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An instantaneous optimization strategy based on efficiency maps for internal combustion engine/battery hybrid vehicles

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ABSTRACT

This paper presents an instantaneous optimization algorithm based on the knowledge of the efficiency maps of the internal combustion engine (ICE) and the generator for the energy management system in hybrid electric vehicles. The proposed method formulates a new cost function representing the analytical expression of the overall energy efficiency of the hybrid energy source (i.e. ICE/generator set + battery pack) which is calculated based on the energy flow at the DC bus. Engine operating points are determined by assessing not only the efficiency map of the engine but also the efficiency map of the generator and the charge/discharge efficiency of the battery pack in order to maximize the efficiency of the energy delivered from the hybrid energy source to the drive system. The performance of the proposed method is analyzed and demonstrated on a hybrid electric bus developed in MATLAB/Simulink for different driving cycle conditions and the results have been compared with alternative optimization methods such as equivalent consumption minimization strategy (ECMS), model predictive control (MPC) and dynamic programming (DP) approach. The simulation results show that the proposed method provides a competitive performance with a lower computational burden compared to the alternative methods for different state of charge (SOC) ranges and drive cycle conditions.

1. Introduction

Effective control strategies are essential for the energy management system (EMS) of hybrid electric vehicles (HEV) and can be classified into two main categories [1]. These are rule based and optimization based control strategies.

Among rule based control strategies, fuzzy logic controller (FLC) is the most useful approach and widely used in many studies [2–5]. They are applicable in real time, easy to understand, flexible and robust but highly dependent on the application (i.e. powertrain topology and driving cycle) as well as on the selection of the control parameters and membership functions. Rules are extracted from heuristic knowledge, experimental data and even from mathematical models. As it is not based on the formal optimization techniques, cost functions are not defined explicitly and the results are generally suboptimal.

However, optimization based control strategies aim to minimize or maximize a cost function which is a measure of some objectives such as minimization of fuel consumption and exhaust emissions, improving of energy efficiency and driving comfort, weight reduction, and cost-effectiveness. Among global optimization methods, dynamic programming (DP) is the popular one. It is based on the Bellman's Principle of Optimality and widely used in optimization problems of hybrid electric vehicles [6–9]. DP methods guarantee a global solution as the entire driving cycle is assumed to be known a priori. They are not suitable for real time applications but rather for comparison of the performance of other control techniques. There is also a study in [10] which aims to maximize the efficiency of the powertrain by reducing the power losses of the ICE, generator and the battery pack using genetic algorithm. The other global optimization algorithms used in hybrid vehicles can be found in [11].

Real time optimization methods find the optimal solution without requiring any future information but do not guarantee a global solution will be found. However, they are suitable for real time applications. Within instantaneous optimization methods, equivalent consumption minimization (ECM) technique is the most well-known and was first introduced by Paganelli et al. [12,13]. This method formulates a cost function as a sum of the real fuel consumption and the fuel consumption weighted with a penalty function. A penalty function that is related to the SOC variation of the energy storage systems is a simple term and can be added to the cost function easily but it should be chosen carefully as it directly affects the performance of the optimization [14]. At each time in-

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stant, there exists a local optimum that minimizes this cost function. Although this method does not yield a global solution, it is fast and computationally inexpensive. In [15], such an instantaneous optimization control strategy has been developed for a novel series-parallel hybrid electric bus to optimize the cost function which is constituted of equivalent fuel consumption of battery and the real fuel consumption of engine. A similar approach has been also used in [16] for series hybrid electric truck that controls the power flow between the multiple energy sources so as to minimize the fuel consumption. In order to eliminate the sensitivity of the optimization problem to the penalty function, adaptive equivalent consumption minimization strategies (AECM) have been also developed. In these strategies, penalty function is updated adaptively based on the estimated vehicle speed [17].

There are also some studies that have used the combination of rule based and optimization based methods. For example, in [18], a rule based ECM method has been proposed as an optimization strategy for cumulative fuel consumption minimization. A comprehensive overview of the control strategies used in hybrid and plug-in hybrid electric vehicles has been provided in [19,20]. The common objective of all these control strategies is to manage the energy sources in such a way that the controller meets the drive cycle requirements by optimizing a cost function under a variety of constraints.

In this work, a simple and practically implementable real time instantaneous optimization strategy is developed based on the knowledge of the efficiency maps of the ICE and the generator for the energy management system in a series hybrid electric bus. A new cost function to be maximized is defined based on the analytical expression of the overall energy efficiency of the hybrid energy source which is calculated based on the energy flow from energy sources to the DC bus in traction mode and vice versa in regenerative mode. Optimum engine operating points are determined not only according to the individual engine efficiency map but also to the efficiency map of the generator and to the efficiency of the battery pack. Thus, the efficiency of the energy delivered from the hybrid energy source (ICE/generator set + battery) to the drive system will be maximized by optimizing the cost function with the proposed optimization strategy. The rest of the paper is organized as follows. In Section 2, the models of the energy sources are established. A more general representation of the battery terminal voltage including the peukert effect and coulombic efficiency is derived in the battery model and a power search algorithm that gives the maximum generator output power in the operating speed range of the engine is developed in genset model. Then, the proposed optimization strategy is introduced in Section 3. In this section, the architecture of the EMS is presented and the optimization problem with constraints is set up. In Section 4, ECMS and model predictive control (MPC), which were implemented for comparison purposes in simulation study, have been introduced as alternative optimization strategies. Section 5 provides comparative simulation results from the proposed optimization strategy and the alternative strategies applied to the series hybrid electric bus for different driving cycle conditions. Finally, the discussions and the conclusions are given in Section 6.

2. Modeling of hybrid energy source

Hybrid energy source is composed of at least two different energy sources. In this study, these energy sources are the Li-ion battery pack and the diesel engine-generator set (genset). The hybrid energy source in a series hybrid electric vehicle (SHEV) architecture can be seen in Fig. 1. The requested power is distributed between the genset and the battery pack with the aim of optimizing the cost function by the proposed optimization algorithm.

The battery pack and the genset unit that constitute the hybrid energy source have been modeled in the following sections.

2.1. Battery model

Battery pack can be modeled simply as a voltage source in series with charge and discharge resistances as shown in Fig. 2 [21].

$V_{OC}(\mathrm{SOC})$, $R_D(T^\circ, \mathrm{SOC})$ and $R_C(T^\circ, \mathrm{SOC})$ are the open circuit voltage (OCV), equivalent discharge and charge resistances varies with the temperature and the battery state of charge (SOC). The variation of R_D and R_C with SOC and temperature is not linear as formulated in [39],

$$R_{eq} = (z_1 + q(\mathrm{SOC} - z_2))(1 + \alpha(T_{amb} - 300))$$

where z_1 is a constant term, z_2 is the reference SOC value, q is the weighting factor, α is the thermal coefficient and T_{amb} is the ambient temperature. All these parameters can be calculated from the experimental measurements provided by the manufacturer. In this study, we have generated two dimensional look-up tables from the resistance vs. SOC and temperature curves provided by the battery manufacturer in order to model the nonlinear behavior of the internal resistances. D_1 and D_2 diodes can be assumed as ideal since the DC bus voltage is high enough. I_B is the battery terminal current and is calculated as,

$$I_B(k) = P_B(k)/V_B(k) \tag{1}$$

P_B is the required battery power determined by EMS and V_B is the terminal voltage. I_B can also be calculated from the following equation.

$$I(t) = -dQ(t)/dt \tag{2}$$

where k indicates discrete time step in Eq. (1) and t is the continuous time in Eq. (2) such that $t = kT$ and T is the sampling time in second. Eq. (2) can be written in discrete form based on this definitions and notations as,

$$I_B(kT) = -\frac{\Delta Q(kT)}{\Delta(kT)} = \frac{Q((k-1)T) - Q(kT)}{kT - (k-1)T} = \frac{Q((k-1)T) - Q(kT)}{T} \tag{3}$$

Hereafter, for simplicity of notations, kT is denoted as k. Thus, Eq. (3) becomes as follows,

$$I_B(k)T = Q(k-1) - Q(k) \tag{4}$$

When considering λ_c (coulomb efficiency) and p (peukert effect), Eq. (4) can be expressed as,

$$I_B(k)^p \lambda_c T = Q(k-1) - Q(k) \tag{5}$$

$Q(k)$ is the electric charge, generally provided in A h and represents the battery capacity. p is the peukert number which is directly related with the internal resistance of the batteries and has a significant effect at high discharge current. λ_c is the coulomb efficiency which is the ratio of the number of charges that enter the battery during charging process to the number of discharge that is extracted from the battery during discharging process. It depends on the battery temperature and the SOC of the batteries. The dependency of the coulomb efficiency to the SOC in lithium-ion batteries can be expresses as [22],

$$\lambda_c = (-0.0197\mathrm{SOC} + 100)\% \tag{6}$$

Both p and λ_c are calculated experimentally (i.e. $1 < p < 1.2$, $0.95 < \lambda_c < 1$). There is a linear relationship between OCV and SOC [23] that can be defined as,

$$\overline{V}_{OC} = \overline{K}_1 \overline{\mathrm{SOC}} + \overline{K}_2 \tag{7}$$