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# Markov velocity predictor and radial basis function neural network-based real-time energy management strategy for plug-in hybrid electric vehicles

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ABSTRACT

Power management strategy of plug-in hybrid electric vehicle for real-time application is a major challenge as the driving pattern is unknown beforehand. In this work, an innovative real-time power management strategy framework is proposed, including short horizon driving pattern prediction, driving pattern recognition, parameter off-line optimisation, parameter on-line prediction modelling, and power management strategy real-time application. A group of characteristic parameters is used to recognise driving patterns and the engine and motor working points are optimised globally by distributed genetic algorithm off-line. The optimised results approximation model is built on the basis of a radial basis function-neural network. Based on a linear programming algorithm, the higher order Markov velocity predictor is designed to obtain the short-horizon driving conditions. Combining the optimisation results approximation model, the real-time power management strategy is proposed. The on-line optimisation power management strategy comparing to the rule-based is analysed and the MATLAB/Simulink/AVL Cruise co-simulation results demonstrate that the fuel economy of real-time power management strategy improved by 16.3%, 12.7%, and 9.1% in HWFET, LA92, and Japanese urban driving patterns, respectively, which is largely higher than with a traditional rule-based strategy and slightly lower than, or approximately equal to, the global optimisation strategy.



## 1. Introduction

Due to the merits of plug-in hybrid electric vehicle (PHEV), such as environmental friendliness, low exhaust gas emission, long driving range and good fuel economy, PHEV catches more and more attention from research institutes and automaker [1]. One internal combustion engine and one or two permanent magnet synchronous motors (PMSM) are usually included in a PHEV [2]. Therefore, the power distribution between engine and motors becomes very important and a good power management strategy (PMS) of PHEV can reduce fuel consumption, and decrease exhaust gas emissions effectively [3]. Many studies of hybrid electric vehicle (HEV) or PHEV are focused on PMS: rule-based PMS and the optimisation-based PMS are two categories of HEV or PHEV [4]. In Ref. [5], an overview of the deterministic rule-based energy management strategies of PHEV is given, and an analysis on which strategy is more suitable to maximize PHEV performance is provided. In Ref. [6], a conventional fuzzy logic control-based PMS with features of intelligence and adaptability is proposed. Deterministic rule-based PMS and fuzzy logic rule-based PMS are welcomed by engineers greatly because their advantages of reliability and easy development. There are many more studies concentrating on optimisation-based PMS and a variety of intelligent methods, for example, an intelligent PMS is developed and evaluated for a PHEV in Ref. [7], and the proposed adaptive intelligent PMS can learn while it is running and makes proper adjustments during its operation. A bi-level optimal framework for the dual-motor-driven system is proposed in Ref. [8], which is applied to find the optimal design parameters of PMS. A rule-based PMS extracted from dynamic programming (DP) algorithm for real-time implementation of range extended electric vehicle is established in Ref. [9]. An intelligent PMS for a hybrid vehicle is proposed in Ref. [10], which based on machine learning algorithm. A method which first

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combines auxiliary particle filter and the iterated extended Kalman filter (APF-IEKF) to improve fuel economy is proposed in Ref. [11]. A dynamic programming algorithm that has a tolerable computational load to optimize the dose and size for a ground-vehicle to reduce emission is proposed in Ref. [12]. An optimal control-based PMS considering battery state of health for a HEV is proposed in Ref. [13], which effectively reduces battery wear with only a relatively small penalty on fuel consumption. The quadratic programming (QP) [14] based PMS can control the battery current effectively, which makes the engine work more efficiently and thus reduce the fuel consumption. An adaptive simulated annealing genetic algorithm(ASA) [15] based PMS is used in a hydraulic hybrid vehicle (HHV), which effectively improves the components' parameters and enhances the fuel economy. A hybrid simulated annealing approach(HAS) [16] is used to design PMS for EVs, and the proposed PMS resulting in a cost reduction of 1.94% in a 2000 EV scenario. Real-world road geometry information is utilized in Ref. [17] to design a PMS by using an equivalent consumption minimization strategy (ECMS). A novel optimal PMS for PHEVs against uncertain driving conditions using the particle swarm optimization (PSO) algorithm is proposed in Ref. [18], The results illustrate that the reduction in energy loss can be up to 1.76% for the uncertain driving cycles. The neural network (NN) based PMS is proposed in Ref. [19] for a power-split PHEV, which consists of two neural network modules that are trained based on the optimized results obtained by DP method. A novel hybrid genetic algorithm (HGA) is proposed in Ref. [20] to improve the fuel economy of a plug-in hybrid electric bus (PHEB), which combines an enhanced genetic algorithm (EGA) with simulated annealing (SA) to increase the convergence speed and global searching ability of HGA. A multimode switched logic PMS based on a novel hierarchical clustering algorithm for a particular city bus route is proposed in Ref. [21] for a PHEB to improve fuel economy. The model predictive control (MPC) method has also been successfully applied to design the PMS of PHEV in Ref. [22], which gives a comprehensive review of this method for the first time. A global optimal solution can be obtained by DP-based PMS in the certain driving pattern, but due to the reason that the driving pattern is unknown prior and the demerit of heavy calculation burden, DP-based PMS cannot be used on-line. In addition, the convex programming [23] is used to design PMS for a series plug-in PHEB, and the efficiency of powertrain from tank to wheel is analysed. The power loss of engine and motor is regarded as the quadratic function of torque, the suboptimal solution is obtained by convex optimisation. In the literature [24], the non-dominated sorting genetic algorithm-II (NSGA-II) is used to optimise the control parameters of PMS in several different typical driving patterns for a PHEV. The parameters are conflicting to each other; therefore, this is a multi-objective optimisation problem, and NSGA-II algorithm is good at settling this kind of problem. Some studies regard the electric vehicles and residential multi-family houses as a system. In Ref. [25], the charging influence of an electric vehicles on residential houses grid was considered from the aspects of energy, environmental and economic performance by analyzing a set of seven electric vehicle charging profiles representing different scenarios. The simulation results indicate that whatever the electric vehicles charging profile is, the proposed micro-trigeneration system [26] allows for a reduction of the annual primary energy consumption (around 6.6%), the carbon dioxide equivalent emissions (in the range of 11–12%) as well as the operating costs (about 19.9%) in comparison to a conventional system.

However, all the optimisation-based PMS on the basis of aforementioned methods cannot be used in real time control purpose. Many researchers devote their effort to realize the on-line application of the optimisation-based PMS and the driving pattern prediction-based PMS is becoming the study focus gradually. Based on the driving cycle estimation methods, a novel correctional DP algorithm based global optimal PMS for the PHEB is proposed in Ref. [27] to optimise fuel economy and drivability. Three kinds of velocity predictor are compared in Ref. [28], such as exponential velocity predictor, Markov velocity predictor and neural network velocity predictor, then the MPC-based predictive power management strategy (PPMS) is designed for a power split HEV. Based on the predicted velocity, the optimisation process is carried out in prediction horizon. A driving-behaviour-aware stochastic PPMS is proposed in Ref. [29], which is based on Markov velocity predictor. The k-means method is utilised to classify the stochastic driving behaviours between two stop stations for a PHEB. A neural network-based velocity predictor is presented in Ref. [30] for a dual motor propulsion system, and the PPMS based on the velocity predictor is designed. One of the important problems to predict future driving cycle is driving pattern recognition (DPR) and there are also many researchers focus on this area. A looking-ahead control strategy based on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure communication (V2I) in the intelligent transportation systems (ITS) for a class 8 parallel hybrid heavy duty vehicle is proposed in Ref. [31], which seeks to estimate the forthcoming power events in advance and manage the alternative power source depending on this advanced knowledge. The simulation results indicate that the fuel economy improvement was about 4% and 13% on real-world flat terrain highway driving cycle and real-world mountain terrain highway driving cycle, respectively. Ericsson analysed the effect of many driving pattern factors on fuel consumption and exhaust emission in Ref. [32], and screened out the sixteen essential parameters from sixty-two.

The purpose of this work is to further improve the fuel consumption of a PHEV. According to the practicability of the rule-based energy management strategy, some studies focus on the optimization of the rule-based energy management strategy for a PHEV to improve the fuel economy. An optimization based rule energy management strategy is developed and validated in Ref. [33]. The control rules are extracted from the offline optimal energy management strategy results, by constraining the engine operating points to an optimized working area. However, this optimization-based rule development method is more suitable to fixed-pattern driving circumstances, because the optimal energy management strategy results depend on fixed driving cycles. In order to achieve the real-time control purpose in unfixed driving cycles, the optimization-based real-time energy management strategy combined higher order Markov chain velocity predictor with radial basis function-neural network (RBF-NN) based engine working point optimization results approximation model is purposed in this paper. The main contributions of this paper are following.

(1) A higher order Markov chain velocity predictor is proposed to predict short-horizon driving patterns, which the linear programming algorithm is used to calculated the weight vector of emission probability matrix. Comparing with other velocity predictor, such as the first order Markov chain, the velocity prediction accuracy is improved significantly.
(2) Considering the balance between computational complexity and feature completeness of the drive condition, fifteen characteristic parameters are used to form a driving pattern recognition system based on several driving cycles. The key characteristics of driving conditions of PHEVs are covered, which can describe and predict the whole working conditions, and improve the accuracy of the driving pattern recognition model.