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Review Article

A Comprehensive Overview of Hybrid Electric Vehicles

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As the environmental pollution and energy crises are getting more and more remarkable, hybrid electric vehicles (HEVs) have taken on an accelerated pace in the world. A comprehensive overview of HEVs is presented in this paper, with the emphasis on configurations, main issues, and energy management strategies. Conclusions are discussed finally.

1. Introduction

In 1834, the first vehicle, actually a tricycle, powered by battery, was developed. But with the improvement in the internal combustion engine (ICE), ICE vehicles (conventional vehicles) have occupied an absolute share in the market; pure electric vehicles (PEVs) have almost disappeared since 1930's. First, let us investigate the global growth of population and vehicles in the next 50 years [1]. We can see from Figure 1 that the global population will increase from 6 billion in 2000 to 10 billion in 2050, and Figure 2 illustrates the global vehicles will increase from 700 million to 2.5 billion consequently. If all vehicles are powered by internal combustion engines, the gasoline and diesel oil will be depleted quickly, and the emission will result in green house effect. So, the energy conservation and environmental protection are growing concerns around the world.

It is reported that vehicles emission accounts for 39.2% of the total emission in 2007 [2]; there must be a drastic reduction in emission if humans want to avoid catastrophic greenhouse effect, thus the governments all over the world adapt strict emission regulations, for example, Emission Standard of Automobile of Europe IV Standard has been put in practice in Europe since 2005 [3]. Meanwhile, fuel duty taxes were imposed by government; higher crude oil price plus fuel duty taxes result in higher fuel prices. So, Automobile Company sis forced to develop EV for low-emission and high-fuel economy under laws and market together.

EV is a road vehicle which involves with electric propulsion [4–6]. EV can be classified into three types: pure electric vehicles (PEVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs). Today, they are in different stages of development due to existing technology, the major characteristics and features of three types of EV as shown in Table 1. We can see that electric motor drives technique, in which the field-oriented control (FOC) and variable-voltage variable frequency (VVVF) are adapted widely, is the common technique in EV. The battery initial cost and battery management create bottleneck in PEVs in spite of zero emission; these two barriers cannot be solved in the near future, so the HEV is the interim solution before the full commercialization of PEV when there is a breakthrough in battery initial cost and management. FCEV has long-term potential for future main stream vehicles [7–10], however the technology of its cost and refueling system is still in early development stage [4], thus this paper mainly discusses HEV. Different from other papers, control principles of HEV is explained in detail in this paper. This paper is organized as follows. Section 1 is the introduction. Configurations and main issues of HEV are described in Section 2 with emphasis on the energy management (EM). Finally, the main points and significant results of this paper are summarized in conclusions.

Table 1: The major characteristics and features of three types of EV.

Types of EV	PEV	HEV	FCEV
Energy source	(i) Battery	(i) Battery/ultracapacitor (ii) Internal combustion engines	(i) Fuel cells
Propulsion technique	(i) Electric motor drives	(i) Electric motor drives (ii) Internal combustion engines	(i) Electric motor drives
Characteristics and feature	(i) Zero emission (ii) Short driving range (iii) Higher initial costs	(i) Low emission (ii) Longer range (iii) Complex	(i) Zero emission (ii) Highest initial costs (iii) Medium driving range
Major techniques	(i) Electric motor control (ii) Battery management (iii) Charging device	(i) Electric motor control (ii) Battery management (iii) Managing multiple energy sources and optimal system efficiency (iv) Components sizing	(i) Fuel processor (ii) Fueling system (iii) Fuel cell cost
Regenerative braking	(i) Yes	(i) Yes	(i) Yes

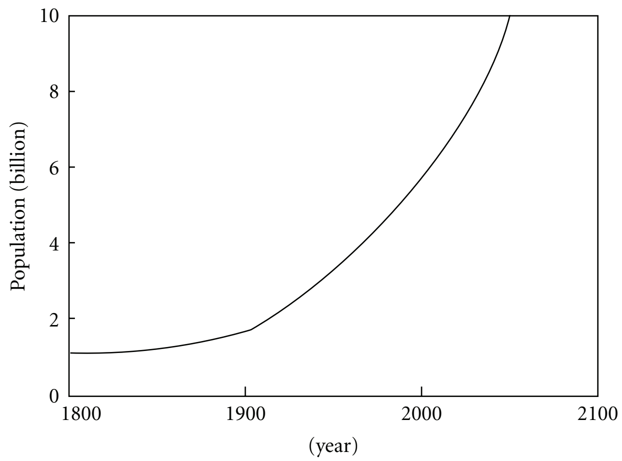


Figure 1: Growth of population.

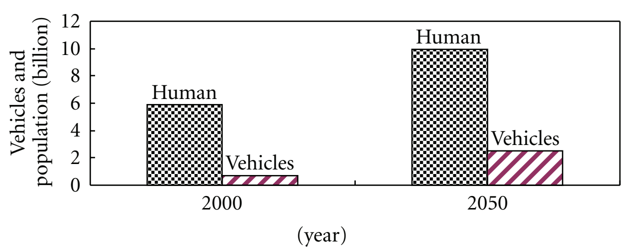


Figure 2: Vehicles and population.

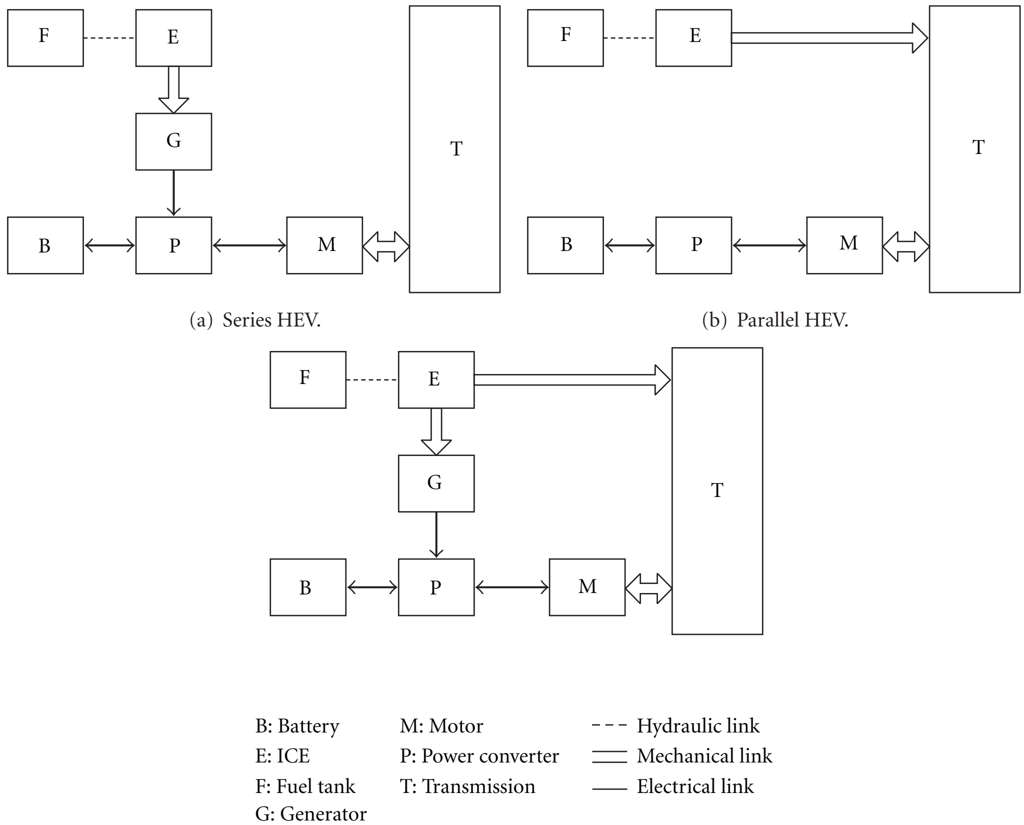
2. Configurations, Main Issues, and Control of HEV

2.1. Configurations of HEVs. According to technical Committee 69 (electric road vehicles) of the International Electro technical Commission, an HEV is a vehicle in which propulsion energy is available from two or more kinds or types of energy sources or converters, and at least one of them can deliver electrical energy [1]. Based on this definition, there are many kinds of HEVs, for example, battery and ICE, battery and capacitor, and battery and flywheel. However, the above definition is not accepted by ordinary people. Generally, they think that HEV is a vehicle having electric motor and ICE, thus this general definition is adopted in this paper. Traditionally, HEV can be classified into three types: series HEV, parallel HEV, and combination HEV [11, 12]. Figure 3 shows the configurations of HEV, arrow represents the direction of the power flow.

2.1.1. Configuration of Series HEV. From Figure 3(a), we can see that the series HEV is composed of ICE, generator, power converter, motor, and battery. There is no mechanical connection between ICE and transmission, thus ICE can operate at maximum efficient point by regulating the output power of battery to satisfy the required power of vehicle. But, the energy from the ICE transmits via generator and motor, so much more energy will be lost. Since the motor is the final and sole drive device, the motor must be larger enough to satisfy performance of vehicle, and thus the regenerative braking power almost can be stored in battery by motor.

2.1.2. Configuration of Parallel HEV. From Figure 3(b), we can see that the parallel HEV allows both the electric motor and ICE to deliver power in parallel to drive the vehicle, that is, ICE and motor can drive, respectively, or together. Different from the series HEV, there is mechanical connection between ICE and transmission, and thus the ICE's rotational speed depends on the driving cycle, so the ICE can operate based on optimal operating line by regulating the output power of battery.

2.1.3. Configuration of Combination HEV. From Figure 3(c), we can see that the combination HEV incorporates the features of both series and parallel HEV, an additional mechanical connection between ICE and transmission is added compared with the series hybrid, and also an additional generator between ICE and power converter is added compared with the parallel hybrid. Although the complexity of structure leads to more costly manufacturing technologies, it is more flexible in control. Some modern HEVs prefer to adopt this system [13]; typical products of HEV are listed in Table 2.



(a) Series HEV.

(b) Parallel HEV.

(c) Combination HEV.

Figure 3: Power flow of HEV.

2.2. Main Issues of HEV. Compare to conventional vehicle, HEV can save fuel for the following reasons.

(i) HEV can store part of the vehicle's kinetic energy in battery while braking or downslope in which otherwise is burnt in the brake drums in the form of heat in conventional vehicle.

(ii) The ICE in an HEV can be designed with a smaller displacement without compromising the performance of vehicle [14].

(iii) HEV can make ICE operate at maximum efficiency point or optimal operating line by regulating the output power of battery to satisfy the required power of vehicle.

(iv) HEV is a multiple energy system; the main issue of HEV is how to optimize the power flow to obtain best fuel economy or low emission at lower cost, which is often referred to as the energy management (EM) problem. The issue will be discussed in next section in detail.

2.3. Control in HEV. The most critical aspect in designing HEV is to get most effective results with controlling conversion of energy on the powertrain. Therefore, the controller design of HEV is the key point of the design process. The aim of this section is to explain powertrain control strategies for HEV and review the latest methods of EM strategies in detail. The aim of the control strategies is to satisfy a number of goals for HEV [15–18]:

(i) Minimization of fuel consumption or maximum of fuel economy.

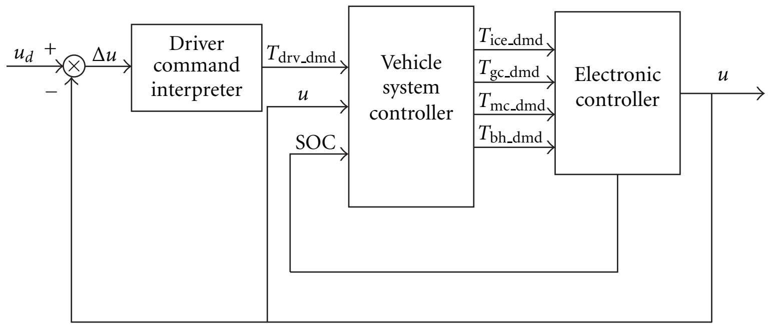
(ii) Minimization of emissions.

(iii) Good drivability.

Table 2: Typical products of HEV.

Products	Configuration	Automobile companies	Year
Prius	Combination	Toyota	1997
Insight	Parallel	Honda	1999
Tino	Combination	Nissan	2000
Civic	Parallel	Honda	2001
Lexus LS 600h	Combination	Toyota	2007
Toyota Auris	Combination	Toyota	2010
Lexus CT 200h	Combination	Lexus	2011

2.3.1. Vehicle Control in HEV. HEV's control system is very complex. The multilevel hierarchical control is an important control method for large-scale and complex system [19, 20]. Thus hierarchical control is adapted widely in HEV control as shown in Figure 4 (series HEV). HEV controller consists of



u_d: Desired speed of vehicle — u: Speed of vehicle
$T_{\text{drv\_dmd}}$: Driver demand — SOC: State of charge
$T_{\text{ice\_dmd}}$: Torque demand of ICE — $T_{\text{gc\_dmd}}$: Torque demand of generator
$T_{\text{mc\_dmd}}$: Torque demand of motor — $T_{\text{bh\_dmd}}$: Torque demand of braking
Δu: Difference of desired speed and speed of vehicle

Figure 4: Block diagram of HEV controller.

driver command interpreter, vehicle system controller, and electronic controller. Vehicle system controller is the decision level to decide the torque demands of motor, generator, ICE, and mechanical brake according to the driver's torque demand, speed of vehicle, and battery's state of charge (SOC), where the SOC is estimated by battery management system (BMS), the speed of vehicle is feed by sensor. Electronic controller is execution level to carry out the command from the vehicle system controller to make corresponding parts work.

(1) *Driver Command Interpreter.* The function of driver command interpreter is to compute the driver's torque demand according to desired speed of vehicle and actual speed of vehicle. Speed of vehicle is controlled by accelerator pedal and brake pedal position. This is a feed control system by adjusting the accelerator pedal and brake pedal position to make the vehicle follow the desired vehicle speed.

(2) *Vehicle System Controller.* Compared to the conventional vehicles, HEV is a multiple energy source, then, how to split the required power among energy sources is called EM. Vehicle system controller performs powertrain control by using EM strategies according to command signals received from driver command interpreter and parameters information feedback from electronic controller. Vehicle system controller can be divided into three function blocks as shown in Figure 5.

(i) Required power of vehicle interpreter.

(ii) Energy management strategies.

(iii) Torque interpreter.

Required power of vehicle interpreter is a function block to convert the driver's torque demand to power demand. HEV is a multiple energy system, different from conventional vehicles which can only output power, battery not only can output power but also absorb power. For a required power, how to split the power required between two energy sources and mechanical brake in order to minimum the fuel consumption or emission is the hot topic among technology developers. In the next section, EM will be discussed. Then, torque interpreter converts the power demand of ICE and mechanical brake to torque demands of ICE, generator, motor, and mechanical brake.

(3) *Electronic Controller.* Electronic controller is the embedded system which carries out the commands from the vehicle system controller to make corresponding parts work. Electronic controller in Figure 4 includes engine control unit (ECU), motor control unit (MCU), generator control unit (GCU), electronic braking system control (mechanical brake) unit, and battery management system (BMS).

Engine control unit is an electronic control unit (ECU) for controlling ICE; it makes the ICE output desired torque coming from vehicle system controller command signal by injecting fuel into the combustion chambers of the ICE. ICE's operating point can be described by torque and speed. In series HEV, there is no mechanical connection between ICE and transmission, then how to control the speed of ICE? There is a mechanical connection between ICE and generator, so ICE's speed is controlled by generator's torque demand. Motor is the final drive device and coupled by mechanical connection to transmission, and so the motor's speed depends on the driving cycle, similarly, motor's operating point can be described by torque and speed usually; the torque demand of motor is computed by driver's torque demand due to mechanical connection to transmission. MCU makes the motor operate at desired torque using FOC echnology usually. Motors, used for traction usually, are also able to become generator during braking or down slope. Hence, the vehicle kinetic energy, which otherwise is burnt in the brake drums in the form of heat, can be converted into electrical energy and sent back to the battery. If the battery is unreceptive, then electronic braking system control unit can be work.

2.3.2. Energy Management for HEV. There have been a number of surveys on EM strategies for HEV. Early EM is designed based on rules for its effectiveness in real time supervisory control of power flow in a hybrid powertrain, which is

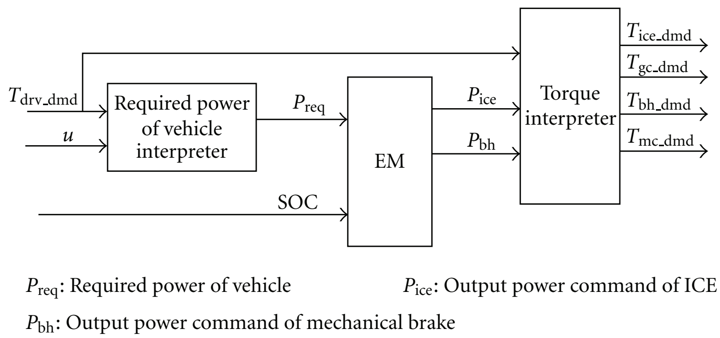


Figure 5: Block diagram of vehicle system controller.

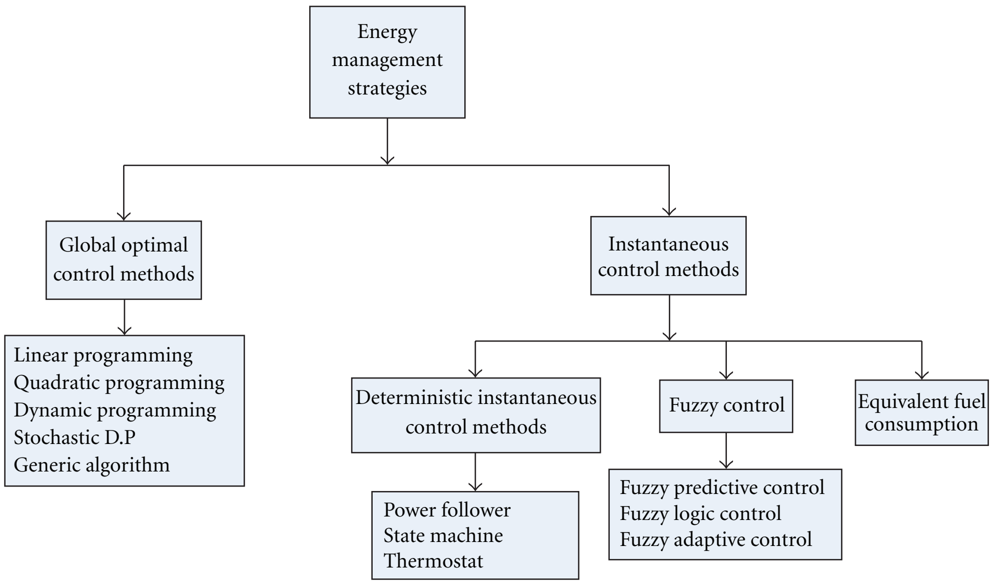


Figure 6: Energy management control strategies for HEV.

set up on the basis of heuristics, intuition, and human expertise. For example, the maximum torque ICE can produce is low at low speed, while the motor is high at low speeds. So, heuristics EM strategies are to make the vehicle run in purely electrical mode from standstill to a low vehicle speed. When the vehicle speeds up from this speed, the ICE will turn on and operate based on optimal operating line. Global optimal control methods are adapted subsequently. In a word, EM for HEV can be divided into two main methods as shown in Figure 6, Global optimal control methods, and instantaneous control methods.

(1) *Global Optimal Control Methods.* Some global optimal control methods based on optimal control theory have been developed recently. These methods aim at minimizing the energy loss or fuel consumption over a given period of time [21]. Due to use of the whole driving information in advance, the global optimum solutions can be found. Obviously, these approaches cannot be used in real time, but they might be basis of comparison for evaluating the quality of other EM strategies. Global optimal control methods used in EM strategies can be divided into the following methods: linear programming (LP) [22, 23], quadratic programming (QP), dynamic programming (DP) [24–27], stochastic dynamic programming (SDP) [28], and genetic algorithm (GA) [29].

Dynamic programming was founded to solve the shortest distance early. EM problem is similar with shortest distance problem, and so it is commonly solved by DP. DP requires gridding of SOC over a given driving cycle with a time discretization step Δt, and thus the optimal trajectory is calculated only for discretized point (SOC, t). But, the computational time increases linearly with the final driving cycle time. An approach, used to reduce the computing time is to split the driving cycle time into a series of time sections and solve an optimization problem for each of these sections. If the fuel consumption over the whole driving time is linearized, then the linear programming can be adopted to solve the optimization problem. Alternatively, if the fuel consumption over the whole driving cycle time is quadratic about variable, then quadratic programming can be used.

(2) *Instantaneous Control Methods.* Although global optimal control methods can obtain global optimum solution, it requires substantial amount of computational time and cannot

be implemented real time. One method that often permits a reduction of computational time is the instantaneous control methods, and it only optimizes at instantaneous time. The greatest advantage of the methods is possible applied for real time. Instantaneous control methods can be divided into deterministic instantaneous methods, fuzzy control methods and equivalent fuel consumption method.

Deterministic instantaneous methods are designed via lookup tables to split the requested power between two energy sources. Deterministic instantaneous methods include power follower control, thermostat [30–36], and state machine [37]. Energy management problem for HEV is a multidisciplinary, time-varying, and nonlinear optimal problem; fuzzy logic control seems to be the most logical approach to the problem. The main advantages of fuzzy control methods are the following [38]: (1) robustness, since they are tolerant to imprecise measurements and component variations; (2) adaptation, since the fuzzy rules can be easily tuned, if necessary. Fuzzy control methods are divided into fuzzy logic control [39], fuzzy adaptive strategy [40], and fuzzy predictive strategy [40].

In equivalent fuel consumption method [41], in addition to an estimation for fuel consumption, variations of the stored electrical energy should be taken into account to guarantee electrical self-sustainability. Thus, variations of the electrical energy are added to cost function via penalty function. Since the fuel energy is not equal to electrical energy, so the equivalence factor is needed to convert the electrical energy to equivalent fuel energy. Then, the optimization problem is converted to evaluate the equivalence factor. All in all, Equivalence factor depends on the driving cycle. Telemetry ECM (T-ECM) [42] and adaptive ECM [41] are adopted to estimate the equivalence factor.

3. Conclusion

Environment protection and energy crisis have urged the development of EV. However, PEV is not widely used currently. The main reason is that they could not satisfy the consumers' need due to high initial cost and short driving range. Thus, BEV will be designed mainly for short range, such as community transportation. Although FCEV has long-term potential for future main stream vehicles due to zero emission and comparable driving range with conventional vehicles, the major challenge for developing FCEV is how to investigate low-cost FC and refueling system. Consequently, HEV can meet consumers' need currently and will grow in faster rate. The main issue of HEV is how to optimize the multiple energy sources to obtain best fuel economy or low emission at lower cost.

This paper has presented an overview of HEV with focus on the configurations, main issues, especially the control of HEV, and it elaborates the EM approaches. The EM problem is the hot research area until now, and it is also the critical technology for HEV. Global optimization approach can obtain global optimum, but it requires substantial amount of computational time and does not implement real time, so the global optimization approach, such as DP, usually serves as a benchmark for evaluating other EM strategies. Instantaneous control methods only optimize at instantaneous time. So, the real-time application becomes possible.

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