Energy Conversion and Management 87 (2014) 410–420

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Optimal control based algorithms for energy management of automotive power systems with battery/supercapacitor storage devices

AnhTu Nguyen *, Jimmy Lauber, Michel Dambrine

LAMIH Laboratory, UMR CNRS 8201, 59313 Valenciennes Cedex, France

ARTICLE INFO

Article history:
Received 19 April 2014
Accepted 12 July 2014
Available online 1 August 2014

Keywords:
Energy management system
Vehicular electric power system
Battery and supercapacitor
Pontryagin's Minimum Principle
State constraints

ABSTRACT

The objective of this work is to show how to control the electric power systems of a vehicle in such a manner that their power flows should be optimized in the sense of energy efficiency. As will be seen, the control problem considered in this work can be formulated as an optimization problem in the presence of several constraints. A systematic approach based on optimal control will be adopted to design the energy management strategies. Then, by means of these strategies, the electric energy will be generated and stored in the most appropriate manner so that the overall energy consumption and eventually the pollutant emissions can be minimized for a given driving cycle. To this end, both non-causal optimization method using the knowledge of the entire driving cycle and causal one are developed for two case studies with different structures of energy storage system. These strategies are then evaluated in an advanced simulation environment to point out their effectiveness.

1. Introduction

Over the years, the demand of electric power consumption in conventional vehicle has become more and more important. This is due to the fact that automotive customers are more and more demanding in terms of performance, comfort and safety for their new vehicles. Hence, the number of auxiliary electric-powered devices has been constantly increased in modern vehicles, e.g. active suspension, electric brakes, catalyst heaters, etc. This increasing demand tends to double or triple the current vehicle electric load [1]. Besides improving the efficiency of the electric components, an effective energy management strategy (EMS) is also crucial to minimize the overall energy consumption of the vehicle.

In this work, the key feature of the studied vehicle consists in the presence of an electrical supercharger (eSC) in the turbocharged air system of the spark-ignition (SI) engine. This device aims at assisting the main turbocharger to reduce the effects of "turbo lag", i.e. slow engine torque dynamics and lack of torque at low speeds. As a consequent, the drivability is significantly improved. The energy consumption of the eSC is provided by the vehicular electric power system. To this end, the vehicle is equipped with an advanced alternator which is controlled in power. Note that this alternator is directly coupled to the vehicle primary shaft; therefore, the engine operating point can be shifted by controlling the alternator output power. This fact offers one degree of freedom for energy optimization as in the case of classical parallel hybrid electric vehicles. However, this small capacity alternator is exclusively used to generate the energy for the electric power system and cannot assist the internal combustion engine (ICE) to propel the vehicle. Note also that the considered alternator can also recover the kinetic and potential energy during the regenerative braking phases. This "free energy" is then stored in the energy storage system (ESS) and will be used later in appropriate ways.

From the above remarks, it is clear that the energy management becomes very attractive to improve the overall energy efficiency of the studied vehicle. Because of industrial specifications, the developed strategies have to satisfy several objectives. First, they can offer a global optimal solution when the driving conditions are perfectly known in advance, i.e. *offline situations*. Second, their adaptations for real-world driving situations (i.e. *online situations*) are straightforward and the resulting causal strategies behave closely as the global optimal ones. Third, the developed strategies must be simple to be implementable with limited computation and memory resources. Fourth, the strategies are based on a systematic approach so that they can be applicable to a large spectrum of component dimension without the need for extensive calibration. For all these reasons, the developed EMSs will be based on an optimal control approach using physical component models of the vehicle.

* Corresponding author. Tel.: +33 (0)3 27 51 14 88; fax: +33 (0)3 27 51 13 16.
E-mail addresses: nguyen.trananhtu@gmail.com (AT. Nguyen), jimmy.lauber@univ-valenciennes.fr (J. Lauber), michel.dambrine@univ-valenciennes.fr (M. Dambrine).

http://dx.doi.org/10.1016/j.enconman.2014.07.042
0196-8904/

Because of the relevance to this work, a brief overview concerning the optimal based energy management issue for hybrid electric vehicle [2,3] will be provided. In automotive framework, there are mainly two methods based on optimal control theory which may offer a globally optimal result in offline situations: Dynamic Programming (DP) [4] and Pontryagin's Minimum Principle (PMP) [5]. DP-based strategies are known to be very costly in terms of computation. Numerous efforts have been devoted to reduce the computation time [6]. These strategies are often used for offline purposes (performance evaluation, component sizing) [7]. Some adapted online versions can be found in [8–10]. Concerning the strategies based on PMP, their optimum could not be global as in the case of DP since the PMP only provides necessary optimality conditions. However, they are much more computationally efficient and the online adaptation is more straightforward. This is the main reason why we only deal with PMP approach in this work. In the literature, many results exist on PMP-based strategies [11,12] or the related Equivalent Consumption Minimization Strategies (ECMS) [13,14]. Besides optimal control based approaches, some rule-based methods for energy management can also be found in literature, see [15–17] and references therein.

The main focus of this paper is to propose a systematic approach to design the energy management strategies that optimize the power flow of the vehicular electric power system. To this end, both online and offline strategies are considered. Thank to these optimal based EMSs, the overall energy consumption of the vehicle is minimized under all driving situations. A preliminary study on the choice of the structure of energy storage system was carried out by our industrial partners. From that, two case studies of electric power system with the same vehicle architecture will be considered. These choices are mainly due to the acceptable cost especially for the energy storage devices compared to conventional hybrid vehicles. The first case study is as in a conventional vehicle where only the battery is used to provide all onboard electric consumption and to make the electric power system more robust against peak-power demands. In this case, the EMS will exploit the freedom that the battery offers to the alternator in deciding the moment to generate electric power. This degree of freedom is generally not used [10]. For the second case study, a hybrid storage system combining a supercapacitor [18] together with a battery will be used. Such a hybrid storage system has been widely used in automotive industry since it has both the high energy density of the battery and the high power density of the supercapacitor [19]. The supercapacitor aims at providing high currents during hard transition phases to protect the battery from fatal damages caused by over-discharge [2]. The supercapacitor is also used to store energy from regenerative braking and to reduce the battery size [19]. As will be seen, battery/supercapacitor hybrid energy storage system is more flexible in terms of optimization than the first one since it offers two degrees of freedom for EMS. However the electric structure and the control design are more complex than the first case.

In this work, we assume that the state constraints concerning the battery are not critical for optimization problem since it can be oversized. However, the supercapacitor may quickly charge and discharge due to its low specific energy compared to the battery [15]. Hence, the state constraints of the supercapacitor should be taken into account. To this end, a new form of penalty function will be proposed by introducing a dummy variable in the expression of the Hamiltonian. The strategies developed in this work are simple to implement, efficient in terms of fuel reduction and of computation times. They can be directly applied to parallel hybrid electric vehicles, and the formulation can be easily generalized to a large family of hybrid vehicles.

The paper is organized as follows. Section 2 first presents the studied vehicle structure with its two different electric power systems. Then, the models of some vehicle components used for control purpose are provided. In Section 3, the optimal control problems are formulated for both case studies and the Pontryagin's Minimum Principle is then applied to design the EMSs. Section 4 is devoted to the implementation issue of the developed EMSs on an advanced dynamic vehicle simulator and the analysis of the obtained results. To this end, the brief description of simulator is first given. Then, a discussion on how to use the optimal control outputs and also a simple adaptation idea to obtain causal strategies from optimal ones are presented. Next, the simulation results are performed to show the effectiveness of the developed strategies. Finally, a conclusion is given in Section 5.

2. Vehicle description and control-based models

The considered vehicle architecture is depicted in Fig. 1. The notations are given in Appendix A.

The vehicle is equipped with a conventional powertrain with 5-speed manual transmission. The alternator is connected to the engine with a fixed gear ratio. The only difference between the two considered case studies consists in their electric power system, i.e. the "Electric System" block in Fig. 1. The power flow of both case studies is described below.

2.1. Case study 1: single storage electric power system

The power flow in this case is sketched in Fig. 2. The direction of the arrows corresponds to the direction of the energy exchange between different components.

The ICE produces the mechanical power P_{ice} from chemical energy (fuel). This mechanical power P_{ice} is divided into two parts. The first part P_{dr} is used for vehicle propulsion. The second one $P_{alt,m}$ is delivered to the alternator and then converted to electrical power $P_{alt,e}$. The alternator generates the power to satisfy the demand P_{loads} of all onboard auxiliaries including the eSC. It is also used to charge the battery when necessary. The battery power P_{bat} can be negative (when it is charged by the alternator) as well as positive (when it provides electric power for all electrical loads). It should be noticed that the eSC is controlled by engine control unit (ECU) which is out of the present work scope. However, its energy consumption profile is known and will be considered as an input of the developed EMSs.

2.2. Case study 2: dual storage electric power system

A sketch of the power flow in this case is depicted in Fig. 3. It is worth noting that Case study 1 is nothing else than a special case of Case study 2 where the supercapacitor and the DC/DC converter are removed from the electric power system.

It can be observed that the consumption of onboard auxiliaries P_{aux} can be powered either by the alternator or by the battery. The battery is also used to charge the supercapacitor through the DC/DC converter. However, the supercapacitor cannot charge the battery in this electric structure; it is exclusively used to power the eSC.

2.3. Vehicle control-based model

The control models are used to develop the energy optimization algorithm. At each sampling time, the energy optimization algorithm computes the optimal control sequences that minimize the energy consumption of the vehicle. For real-time applications, the control model should have a very limited complexity. Hereafter, some control models of the components of interest for both case studies will be described. It is worth noting that for