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Dynamic energy management for a novel hybrid electric system based on driving pattern recognition

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ABSTRACT

This paper focuses on the dynamic energy management for Hybrid Electric Vehicles (HEV) based on driving pattern recognition. The hybrid electric system studied in this paper includes a one-way clutch, a multi-plate clutch and a planetary gear unit as the power coupling device in the architecture. The powertrain efficiency model is established by integrating the component level models for the engine, the battery and the Integrated Starter/Generator (ISG). The powertrain system efficiency has been analyzed at each operation mode, including electric driving mode, driving and charging mode, engine driving mode and hybrid driving mode. The mode switching schedule of HEV system has been designed based on static system efficiency. Adaptive control for hybrid electric vehicles under random driving cycles with battery life and fuel consumption as the main considerations has been optimized by particle swarm optimization algorithm (PSO). Furthermore, driving pattern recognition based on twenty typical reference cycles has been implemented using cluster analysis. Finally, the dynamic energy management strategy for the hybrid electric vehicle has been proposed based on driving pattern recognition. The simulation model of the HEV powertrain system has been established on Matlab/Simulink platform. Two energy management strategies under random driving condition have both been implemented in the study, one is knowledge-based and the other is based on driving pattern recognition. The model simulation results have validated the control strategy for the hybrid electric vehicle in this study in terms of drive pattern recognition and energy management optimization.

1. Introduction

HEVs (Hybrid electric vehicles) serve as an economical and practical solution to the energy crisis. However, high cost and complexity are major issues of hybrid electric vehicles. Dual motors are widely used in various HEV configurations, especially the power-split configuration with a planetary gear train, such as Toyota's Prius, RX400h and Ford's Escape. Since power-split transmission has the ability to provide continuously varied input and output speed ratio via the electrical motor, the ICE (Internal Combustion Engine) can be operated at the optimal speed for fuel economy independent from the vehicle's speed. However, the power-split design is characterized by internal power recirculation which may take place in a closed loop at

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certain speed ratio, leading to significant power losses [1]. On the other hand, the single-motor HEV configuration with an AMT (Automated Manual Transmission) and a wet clutch makes a compromise among the issues of cost and complexity, and is widely used in commercial vehicles [2,3].

Apart from the powertrain configuration, another issue that affects the HEVs' performance is the EMS (Energy Management Strategy) of the hybrid system. The EMS plays an important role on HEVs, in terms of vehicle performance in fuel consumption, emission and durability of power sources, which are subject to frequent power splitting. The energy management for a full hybrid electric powertrain with planetary gear set and dual clutch configuration has been studied and compared with that of the Toyota Hybrid System [4].

The purpose of an EMS is to coordinate all the components of the powertrain in an optimal vehicle operating mode and to determine an optimal power distribution between the motor and the engine under different driving conditions [5,6]. There are various control methods used in the energy management system of HEV. A fuzzy controller has been developed to effectively determine the power split between the electric machine and the internal combustion engine [7]. The energy management controller with multi input fuzzy logic has been developed to improve the fuel economy of a power-split hybrid electric vehicle in a configuration similar to the Toyota Prius [8]. An optimal energy management system for engine/motor hybrid electric vehicles was developed by using improved particle swarm optimization, which effectively reduced the equivalent fuel consumption and energy consumption at specified ECE and FTP standard driving cycles [9]. The equivalent consumption minimization strategy has been developed for parallel hybrid vehicle applications [10]. A stochastic method, which analyzes the power demands based on current operation status and on estimating future driving conditions, has been proposed for the energy management for the minimization of HEV fuel consumption [11]. A sequential approximate optimization approach using radial basis function network has been adopted to optimize the torque control for parallel hybrid electric vehicles [12]. The stochastic dynamic programming has been used to optimize PHEV power management over a distribution of drive cycles [13]. In a recent paper, a control algorithm using dynamic programming has been proposed for optimizing fuel consumption of series hybrid electric vehicles at typical driving modes [14] and this algorithm can be extended for HEV real-time control in the future researches. A multi-mode driving control algorithm using driving pattern recognition has been applied to a parallel hybrid electric vehicle [15]. Based on driving pattern recognition, an adaptive power management control strategy has been proposed for HEV operation control [16]. Furthermore, driving pattern prediction for HEV energy management system has also been discussed in a specific driving range [17].

A dynamic energy management strategy based on driving pattern recognition has been proposed for a novel hybrid electric system in this study. Existing control strategies based on predefined driving cycles cannot fit actual driving patterns, and the optimization techniques can hardly be used in real-time control, due to the difficulties to acquire the knowledge of the driving cycle and the online computational load. The objective of the EMS established in this study is to address this issue. The EMS is implemented in three steps. The first step is to build the model of the system efficiency and set up the basic driving mode switching schedule and the power distribution rule. In the second step, the efficiency based EMS is launched off-line to maximize battery life and the fuel economy. This process is to optimize typical control parameters and establish the mode switching schedule separately for twenty typical driving cycles. The obtained results for each typical driving cycle are saved as in a database for dynamic control of the hybrid vehicle. The third step is to recognize the driving patterns, and then use the control rules of the corresponding typical driving cycles with the maximum similarity. The EMS model is established on MATLAB/Simulink platform and has been used to simulate the fuel economy and battery life under realistic driving conditions. The model simulation results validate the effectiveness of the control strategy for the hybrid electric vehicle studied in this paper.

2. HEV powertrain efficiency model development

2.1. System configuration

This section outlines the series-parallel configuration of the HEV powertrain studied in this paper. As shown in Fig. 1, this hybrid system uses a planetary gear unit (4) as the power coupling mechanism for the engine (1) and the Integrated Starter/Generator (ISG) (9). The operating modes of the proposed hybrid system are determined by the clutch schedule of the multi-plate friction clutch (3) and one-way clutch (2), as shown in Table 1. The output shaft of coupling mechanism is connected with a five-speed AMT to transfer the torque and speed of power sources.

2.2. Powertrain efficiency model development

In order to analyze the hybrid system efficiency under different operation modes, it is necessary to set up the efficiency models on the component level. The component models are then integrated to form the HEV system efficiency model, which is used for the optimization of HEV energy management strategy.

2.2.1. Engine efficiency model

The engine is a highly nonlinear system, and it is difficult to use the theoretical model to accurately describe its complicated operation mechanism. The engine output torque model is usually established based on experiment data for dynamic