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Fuel Consumption and Emission Reduction Power Management Strategy for Hybrid Electric Vehicles

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Abstract

An online power management strategy (PMS) for plug-in hybrid electric vehicles is presented in this paper. This PMS with the capability to reduce both the fuel consumption and the emission, has simple mathematics and excludes a priori knowledge of the driving cycle. The only required information is the driving duration that can be estimated by the driver or by the vehicle information systems, so the proposed method can be easily implemented. Furthermore, an adaptive form of this PMS is presented and its performance is compared with other strategies. Using the online adaptive PMS method, the incoming driving cycle condition is predicted by the vehicle past conditions. In this paper, the engine fuel characteristics are linearized to several zones. At any instant, one of these zones is selected for the engine operation. In each zone, an optimal cost function is minimized for the fuel consumption and the emission reduction. Moreover, different cost functions are defined and used on various engines. Finally, the proposed PMS is simulated in the ADVISOR environment and compared with conventional method.

Keywords

Adaptive Control; Fuel Consumption and Emission Reduction; Plug-in Hybrid Electric Vehicle; Power Management Strategy

Introduction

Increasing fossil fuel consumption has caused significant problems for both governments and societies. These non-renewable resources are depleting very fast. Furthermore, the air pollution and the greenhouse effects of their emissions, damage the general health. Since a big share of the fuel consumption is used by the conventional vehicles, the hybrid electric vehicles (HEVs) are suggested as an effective solution to reduce the fuel consumption. In HEVs, an electric power source is integrated into a conventional internal combustion engine which is downsized. However, the main source of their traction power is still the gasoline engine. The hybridization and downsizing allow for fuel economy enhancements (Katrasnik et al., 2007). Thanks to the presence of an electric power train, these vehicles have the regenerative braking ability that increases the vehicle efficiency (Yu-shan Li et al., 2009).

The latest generation of the HEVs is the Plug-in hybrid electric vehicles (PHEVs) that employ the grid electric energy. For example, they can be plugged into a power grid or a residential photovoltaic system (Gurkaynak et al., 2009). The PHEVs consume 40% to 80% fuel than conventional HEVs (Fajri et al., 2008).

IEEE-USA Energy Policy Committee defines that a PHEV should have at least a 4 kWh battery storage system and ten miles only electric mode driving distance (Shams-Zahraei et al., 2009). Therefore, the PHEVs have a medium storage system that is charged externally. Usually, the electric energy is cheaper than the gasoline (four times in USA (Romm et al., 2006)). Therefore, it is essential to use the stored energy before the end of the trip that makes the PMS more complicated. The PMS defines the component's power share. Many PMSs are proposed and classified into the HEVs and the PHEVs. From the mathematical point of view, the PMSs are classified into rule based and optimization based methods (Bayindir et al. 2011; Wirasingha et al. 2011).

There are many heuristic and fuzzy rule based PMSs in recent literatures (Gao et al., 2010; Hui et al., 2008; Banvait et al., 2009; Mapelli et al., 2009; Li et al., 2010; Chen Zheng et al., 2009; Xiong et al. 2009). A novel rule-based PMS for the PHEVs that focuses on all electric range and charge depletion range operations is presented in (Gao et al., 2010). An engine on-off rule based control strategy with consideration on position of acceleration pedal is proposed in (Hui et al., 2008).

A heuristic solution to a parallel and series-parallel PHEV is proposed in (Banvait et al., 2009). In this paper, the energy management optimizes engine operational efficiency while maintaining battery state of charge. A rule based fuzzy logic control strategy for a parallel hybrid electric city public bus is proposed in (Li et al., 2010). A series-parallel structure for a hybrid electric bus is presented in (Xiong et al. 2009). In this paper, a fuzzy logic PMS, which consists of two fuzzy modules used to determine the operation mode and distribute torques at parallel mode respectively, is studied by numerical simulation. However, the emission reduction is exclusive of consideration in (Xiong et al. 2009). The rule based PMSs are simple, applicable, and can be calculated easily. However, the optimization based PMSs are usually more efficient than the rule based PMSs (Bayindir et al., 2011; Wirasingha et al. 2011).

Generally, the optimization based PMSs are more complicated and accurate than the rule based PMSs and for both, a priori knowledge about the driving cycle is essential. This essential priori knowledge can be delivered by the solutions provided in literatures. However, they can lead to some more additional computational burden. Therefore, these PMSs are unsuitable for the real applications. The optimization methods define and minimize a cost function (Wirasingha et al. 2011). Both of the fuel consumption and the emission production are minimized easily by means of the proper cost function definition. The optimization group includes a wide spectrum of different methods such as the static optimization, numerical optimization, equivalent consumption minimization strategy (ECMS) and analytical optimization methods (Sciarretta et al., 2007).

One of the interesting optimization PMS is dynamic programming (DP) (Shen et al., 2010; Yan et al., 2010). DP is significant time consuming with heavy mathematical burden. Therefore, a two-scale DP is proposed to solve the mentioned problems (Gong et al., 2007; Gong et al. 2008; Gong et al., 2009). Furthermore, the driving cycle prediction can be done by the new geographical systems like GPS, GIS, and traffic information system (Zhang et al., 2010; Abdul-Hak et al., 2009; Gong et al., 2008; Gong et al., 2007). (Moura et al., 2011) uses a stochastic dynamic programming to optimize PHEV power management over a distribution of drive cycles, rather than a single cycle by means of Markov chains. An optimization PMS by using the Pontryagin's minimum principle for the PHEVs is proposed in (Stockar et al., 2010). The equivalent fuel consumption strategies (ECMS) are proposed by (Mapelli et al., 2009; Tulpule et al., 2009; Zhang et al., 2010). An artificial neural networks monitoring and fault diagnosis system for electric vehicles is proposed by (Kalogirou et al., 2000) that can be improved for energy management optimization.

This paper presents a PMS that is inspired from (Kessels et al., 2008; Koot et al, 2005), and ECMS method. The presented PMS is designed for the fuel consumption and the emission reduction. The different forms of this PMS and their effects are discussed in this paper.

The proposed PMS is an applicable and accurate method with the simple mathematic equations. Therefore, it has the advantages of the optimization and rule based methods and can be done online. This strategy just needs the driving duration that can be easily estimated by the driver or the geographical and information systems.

This paper is organized as follows: An adequate vehicle model is presented in Section 2. The background of the proposed PMS and its mathematics are discussed in Section 3. The zone selection procedure is discussed in Section 4. In Section 5, an adaptive form of the proposed control strategy is discussed, and the simulation results are presented in Section 6. Finally, conclusions are stated in Section 7.

Problem Definition

It is expected that PMS maintain the vehicle performance and at the same time reduce the fuel consumption and emission. The strategy should be practical and easily applicable on the vehicle. Furthermore, the PMS should be causal. However, some predictive control strategies have been developed with some priori knowledge, but it can lead to some additional computational burden. The presented PMS has a little dependence on a priori information. Essential priori information for the proposed PMS is just the driving durationthat can be estimated by the assumption on the constant acceleration and deceleration rate as well as the speed limits for each road (Gong et al., 2007; Gong et al., 2008). The proposed PMS with simple mathematics can be supported by common processors. Therefore, the presented PMS is practical and can be applied easily to the vehicle.

A power management strategy for HEVs is presented in (Kessels et al., 2008). The idea of (Kessels et al., 2008) is that the engine should work in the area with high (or low dependence on the engine map) slope when the *SOC* of the battery is low and work in the area with low (or high) slope when the *SOC* is high. Therefore, PMS can be compatible for engines like the Prius, but it is unsuitable for engines with a rugged fuel map like SI41.

Fig. 2 and Fig. 3 show that the fuel consumption decreases if the engine speed descends with constant power. Therefore, in series PHEVs or in the topologies that the speed of the engine is controllable; the engine operation at low speeds will be suitable.

The slope of each zone is an important parameter of the proposed PMS. Typically, the slope of each zone (λ_{fi}) is constant, where *i* indicates the zone number. λ_{fi} represents the extra fuel mass flow needed to produce a small amount of mechanical power by the engine.

$$\lambda_{fi}(P_m,\omega) = \frac{\partial f(P_m,\omega)}{\partial P_m} \tag{17}$$

The slopes of different zones and curves are calculated and gathered in a lookup table. Furthermore, the similar lookup tables are prepared for emission characteristics. The characteristics of these emissions for SI41engine are shown in the Figs. 6-8.

The variations of HC and CO against power changes are similar to the fuel usage variations. Consequently, the attempt on fuel reduction causes a reduction of CO and HC emissions. However, the difference between the NO_x and the fuel characteristics is significant. In fact, there are some zones with high NO_x emission in the optimal fuel consumption area. This difference can have important effects on the PMS for NO_x reduction. Hence, for reduction of the NO_x emissions, these zones can be avoided. Certainly, the fuel consumption rate is increased, but it is not significant. In fact, the engine operating point is still in the optimal fuel usage area , inside of which there are just some holes. Thus, a suitable balance between fuel usage and NO_x emission is achieved.

Different engines have various fuel and emission characteristics. Consequently, this strategy performance and its setting will be different from each other. There is more discussion about the effect of engine characteristics on the PMS results in Section 6.

The emission curves should be discretized and linearized same as fuel consumption curves. The slope of each zone of the HC, CO and NO_x characteristic curves are given in (18)-(20), respectively.

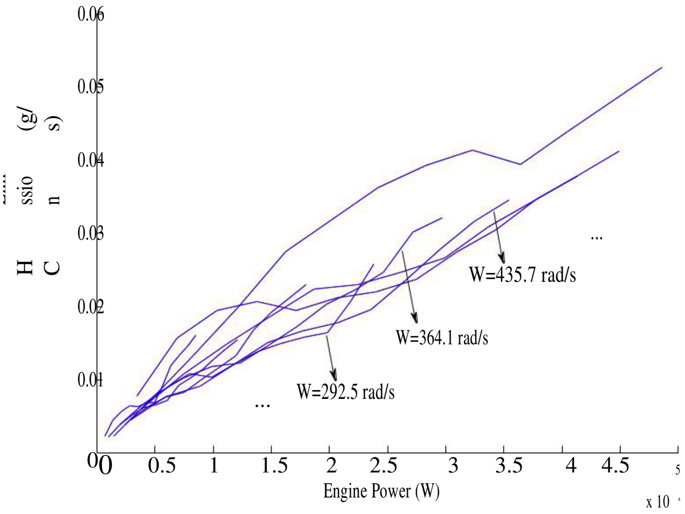

FIG. 6 HC EMISSION MAP CHARACTERISTIC FOR SI41 ENGINE

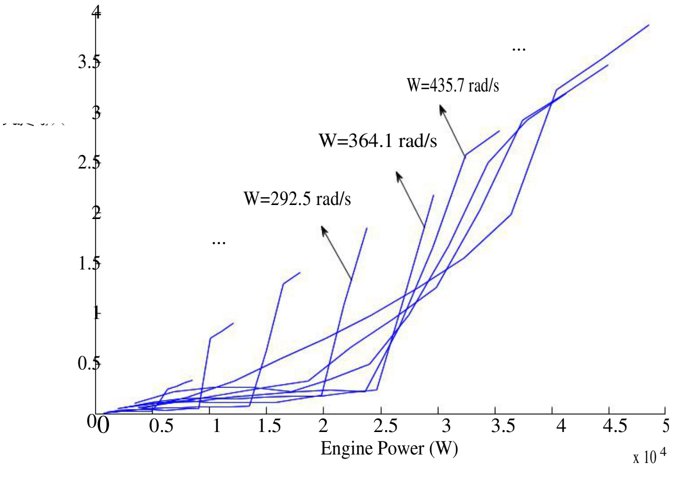

FIG. 7 CO EMISSION MAP CHARACTERISTIC FOR SI41 ENGINE

Another simulation is performed for the SI63 engine. The features of this engine have some differences with the SI41 engine. For instance, the SI63 emission and fuel characteristics are almost similar together. Therefore, the zone correction for the NO_x emission cannot be performed for this engine. The SI63 NO_x characteristic is shown in Fig. 18. The simulation results for five combined driving cycles are calculated. Then the average value for these cycles is calculated for each condition, which is shown in Table 6. There is a considerable increase in the fuel saving and emissions for the adaptive strategy, which is in accordance with the results of the SI41 engine. However, the change in the cost function has a little change in the fuel and emission results of the SI63 engine whose characteristics are very important in the presented PMS method.

Conclusions

This paper has presented a powerful online power management strategy for the parallel PHEVs. This PMS excludes from the need of complex mathematics as well as a priori driving cycle information. Due to these features, the proposed PMS is an applicable strategyand can reduce the emissions and the fuel consumption as well.

Furthermore, an online adaptive version of this PMS has been presented. In particular, the adaptive PMS has reduced the fuel consumption in the combined driving cycles. However, the emission has been increased in this case. Therefore, the use of the adaptive PMS is dependent on the environmental laws.

The engine characteristics have an important role in the performance of this PMS. In fact, this PMS has been established based on the engine characteristics. Therefore, the emission and the fuel consumption reduction have varying intensity for different engines. However, these effects are almost similar.

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