Powertrain architectures of electrified vehicles: Review, classification and comparison

Guang Wu, Xing Zhang, Zuomin Dong*

Department of Mechanical Engineering, University of Victoria, Victoria, British Columbia, Canada

Received 25 November 2013; received in revised form 22 April 2014; accepted 26 April 2014
Available online 13 May 2014

Abstract

Increasingly stringent regulations and customers’ demand for high fuel economy led to rapid developments of distinct alternative powertrain solutions, especially electrified vehicles. Fusion of electric machines into powertrain greatly diversifies powertrain architectures and enriches means to save energy. In this review work, conventional classification of hybrid electric vehicle (Series, Parallel and Power-split HEVs) is expanded to all electrified vehicles (xEV) by including Pure Electric Vehicle (PEV) as the fourth primary type of electrified powertrain architecture; In addition, electrification level of powertrain is analyzed and incorporated into new classification method as the second index; different variants of PEV, Series, Parallel and Power-split HEVs are presented with corresponding patents or products; more complex electrified powertrains are also illustrated by decomposing them into two or more of the four fundamental types and sub-types. This review work is based on comprehensive and up-to-date summary of current development in this field.

© 2014 The Franklin Institute. Published by Elsevier Ltd. All rights reserved.

1. Introduction

Environmental concern, fuel efficiency and energy supply security push governments, automotive companies and research institutes to explore environmentally-friendly, efficient and sustainable personal transportation solutions. Fuel consumption and tailpipe emissions have been critical topics in transportation sustainability. It is projected that world petroleum and other liquids supply through 2040 will further increase by 30% on the basis of 2011 due to expected energy demand [1]. As part of response to the energy and environment crisis in transportation

*Corresponding author.
section, researchers around the world are working on a wide range of strategies and techniques to reduce petroleum consumption and cut tailpipe emissions. For example, the 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards will take effect in U.S. from 2017 model year [2]. As shown in Fig. 1, fuel economy requirements for passenger cars and light-duty trucks will be enhanced by about 50% and 35%, respectively [1].

There are a bunch of advanced technologies that help to reduce petroleum consumption and tailpipe emissions. One straightforward approach is to enhance powertrain efficiency and lower vehicle resistance forces. This technical path can be further divided into four major technical categories: engine, transmission, vehicle techniques and hybrid techniques. A comprehensive survey of those techniques can be found in [3]. Hybridization of powertrain is widely considered as a practical and effective solution to remarkably improve ICE efficiency and emissions in near future [1, p. 70] [2, p. 250–260]. Hybrid vehicle (HV) is defined as a vehicle with two or more energy storage system (ESS), both of which must provide propulsion power—either together or independently [4]. Specifically, in addition to conventional fuel tank, the secondary ESS could be flywheel, compressed air tank, battery, ultracapacitor as well as combination of battery-ultracapacitor, as summarized in right-bottom block of Fig. 2 [5–7]. These types of HVs differ from each other greatly from operation principle, performance and FE benefits as well as costs. Those HVs equipped with battery as ESS are in a monopoly position from aspects of both count and type, in comparison with other competitors. Therefore, in this review hybrid vehicle refers only to HVs with battery as ESS.

The second strategy of reducing petroleum consumption is to shift use of petroleum to other energy sources. Various alternative energy sources and corresponding powertrains are summarized at two sides of Fig. 2, according to energy sources, on-board energy and propulsion systems. Primary solutions include flexible-fuel vehicle (FFV) and electrified vehicles. Although flexible-fuel vehicle (FFV) will continue expanding market penetration, vehicle electrification will be the most practical and influential choice in the following decades for a couple of reasons: (a) electric energy is pivotal element for diversification of energy sources, beneficial for energy security; (b) petroleum will continue to be primary fuel of on-land vehicles in decades, so hybridization of vehicle will play a critical role in improving mass-production vehicle efficiency and reducing emissions; and (c) hybrid electric vehicles shown at left-bottom corner of Fig. 2 is intersection of electrification and hybridization approaches, providing a wide range of technical

Fig. 1. Projected average CAFE compliance targets (miles per gallon) by vehicle footprint (square feet), model years 2017–2025 [1]. (a) Passenger car and (b) light-duty truck.
Electrified vehicle, especially hybrid vehicle, combines hybridization and electrification, possessing special potential. Powertrain architecture, which refers to topological relation and energy flow among powertrain components, is another important index of xEV powertrain. Architecture design and selection prior to development of an EV is a critical procedure since powertrain architecture will cast significant influence on future design, control and optimization. However, identifying a desirable architecture in the early stage is a very challenging task. Unlike conventional powertrain, architecture of xEV powertrain refers to more variables (e.g., number of electric machines (EMs), type and count of coupling/switching devices, transmission selection and topological relationship of components). In addition, a specific architecture could operate in different mode by changing states of coupling devices, transmission and EM(s). Furthermore, powertrain architecture interacts with disparate powertrain management strategies, further complicating selection of an appropriate architecture. Many scholars have categorized xEV into Series Hybrid, Parallel Hybrid and Power-split Hybrid, with emphasizes on EM, power electronics or modeling, respectively [5–11]. Nevertheless, with fast progress and diversification of those basic types, conventional framework should be updated and further fractionized to keep pace with latest development. Meanwhile, electrification level, which has great impact on architecture design and selection, breaks up electrified vehicle into five categories of hybrid vehicle (micro HEV, mild HEV and strong HEV, Plug-in Hybrid Electric Vehicle (PHEV), Extended Range Electric Vehicle (ER-EV)), PEV and Fuel Cell Electric Vehicle (FCEV), as shown in Fig. 2. A number of architectures are not suitable for all levels of electrification. Hence, it should be a helpful work for architecture selection and design to categorize xEV architectures systematically, based on comprehensive review of various architectures with electrification levels in consideration. To keep pace with advances of xEV field, this review work enriches and subdivides conventional classification framework further, with inclusion of PEV and consideration of electrification level. Please note that FCEV, whose architectures are essentially interchangeable with PEV and not closely related to hybrid vehicle, is excluded in this review work.
The purposes of this research work include three parts: (a) offering an extensive overview of xEV powertrain architectures, especially those with promising application potentials; (b) providing a systematic classification based on electrification level and one set of fundamental architectures; and (c) comparing different architectures. In Section 2, xEVs with different electrification levels are analyzed. In Section 3, various PEV architectures are reviewed and compared. In Section 4, fundamental hybrid vehicle powertrain architectures are identified and analyzed. In Section 5, compound hybrid vehicle architectures analyzed based on PEV architectures and fundamental HEV architectures. Results and conclusions are include in Section 6.

2. Relationship among xEVs with different level of electrification

Electrification level that is normally indicated by battery voltage, stored energy and power determines capacity of electric path and constrains energy-saving “tools” of each xEV. Table 1 lists primary features and efficiency-enhancing capabilities of six xEVs of different electrification levels. Micro HEV is the simplest and most economic hybrid solution, with only 12 V stop–start function that can turn off engine or cut off fuel supply during idling time and restart it immediately after Vehicle Central Controller (VCC) detects driver's intention to launch vehicle; mild HEV has higher voltage and more powertrain EM. Compared to micro HEV, mild HEV can also provide limited power-assist capability and even possible regenerative braking (RB) capability. Representative mild HEVs are GM Chevrolet Malibu with eAssist system and HONDA Insight with Integrated Motor Assist (IMA) system. The eAssist system substitutes conventional starter with a Belted Alternator Starter (BAS) to minimize changes to engine, while the IMA system removes conventional starter and installs a disk motor between flywheel and transmission that can start and boost engine. Strong HEV (or full HEV) can run like a PEV at low speed (even medium speed as accelerator pedal pressed gently) and has stronger power-assist capability and RB capability. Since boundary between mild HEV and strong HEV is rather dim, the evaluation criteria used for mild and strong hybrid full-size pickup are borrowed, where the recovered energy by regenerative braking during deceleration over the Federal Test Procedure is at least 15% and 65%, respectively [2, p. 534]. Toyota Prius and Ford Escape are the well-known strong HEV passenger car and SUV, respectively. One important reason for mild HEV and strong HEV achieving lower fuel consumption is smaller engine volume than counterpart ICE vehicle. All the three electrification levels discussed above achieve higher powertrain efficiency by enhancing ICE efficiency, exclusively via the first strategy.

With comparison to the three hybrid vehicle without charger, another three types of electrified vehicles (PHEV, ER-EV and PEV) have bigger and more powerful battery package with

<table>
<thead>
<tr>
<th></th>
<th>Micro HEV</th>
<th>Mild HEV</th>
<th>Strong/full HEV</th>
<th>PHEV</th>
<th>ER-EV</th>
<th>PEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idle-stop</td>
<td>◎</td>
<td>◎</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Power assist</td>
<td>○</td>
<td>○</td>
<td>◎</td>
<td>◎</td>
<td>○</td>
<td>-</td>
</tr>
<tr>
<td>RB</td>
<td>○</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
</tr>
<tr>
<td>PEV driving</td>
<td>○</td>
<td>◎</td>
<td>○</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
</tr>
<tr>
<td>Charger</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
</tr>
<tr>
<td>Voltage</td>
<td>12</td>
<td>48+</td>
<td>300+</td>
<td>300+</td>
<td>300+</td>
<td>300+</td>
</tr>
<tr>
<td>Effectiveness (%)</td>
<td>2–4</td>
<td>8–11</td>
<td>20–35</td>
<td>50–60</td>
<td>&gt; 60</td>
<td>&gt; 60</td>
</tr>
</tbody>
</table>

◎: full capacity; ◎: partial capacity; -: inapplicable.
normally over 300 V voltage to store electric energy from grid system [12]. PHEV generally supports PEV driving around 20 km, like Honda Accord Hybrid and Plug-in version of Toyota Prius. PHEV can realize a noticeable reduction of fossil fuel consumption by shifting one portion of energy usage to electric energy. Still, due to power limit of electric system, ICE will be often turned on in the process of harsh acceleration or climbing slope even if energy in battery can still allow driving in PEV mode. ER-EV is invented by GM for its Chevrolet Volt to emphasize its full-performance, all-electric capability. ER-EV is essentially one PEV with ICE as backup energy source, and can remarkably further reduces gasoline consumption and reduces engine cold starts due to bigger and more powerful battery [12]. PEV is exclusively by EM(s) that is powered by electric energy in battery. Current mass-production PEVs include Mitsubishi i-MiEV and Tesla Model S et al. [13]. Generally higher electrification level can lead to bigger fuel economy benefits. Due to lack of enough reliable data and argument about practical effectiveness of each electrification level, only some reference ranges of effectiveness are listed in Table 1 [3].

3. PEV powertrain architectures

Different PEV powertrain architectures can be classified by locations and number of EM(s), type of transmission, number of transmission gears et al. Here, three primary PEV architectures are analyzed and compared.

3.1. Type-a: PEV with one EM and no transmission

This is the simplest layout and widely employed by almost all PEVs on market. This type of PEV architecture is relatively similar to conventional vehicle except absence of clutch and transmission. Battery powers EM to output torque to differential via one-speed reduction gear. Propulsion motor, main reduction gear and differential are often merged into a compact package to reduce vehicle weight and installation space. The schematic expression of this architecture and representative Nissan Leaf powertrain is shown in Fig. 3.

\[
P_{\text{prop}} = V_{\text{bat}}i_{\text{bat}}\eta_{\text{bat}}\eta_{\text{inv}}\eta_{\text{m}}\eta_{\text{fd}}\eta_{\text{w}}
\]

where \(P_{\text{prop}}\), \(V_{\text{bat}}\), \(i_{\text{bat}}\), \(\eta_{\text{bat}}\), \(\eta_{\text{inv}}\), \(\eta_{\text{m}}\), \(\eta_{\text{fd}}\) and \(\eta_{\text{w}}\) indicate propulsion power, battery voltage, current, battery efficiency, inverter efficiency, motor efficiency, final drive efficiency and wheel efficiency respectively.

Several advantages of EM over ICE are key reasons, as shown in Fig. 4, enabling this simple architecture: (a) larger speed range of EM enables this type of PEV to reach high speed without...
help of additional higher gears; (b) huge torque output at low speed allows the PEV to accelerate fast enough without lower gears for torque amplification; (c) EM has capacity to launch vehicle at zero speed, while ICE has to run at idle speed (about 800 rpm) to launch vehicle with assistance of clutch or torque converter (TC); (d) in comparison with ICE, efficiency of EM can be more than 85% and efficiency map within whole operating zone is quite flat, compared to that of ICE. Therefore, the first two features enable one-speed PEV to achieve high speed and harsh acceleration at low speed; the third advantages makes it possible to eliminate coupling devices from powertrain for vehicle launching; the last feature determines that PEV can achieve desirable fuel economy (FE) at different scenarios without multiple gear ratios.

This architecture possesses a series of apparent advantages. It simple layout is beneficial for reducing installation space and weight lighting; the single-speed reduction gear should be more cost-effective than variable-gear transmission; driveline loss can be further reduced as fewer gear pairs and absence of hydraulic components; control of gear shifts and related drivability problems are totally eliminated. Admittedly, this architecture is not really perfect. The single-speed reduction gear cannot avoid an apparent efficiency drop as EM is operating near boundary of the efficiency map (very low or high speed, low torque output); EM can only output a portion of its maximum power at low speed, which reversely increases EM size and costs.

3.2. Type-b: PEV with one EM and multiple-speed gearbox

Type-b PEV architecture is improved on the basis of type-a by inserting a multiple-speed gearbox between EM and differential, as shown in Fig. 5. The added gearbox, which helps to overcome those shortcomings of type-a PEV, makes type-b architecture more like a conventional vehicle except without coupling device. Generally speaking, number of this gearbox does not
exceed four. According to previous research, the added gear ratio could increase FE by 2–5%, depending on driving cycles and vehicles [15,16].

This PEV architecture can be realized in various forms. Three representative two-speed gearboxes – one parallel-shaft gearbox and two planetary gearboxes – are shown in Fig. 6. The most straightforward idea is to convert manual gearbox, as shown in Fig. 6(a). Torque from EM is amplified by speed reducer assembly, which is a sleeve gear idly mounted on output shaft. The synchronizer assembly can be shifted to mesh with either left or right gear to produce high and low gears. Considering that manual gearbox is most economic and efficient one, this design will not apparently increase frictional loss and costs [15]. On the other hand, torque gap and vehicle jerk during gearshifts may deteriorate driver's comfort. Therefore, PEV with frictional automatic transmission (AT) gearbox should be able to achieve better comfortability. Key component of this planetary gearbox is a couple of planetary gear sets (PGSs). A PGS consists of sun gear, ring gear, carrier gear and a set of pinion gears, as shown in Fig. 6(b). The relationship among three ports (sun gear, ring gear and carrier gear) of planetary gear set (PGS) is expressed mathematically by formula 1–3, whose linearity can be represented by level diagram, as shown in Fig. 6(b) [17–19].

This PGS is also key element of power-split hybrid architectures introduced in Section 4. Fig. 6(c) and (d) are two typical PEV architectures with two-speed planetary gearbox. The second planetary gear sets (PGSs) in both planetary gearboxes always serve as a reduction gear and states of brake 1 (BR1) and BR2 determined engaged gear. Specifically, as BR1 is engaged and BR2 is open, all gears of first planetary gear set (PGS) rotate with identical speed and high gear is selected; conversely, BR2 locks ring gear of first PGS and rotation speed of carrier gear is slower than EM.

\[
\frac{\omega_i}{R_s + R_r} + \frac{\omega_r}{R_s + R_r} = \omega_c
\]

(2)

Fig. 6. Representative architectures PEV with two-speed gearbox. (a) Parallel-shaft gearbox [20], (b) Level diagram of PGS, (c) Planetary gearbox 1 [16] and (d) Planetary gearbox 2 [21].
\[
\frac{R_s + R_f}{R_s} T_s = T_c 
\]

\[
\frac{R_s + R_r}{R_r} T_r = T_c 
\]

where \( \omega_s, \omega_r, \omega_c \) are rotation speeds of sun gear, ring gear and carrier respectively; \( R_s, R_r, R_s \) are radii of the three gears correspondingly.

3.3. Type-c: PEV architecture with more than one EM

This is a comprehensive group that covers different architectures with two or more EMs. Four mainstream architectures of PEV with two or more EMs are shown in Fig. 7.

PEV with two EMs mounted front and rear axle is described as Fig. 7(a). This architecture type is a flexible one. It allows vehicle to run in rear-wheel-drive (RWD), front-wheel-drive (FWD) and AWD modes based on states of EM1 and 2. In addition, RWD and FWD can be controlled to be active at different speed zone, which produces actual 2-speed transmission. When power or torque demand is more capability of single EM, AWD mode can be activated. Fig. 7(b) shows PEV architecture with two identical EMs but without transmission nor differential [22]. Equal torques from EM1 and EM2 are sent to left and right wheels directly when vehicle is running along straight line. As wheels are to be steered, controller (not shown) will coordinate torque outputs of two EMs to produce speed difference between two driving wheels. A similar PEV architecture without neither transmission nor differential is like Fig. 6(d). Four “pancake” hub-in wheels drive corresponding wheel. This design can free up packaging space and spare more space for battery package, cargo and passengers. Another advantage is its operation flexibility: FWD, RWD and AWD all possible. Meanwhile, limited installation space for those EMs determines strict requirement for EM size. Pretean Electric Ltd. built a

Fig. 7. Representative PEV architectures with two or more Ems.
demonstration car based on Mercedes-Benz E-class [23]. Fig. 7(c) shows a torque-coupling PEV architecture with two EMs that are connected to sun gear and ring gear of PGS. One additional clutch (not shown) can also be added to reduce one degree of freedom of the PGS, then the two EMs can propel vehicle via different but fixed gear ratios. No PEV with this architecture has been found by authors, but it is embodied in GM Chevrolet Volt as one PEV-driving mode. More details will be discussed below.

4. Basic architectures of hybrid vehicle

Classification of architectures of hybrid electric vehicle is more complex than PEV because hybrid vehicles refer to ICE, EM(s), coupling device(s), transmission as well as their locations. There are a huge number of architectures for HEVs, PHEV and ER-EV. The mainstream classification method is to categorize those architectures into series, parallel and power-split architectures. This classification frame provides key insights to how to distinguish different architectures, while newly-emerging variants of each major group demands more specific and systematic classification method with consideration of electrification level. In addition, the conventional method takes limited consideration of more advanced multiple-mode xEV architectures that can work in PEV mode(s) and/or more than one basic hybrid modes. In this section, classification of fundamental HEVs will adhere to the same frame but more different variants of each major group will be analyzed; primary multiple-mode HEV architectures will be discussed in next section.

4.1. Series hybrid architectures

A series hybrid, often applied on locomotives, generally consists of a gasoline or diesel engine, an electric generator (EM1) and motor (EM2), energy storage system (ESS) and VCC et al. Series HEV has different layouts, some of which are illustrated graphically in Fig. 8. The engine-generator assembly converts chemical energy of petroleum into electric energy that is further sent to traction motor to produce mechanical power to propel vehicle. A general power flow formula is shown in Eq. (5).

\[ P_{\text{prop}} = (P_{\text{eng}} \eta_{m1} + P_{\text{bat}} \eta_{\text{inv}} \eta_{m2} \eta_{dl} \eta_{w}) \]

where \( P_{\text{prop}}, P_{\text{eng}}, P_{\text{bat}}, i_{\text{bat}}, \eta_{\text{bat}}, \eta_{m1}, \eta_{\text{inv}}, \eta_{m2}, \eta_{dl} \) and \( \eta_{w} \) are propulsion power, engine output power, battery power, efficiencies of battery, EM1, inverter, EM2, driveline and wheel respectively. For more information about power flows in various operation cases, like regenerative braking and charging battery during ideling time, many references are available.

Those architectures can also be modified by replacing EM2 and differential with two or four in-wheel motors, analogous to Fig. 7(d).

Fig. 8. Series HEV architectures. (a) Front-engine rear-drive, (b) Rear-engine rear-drive and (c) Front-engine front drive.
Series HEV is advantageous in many aspects over other HEV architectures. For example, no mechanical path between the engine and the wheels enables ICE to operate at peak-efficiency zone and reduce fuel consumption, even if during busy traffic time; absence of mechanical connection also greatly releases constraint of installation space; huge traction torque of EM2 allows Series HEV to provide outstanding towing capacity at low speed, very suitable for mining truck; during deceleration stage, powerful traction motor EM2 switches to a generator state, recapturing more kinematic energy via regenerative braking; compared with parallel and power-split hybrid vehicles, Series HEV can be well managed using a relatively simple control system; However, a series of shortcomings hinder wide acceptance of series hybrid powertrain: (1) multiple energy conversions reduce overall efficiency of Series HEV, especially when vehicle is at high speed; (2) EM2 is the only direct power source, which means EM2 and electronics should meet maximum power demand, increasing costs, weight and installation space; and (3) the power of engine is unable to provide direct torque while electrical units fails or torque demand is beyond capability of EM2. All these characteristics decide that Series HEV is primarily used on city bus that experiences frequent start-stop, idling, deceleration and acceleration [11]. In 1999 GM launched the series version of EV1, which is powered by a gas turbine engine and a high-speed permanent-magnet AC generator. In 2006, PML Flightlink demonstrated an in-wheel electric motor for cars called the Hi-Pa Drive based on a Mini dubbed the “Mini QED” [24].

From aspect of electrification level, Series architecture is not only feasible for Strong HEV but also for PHEV and ER-EV thanks to inherent powerful electric system. For example, Fisker Automotive delivered Fisker Karma – the first and only one Series PHEV so far [25]; Series HEV is an operation mode of the unique ER-EV, Chevrolet Volt [16]; another landmark hybrid vehicle with Series architecture is 2014 Honda Accord Hybrid, which includes HEV version and PHEV version [26,27]. More details about architectures of Volta and Accord Hybrid will be discussed in Section 5.

### 4.2. Parallel hybrid architectures

Parallel hybrid powertrain means that engine and electric motor are connected with fixed speed ratio to provide driving torque to wheel, separately or together. EM can work as an engine booster or generator to optimize efficiency of ICE, according battery state and working load. Parallel hybrid architecture is mainly composed of ICE, EM, transmission, coupling device, battery package and VCC. One important variable of Parallel xEV architectures is location of EM relative to other components. Fig. 9 depicts a representative powertrain architecture that is adopted in most conventional Front-Wheel-Drive (FD) or Rear-Wheel-Drive (RD) vehicles. C, D and Trans stand for clutch, differential and transmission, respectively. Transmission could be any of manual transmission (MT), AT, dual-clutch transmission (DCT) and continuously variable

![Fig. 9. Possible location for EM in parallel architectures. (a) Representative RWD powertrain [28] and (b) Schematic overview of powertrain.](image-url)
transmission (CVT). The clutch may be replaced by torque converter if AT or CVT is selected. Unlike series HEV or power-split HEV, Parallel HEV requires engine to be rigidly linked to wheel. Those numbers within circles indicate possible positions where EM could be mounted to formulate a Parallel HEV. There are a lot of means to merge two torque paths, but those details are not focus of this work and not introduced separately. According location of merging point of torques from ICE and EM, five different parallel architectures can be derived from the basic architecture, as shown in Fig. 10. It should be emphasized that some variants that will be illustrated later do not belong to any of the five categories. One general formula used to calculate merged torques from ICE and EM is shown in Eq. (6).

\[
T_{prop} = T_{eng}i_{eng} \eta_{d1} \eta_w + T_m i_m \eta_{d2} \eta_w
\]

where \(T_{prop}\) is practical propulsion torque, \(T_{eng}\) and \(T_m\) are torques from ICE and EM, \(i_{eng}\) and \(i_m\) are overall gear ratios from ICE and EM to wheels, \(\eta_{d1}\) and \(\eta_{d2}\) are overall driveline efficiencies for ICE and EM, \(\eta_w\) is wheel efficiency. It can be seen that Parallel hybrid vehicles need less energy conversions than Series hybrid vehicles.

A summary of relationship among those architectures is shown in Table 2. It is clear that none of the five parallel architectures is applicable to all electrification levels. Type a and b can only operate in hybrid mode, like a regular parallel HEV; the remaining three types enable vehicle to operate in PEV mode by disengaging clutch and to operate in hybrid mode. More detailed comparisons are followed.

<table>
<thead>
<tr>
<th>Type-a</th>
<th>Micro HEV</th>
<th>Mild HEV</th>
<th>Strong HEV</th>
<th>PHEV</th>
<th>ER-EV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-b</td>
<td>◎</td>
<td>◎</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type-c</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td></td>
<td>◎</td>
</tr>
<tr>
<td>Type-d</td>
<td>◎</td>
<td></td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
</tr>
<tr>
<td>Type-e</td>
<td>◎</td>
<td></td>
<td></td>
<td>◎</td>
<td>◎</td>
</tr>
</tbody>
</table>

Fig. 10. Parallel hybrid architectures. (a) type-a parallel architecture, (b) type-b parallel architecture, (c) type-c parallel architecture, (d) type-d parallel architecture and (e) type-e parallel architecture.
4.2.1. Type-a parallel architecture

This type is suitable for both micro HEV and mild HEV. Compared to other architectures, this one is the most cost-effective parallel hybrid with limited changes to conventional powertrain platform. For micro HEV application, regular starter will be replaced by an EM with power of 3–5 kW; engine control unit (ECU) together with built-in control algorithm and pedal sensors should be able to detect driver's intention and launch engine fast and smooth. This feature is one economic and effective approach to save fuel for urban vehicles. For mild HEV application, the EM of power typically 7–12 kW can also provide power assist to ICE and modest regenerative braking [29]. In addition, the EM can assist ICE by extracting power from battery when load is light or charging battery under heavy load, improving ICE efficiency. Belted alternator starter (BAS) of GM is a representative mild HEV of this architecture; the more powerful second-generation BAS, eAssist, has been used on 2013 Malibu and 2012 Buick Regal [30]. Since ICE needs to keep rotate with EM all the time, this architecture is not suitable for PEV driving due to undesirable ICE friction torque.

4.2.2. Type-b parallel architecture

This architecture requires EM to be mounted within narrow space between engine flywheel and transmission/coupling device. This architecture shares common energy-saving capabilities with type-a parallel architecture and cannot propel vehicle in PEV driving mode with ICE static, either. One typical implementation of this architecture Honda Integrated Motor Assist (IMA) system, with a “pancake” motor mounted on flywheel. Details about IMA can be found in related patents [31]. Since this architecture is more costly than type-a architecture and compatible with one electrification, Honda is the only one major manufacturer producing it until now. According to joint technical support document, this architecture is not listed as promising solution due to its high costs [3].

4.2.3. Type-c parallel architecture

This hybrid, often named as pre-transmission (P2) parallel hybrid can be used to mild HEV, strong HEV, PHEV and ER-EV. When power demand is low, EM can support PEV driving up to dozens of mph. Since the EM can be isolated from ICE by a clutch, xEVs of this type can operate in PEV driving without wasting torque against ICE friction. As power demand is beyond capacity of electric system or battery State of Charge (SOC) drops below pre-defined threshold value, engine will be ignited and clutch engaged gradually. During the mode transition, EM may play the roles of traction motor and starter via controlled clutch friction at the same time, depending on whether a separate starter is available [32]. Stronger capacity for regenerative braking due to more powerful electric system also contributes to cut fuel consumption.

It appears that P2 hybrid is a very promising architecture thanks to its balance in costs, size, energy-saving potential and operation flexibility. This architecture actually is primarily realized via transmission hybridization by combining EM into different type of transmissions [33–35]. A lot of OEMs and transmission suppliers are working on developments of hybrid transmissions. Primary transmission choices include AT, DCT and CVT. Representative models with hybridized versions of three transmissions include Volkswagen Jetta Hybrid, Accura RLX Sport Hybrid and Nissan Pathfinder Hybrid [13,36,37]. On the other hand, this architecture requires more changes to conventional powertrain and accessory units: (1) since the EM can support PEV driving, battery package should have more powerful and bigger than counterparts in aforementioned two types; (2) the EM is generally incorporated into transmission as one sub-system of hybrid transmission to reduce installation space, so one key issue from aspect of architecture is the mechanical design combing EM and transmission within limited space; and (3) some accessory units, like air conditioner and power steering system, should be modified to work normally in PEV driving mode since ICE does not rotate.
4.2.4. Type-d parallel architecture

This post-transmission architecture often shares many features with P2. For example, this parallel architecture should also be possible for up to four xEVs; PEV driving without rotating ICE is allowed as long as power and energy demands are met. The biggest difference between pre- and post-transmission Parallel hybrid is that this architecture requires EM to be linked to wheels via a fixed gear ratio. Absence of transmission between EM and wheel allows continuous power output. This feature provides a path to use efficient and economic automated manual transmission (AMT), which suffers from torque gap during gearshift, by filling torque gap from engine during gearshift. That torque-gap-filler concept is explained in Fig. 11. Although AMT option could further enhance efficiency and potentially lower costs, fixed gear ratio between EM and wheel does bring disadvantages: (1) EM must have a wide speed range to reach top vehicle speed; (2) EM power output at low speed is constrained; and (3) fuel economy in PEV mode is constrained since operating point of EM is totally determined by vehicle speed. Many innovative invention and even prototypes are presented to add additional gear ratios and maintain torque-gap-filler function, which will be discussed in more detail in Section 4.2.6.

4.2.5. Type-e parallel architecture

Type-e is the AWD version of P1 parallel vehicle architecture. Compared to P1 and P2 parallel architectures, this type can maintain conventional powertrain architecture except the added traction motor system mounted at rear axle. In addition to more driving modes, this type also allows more installation space for EM and controller [38].

4.2.6. Parallel architecture with dual transmissions

One inherent feature of all of the five types listed in Fig. 10 is lack of separate transmission for EM. There are other parallel architectures that are not converted from the conventional architecture, as shown in Fig. 12. The two new architectures can be thought as further development of type-d and type-e architectures with separate transmission for EM. Therefore, these two architectures are able to operate like type-d and type-e parallel hybrid vehicles.

Further development of two separate transmissions for ICE and EM is fusion of the two transmissions, especially when one or two of the transmissions are AMT. Related to hybrid versions of AT, DCT and CVT, this type of hybrid transmission includes two sub-transmissions and is featured by three connecting ports for ICE, EM and final drive, respectively, as shown in Fig. 13. Actually, this architecture can be seen as mix of type-c and type-d parallel architectures.

As kernel component of this kind of architecture, two three-port hybrid transmissions from Oerlikon Graziano and FEV are shown in Figs. 14 and 15 [39,40]. It should be noted that there are more parallel architectures not covered in this review, partly due to their uncommon structures. The key to achieve continuous torque output and smooth gearshifts from both ICE and

![Fig. 11. Torque gap filler principle.](image-url)
EM is to guarantee that there is at least one torque path to wheel anytime. More details about the two hybrid transmissions are available in patent documents [40,41].

4.3. Power-split hybrid architectures

Power-split hybrid powertrain consists of power-split device (PSD), an ICE, two EMs, ESS and VCC. Power-split architectures is a compromise between series and parallel hybrid to possess advantages of both series and parallel hybrid [14]. Engine torque is split into two parts
by, which are delivered to output shaft via efficient mechanical path and less efficient electric path. PGS has two important features: (1) rotation speeds of three ports (sun gear, ring gear and carrier gear) are only subject to Eq. (1), so rotation of ICE can be controlled to operate within peak-efficiency zone and (2) torques into three ports of PSG should be proportional to each other, as shown in Eqs. (2)–(3), so EMs should have big output torques and power-split hybrid architectures are not fitting for micro HEV and mild HEV, unlike parallel hybrid architectures. Since ICE can always operate efficiently, power-split xEVs can reach remarkable FE improvement and currently dominate hybrid vehicle sector. However, this type of powertrain also suffers from limitations of PSG. For example, the ratio of power via two paths relies heavily upon vehicle speed, so power-split hybrid vehicles are efficient only within a certain speed range, otherwise, overall efficiency will be lowered apparently by multiple energy conversion [18,43,44]; power-split architectures require ICE and EMs are bonded together by PSD, which limits flexibility of layout; compared to parallel hybrid architectures, this type is generally more expensive; torque constraints can limit towing capacity and acceleration.

There are a lot of power-split architectures. Three fundamental power-split xEV architectures are input-split, output-split and compound-split architectures [18]. More complicated power-split can be generated from the three fundamental architectures. Input-split architecture requires ICE, EM1 and 2 are connected to three ports of PSD and output shaft is connected with one of EM1 and 2, as shown in Fig. 16(a); Output-split architecture requires ICE, one EM and output shaft are connected to three ports of PGS and the second EM is linked to ICE fixedly, as shown in Fig. 16(b) [29]; compound-split architecture is more complex since compound PSD contains two interconnected PGSs, which are bonded by two compound branches inside PSD. The remaining
four ports (two single ports and two compound ports) are linked to ICE, EM1 and 2 and output shaft, respectively, as shown in Fig. 16(c). For any basic power-split architecture type, a number of variants can be generated by changing locations of ICE and EMs and replacing PSD. Different power-split architectures of the same group are not essentially different. Here, only a tiny portion of architectures in each group are listed to reveal features that identify different power-split architectures. From a broad perspective, the assembly of PSD and motors connects ICE and differential to explore potential of ICE in efficiency and torque output, so this assembly is also called hybrid transmission [45].

Architecture of input-split hybrid is the most popular power-split one since it is the only one suitable for full-range single mode hybrid system within the three basic power-split architectures [18]. Many researchers have conducted related theoretical analysis and simulation about efficiency of power-split hybrid [46,47]. Toyota Prius and Ford Escape Hybrid are representative passenger car and SUV of this type. Fig. 17 summarizes architectures of important input-split hybrid vehicle on market. The Toyota hybrid system has experienced three generation, as shown sequentially in Fig. 17(a)–(c). The first generation, also called THS, was initially applied on Prius. The second and third generations, named as Hybrid Synergy Drive (HSD), share basic input-split architecture of THS, but additional PGS as torque multiplier is added to enhance efficiency at high speed. Ford Hybrid System (FHS), shown in Fig. 17(d), is quite similar to THS and HSD, but the EM2 torque is sent to wheel via gear pairs, rather PGS-based torque multiplier.

Compound PSD for compound-split hybrid vehicles is also possible to fit for input-split hybrid architectures. Fig. 17(e) presents an input-split architecture with compound-split PSD. Although the compound PSD generally contains four ports, one compound port can be left unconnected and other three ports are connected with ICE, two EMs as input-split structure. Actually, this input-split architecture is adopted by GM 2-mode hybrid system [48,49].

Fig. 17. Representative input-split architectures.
Compared to input-split hybrid architectures, output-split architectures have different efficiency characteristics. Two representative output-split architectures are listed in Fig. 18. To some extent, output-split hybrid architectures are similar to two-motor EV in Fig. 7(c). In low-speed range, output-split hybrid vehicle is less efficient due to inner power cycle. However, as output speed increases, efficiency will be enhanced as power through electric path is decreased until output shaft speed reaches node point, where all power is transmitted through mechanical path. If output speed continues to increase, loss on electric path will increase, impacting overall efficiency. This type of architecture is not suitable for single-mode hybrid vehicle, but it can be used as a sub mode on multiple-mode hybrid vehicles [18]. The only available xEV on market with output-split architecture is GM Chevrolet Volt, which will be introduced in more detail latter [16]. Compound-split PSD is also applicable for this power-split hybrid type by leaving one compound port unconnected and the other three port coupled with ICE, two EMs and output shaft in out-split pattern.

Compound-split transmissions have two PSDs, which are connected fixedly to reduce 2 DOF. So, compound-split hybrid system has also two DOFs to control. Compound-split transmissions can provide two node points and achieve high efficiency between the two node points. Another advantage of this architecture is that less torques from EMs are required. Limitation of this type includes more complicated structure and low system efficiency at low speed. A representative architecture is listed in Fig. 19.

**5. Architectures of compound hybrid architectures**

Compound xEVs are those capable of operating in more than one basic hybrid modes. Theoretically, compound architectures can be flexible enough to operate in all operating modes in a single architecture, but the excessive complexity of architectures and related costs will eventually counterbalance benefits from additional flexibility. Additionally, some combinations are not profitable due to overlap of advantages. Therefore, only a tiny portion of combinations of basic architecture are practical. In this review work, four types of compound xEV architectures, which are Series/Parallel, Series/power-split, Parallel-Parallel, Parallel xEVs
and GM's two-mode hybrid system, are analyzed to demonstrate how to decompose compound architectures from perspective of basic PEV and hybrid architectures.

5.1. Series-parallel xEV architectures

This type of xEVs inherits two-motor hybrid system from series xEV architectures and incorporates a new coupling device and transmission to deliver ICE torque to wheels mechanically. SP-xEV architectures can operate in series mode or parallel mode or blend of two modes according to traffic environment and driver's demand, overcoming limitations of basic series or parallel hybrid vehicles. With direct torque from ICE, requirement for electric system can be decreased. In comparison to power-split hybrid architectures, series-parallel architectures are more flexible and controllable in ratio of power distribution, operation modes and powertrain layout.

Fig. 9 is reused here to identify possible series-parallel xEV architectures. EM1 should be linked to ICE to form ICE-generator assembly, and EM2 needs to be connected to differential directly or via transmission. Hence, positions 1–3 are possible for EM1 (main generator), and EM2 (main motor) can be mounted at positions 3–5. Eight basic architectures with two EMs are summarized in Table 3. Each architecture is different from others. For example, the first row belongs to pre-transmission SP-xEVs and allows for multi-speed PEV driving mode; the last two rows are post-transmission SP-xEVs; the second and third rows are different for that the second row is FWD powertrain, while the last row is AWD; in the first and second columns, conventional starter is replaced by more powerful starter-generator with additional functions of generator and engine booster; The third column allows EM1 to propel vehicle and absorb kinetic energy during deceleration without engaging engine. Actually, each architecture can also be seen as blend of two basic parallel architectures. For example, the 1st one combines type-a and type-c parallel architectures, and the 8th one combines type-c and type-e architectures.
The eight basic SP-xEV architectures share fundamental principle, so only the 6th architecture is illustrated in detail. This architecture is adopted for Ecocar 2 competition car of University of Victoria. When ICE is not turned on and clutch is open or transmission at neutral gear, EM2 propels vehicle exclusively in PEV mode; as ICE is launched by EM1 but clutch keeps open, ICE-EM1 works together to generate electricity to support EMS, which is series mode; when VCC commands ICE to transmit torque directly to differential, both clutch and transmission will be engaged and battery can be charged or discharged; ICE-driving mode is actually a special case of parallel mode with two EMs rotating freely with wheels Figs. 20 and 21.

Many institutions and manufactures have launched related research toward a specific architecture. Hyundai Sonata has the 1st architecture of Table 3; the 2nd architecture is further development of Honda IMA system used on Insight [50]. Ohio State University developed a hybrid powertrain with the 7th architecture for Challenge-X competition sponsored by General Motors and United States Department of Energy in 2008 [51]; Shanghai Jiao tong University from China researched a Series-Parallel Hybrid Electric Bus with the 4th architecture [52]; NISSAN HINO is a hybrid powertrain with the 1st architecture [53]. Other types of SP-xEV architectures can be obtained on the basis of these eight architectures. For example, Honda patented one architecture that is modified from 5th one by adding the second clutch between EM2 and differential [54,55]. Another important method to expand SP-xEV architectures is to change the coupling device. For example, conventional disk-type clutch can be changed to one PGS, with ICE-generator assembly connects to one port and traction motor to the second port. By control DOF of PGS via clutch or brake, ICE-generator assembly can be connected to or isolated from road [56]. 2014 Honda Accord Hybrid employs a special architecture that can be derived from any of the first four SP-xEV architectures in Table 3 [57,58]. The major highlight of this design is absence of mechanical or hydraulic transmission. The EM1–EM2 combination in series mode is considered as electric CVT connecting ICE and differential; in parallel mode the ICE provides torque with two EMs to differential via drive shaft. The prerequisite of this idea is that two EMs are powerful enough to meet torque and power demands without torque from ICE.

![Fig. 20. Operation modes of 6th SP-xEV architecture. (a) PEV mode, (b) Series mode, (c) Parallel mode and (d) ICE-driving mode.](image)
5.2. Compound architecture involving power-split architectures

Power-split hybrid architectures can be converted to multiple-mode architectures by adding extra clutches and brakes or employing compound-split PSD. Since power-split architectures include two powerful EMs, multiple-mode hybrid vehicles with series and one power-split hybrid mode is reasonable; compound-split PSD can be used for input-split and output-split hybrid vehicles, so it is natural to develop compound hybrid vehicles with multiple power-split hybrid modes; parallel hybrid architectures need less motors than power-split architectures, so the multiple-mode hybrid vehicles with parallel hybrid mode(s) and power-split hybrid mode(s) are quite possible technically. This part will decompose two compound hybrid vehicles into basic hybrid architectures and PEV architectures.

5.2.1. Chevrolet Volt – PEV and series and output-split

Volt is the first and only one ER-EV with 40 miles of PEV driving distance. Volt can work like a PEV in either first or second PEV mode without turning on ICE as long as battery SOC is
above threshold value. The schematic architecture of Volt is shown in Fig. 22(a) [59]. By locking brake (B) and unlocking two clutches, C1 and C2, EM2 provides torque to output shaft exclusively; transition from first to second PEV mode is achieved by unlocking brake and locking C2, as shown in Fig. 22(c). As long as EM(s) is not able to support PEV drive due to SOC or excessive power demand, one of two hybrid modes will be activated with engine being turned on. Series hybrid mode requires that ICE is tied to EM1 via C1 to generate electric power that will be converted to mechanical energy by EM2 or chemical energy by battery, shown in Fig. 22(c). Series hybrid mode is efficient at low-speed driving and insensitive to vehicle speed change. Another hybrid mode, output-split hybrid mode is realized by engaging two clutches and leaving brake unlocked, shown in Fig. 22(d). This design helps Volt to be efficient in both PEV modes and hybrid modes.

5.2.2. GM 2-mode hybrid system – input-split and compound-split

This GM 2-mode hybrid system is used on GMC Yukon and Chevrolet Tahoe. Fig. 23(a) shows the essential architecture schematically, but one clutch and brake are omitted for convenience [48,49]. This compound hybrid architecture is designed to operate in two power-split modes: input-split and compound-split mode. Input-split mode has one node point and compound-split has two node points. As vehicle speed is launched, input-split mode is activated by engaging C1 and brake and disengaging C2. The third PGS functions as a torque amplifier and the first and second is a compound-split PSD. ICE, EM1 and EM2 are coupled with 1st and 2nd ring gear and 2nd sun gear, respectively, as shown in Fig. 23(b). This input-split architecture is similar to Fig. 17(e). As vehicle speed reaches the node point of input-split mode, rotation speed of EM1 drops to zero. At this moment, the 2nd and 3rd carrier gears are bonded by

![Fig. 23. Architecture of GM 2-mode hybrid system. (a) 2-mode schematic architecture and (b) First hybrid mode and (c) Second hybrid mode.](image-url)
engaging C2, the 3rd ring gear is released by unlocking brake. Operation mode is shifted from first mode to compound-split mode, as shown in Fig. 23(c). Actually, the node point in input-split mode is also the first node point of compound-split mode. So, this architecture has only two node points, rather than three. Powertrain efficiency will be close one before vehicle speed reaches the 2nd node point. After that, as increasing power will enter electric path, overall efficiency will be lowered fast.

6. Conclusions

As concerns of environment deterioration and energy supply security keep increasing, various technologies are being advanced to challenge currently dominating internal combustion engine vehicle. This review work firstly summarizes those proposed solutions and identifies electrified vehicle (xEV) as a promising technical trend. The purpose of this review work is to classify and compare different xEV architectures logically and provide insights into selection and design of powertrain architecture. Prior to classification of xEV powertrain architectures, electrification levels are defined according to applicable energy-saving functions. On the basis of widely-accepted hybrid powertrain classification method, an improved xEV classification method is proposed to organize various electrified powertrains systematically. As a critical step, four primary types of xEV architectures (PEV, Series HEV, Parallel HEV and Power-split HEV) are identified to enable new classification suitable for all electrification levels. In addition, a wide range of xEV powertrains are reviewed and organized in the new classification framework based on electrification level and relationship with four primary types of xEV architecture. Furthermore, more complex xEV powertrain architectures are analyzed by decomposing them into limited fundamental architectures. This review work, based on extensive references to industry products, patents and research papers, not only provides an up-to-date summary of electrified powertrain architecture, but also presents relationship of different architectures in a the new classification framework.

References


K. Koprubasi, Modeling and control of a hybrid-electric vehicle for drivability and fuel economy improvement, The Ohio State University, Columbus, 2008.

Weiwei Xiong, Yong Zhang, Chengliang Yin, Optimal energy management for a series-parallel hybrid electric bus, Energy Convers. Manag. 50 (2009).


Yi Ren, Shenglin Yan, Jun Li, Hybrid power driving system and gear position operation method thereof, Patent US 2011/0160015 A1, 30 June 2011.


B. Conlon, P. Savagian Alan Holmes et al., Output split electrically-variable transmission with electric propulsion using one or two motors, Patent US 7867124 B2, 11 January 2011.