serving for the basic functions such as ignition, cranking and lighting [Emadi et al., 2003]. Then, more and more electronic devices are installed into the vehicle, such as the air conditioner, the safety control system, and other miscellaneous vehicle-borne electronic devices. Furthermore, some previous mechanically, pneumatically or

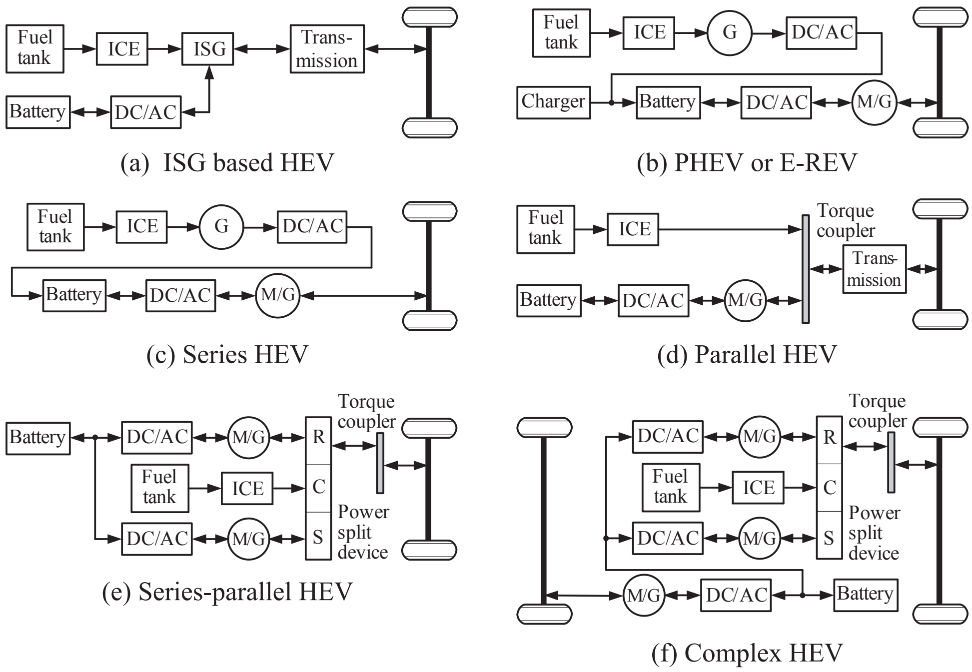

Fig. 1 Powertrain arrangements

hydraulically driven systems are gradually developed to the electrically driven system, such as the steering system and CVT.

Research shows that the electric energy demand of automobile increased from 100 W of the early 1990s to typically about 1 kW by the 1990s, resulting that the voltage level of the power network keeps increasingly from 6 V to 14 V in 1950s, 42 V in 2000s, 300 V or even higher at very recently years [Emadi et al., 2006]. Although the 14 V power network is prevailing in last decades, the 42 V power network, as shown in Figure 2 [Rajashekara, 2003], is widely investigated, considering the tradeoff that the higher voltage level will offer the advantages of the lower output current and smaller wire harness which reduce hardware cost and increase the power network efficiency, and the disadvantage that it potentially increases the dangerousness to passengers, which meets the safety requirement. Moreover, the 42 V power network can be easily connected with the ISG in the micro and mild hybrid HEV [Lee and Cho, 2005]. GM Silverado PU and Saturn Vue have the 42 V power network.

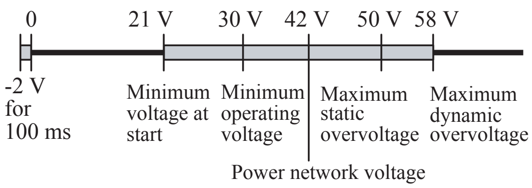

Fig. 2 Typical operating voltage criteria for 42 V power network

In order to be compatible with the current 14 V vehicular devices, the power network with 42 V bus are normally designed as dual 14/42 V voltage [Keim, 2004]. For instance, Toyota Crown is equipped with 14/42 V dual voltage power network.

Recently, more and more automakers put efforts to improve the network voltage attracted with the enormous advantages of higher voltage level network. Honda Civic and Accord has 144 V network. Toyota Prius has boosted its maximum network voltage to 288 V, 500 V, 650 V, respectively, from generation I to II and III. Some prototypes are built even with 800 V - 900 V power networks.

Currently, a multiple voltage level configuration has been developed, that is, the 144 V - 650 V DC bus supplies for the motor drive, the 42 V for the power accessory, and the 14 V, 6 V for the electronic accessory [Miyaki and Mizutani, 2007]. Based on the dual 14/42 V voltage power system architectures [Perreault and Caliskan, 2004], the multiple voltage level architectures are illustrated in Figure 3.

The high voltage DC bus can be obtained by the DC/DC conversion of the high voltage battery, which is assumed as 200 V referencing to the battery voltage of the Toyota Prius. Then, the middle 42 V DC bus has two possible sources, namely, the high voltage DC bus or the high voltage battery. As for the 42 V DC bus and the 14 V DC bus, they may be in cascaded connection, in paralleled connection, or in integrated connection via a dual output DC/DC converter. It should be noted that the 36 V and 12 V batteries are

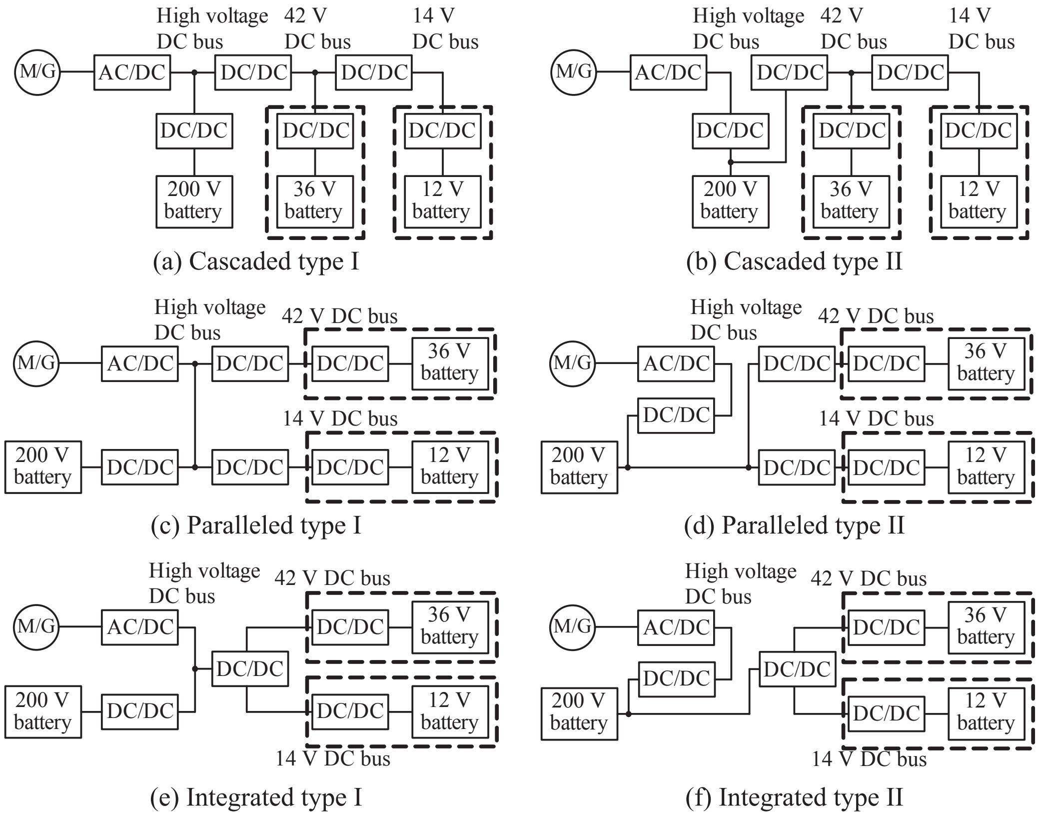

Fig. 3 Multiple voltage level network architectures

not indispensable.

6. CONCLUSION

The power network of HEVs is designed to pursue the high overall efficiency and less emissions under power management control. According to different types of HEVs, the power network has various powertrain arrangements, although having similar main components. With increasing electric load demand, the voltage level of the power network keeps increasing. The multiple voltage level architectures are identified to be promising.

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