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Disturbance rejection of battery/ultracapacitor hybrid energy sources ☆

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ABSTRACT

This paper contributes an active control strategy to reject disturbances in hybrid energy source systems applied in hybrid electric vehicles. The disturbances include persistent disturbances introduced by engine torque ripples compensation, and transient disturbances caused by transient load power demands. The disturbance rejection is achieved via singular perturbation theory. The original system is a Port-Controlled Hamiltonian (PCH) system, and the controller is designed based on interconnection and damping assignment. Experimental results verify the effectiveness of the disturbance rejection control.

1. Introduction

In the context of the worldwide energy conservation and emission reduction, the study of electric vehicles (EVs) and hybrid electric vehicles (HEVs) appeals to numerous researchers. In EVs, where fuel cells or batteries serve as a primary energy source, a main issue is to deal with the transient power during acceleration and deceleration. Exposing to such rapid power variations, fuel cells or batteries, having relatively low specific power, will reduce the life cycles. Consequently, researchers have proposed to integrate ultra-capacitors (UCs) to achieve a complementarity between the specific energy and the specific power, so as to provide a better performance (Lin & Zheng, 2011; Thounthong, Rael, & Davat, 2009; Wong, Idris, Anwari, & Taufik, 2011; Zandi et al., 2011). In Hilairet et al., 2013, the authors have chosen a load which has to be known and expressed as a resistance. In our paper, the disturbances could be sinusoidal, step or others forms. This transient disturbance appears not only in EVs but also in HEVs. Yoo, Sul, Park, and Jeong (2008), Cao and Emadi (2009), and Laldin, Moshirvaziri, and Trescases (2013) present the hybridization of battery and UC applied in HEVs. UC, due to its high specific power, is able to provide high energy in a short time and afford large numbers of charge-discharge cycles (Winter & Brodd, 2004). In the aforementioned references, the function of UC in the hybrid structures of energy sources is mainly to supply reversible impulse energy, in other words, is to supply or capture the transient power during acceleration or deceleration.

This paper studies the battery/UC hybrid energy source applied in HEVs and considers not only transient disturbances, but also persistent periodical disturbances. In our context, these periodical disturbances are caused by the compensation of the torque ripples of the internal combustion engine (ICE) through the electrical drive (Cauet, Coirault, & Njeh, 2013; Njeh, Cauet, Coirault, & Martin, 2011). This will be elaborated in the following sections. Thus, the UC is able to absorb both the transient and the persistent current disturbances causing battery wear. Moreover, instead of modelling the electric machine as a resistive (and inductive) load of the energy sources system (Ayad et al., 2010; Hilairet et al., 2013), this paper considers it as an exosystem (see Fig. 1). Thus, the disturbances can be considered as an exogenous disturbances generated by this exosystem.

There exist some well-developed theories dealing with exogenous persistent disturbances. Tracing back to 1970s, Francis and Wonham have studied time invariant linear systems with exogenous disturbances (Francis & Wonham, 1976; Francis, Sebakhy, & Wonham, 1974). In 1990s, Byrnes and Isidori have extended the related theories into non-linear systems (Byrnes, Priscoli, & Isidori, 1997; Byrnes, Priscoli, Isidori, & Kang, 1997; Isidori & Byrnes, 1990). Afterwards, van der shaft has applied and extended the theories into port-controlled Hamiltonian (PCH) systems (Gentili &

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van der Schaft, 2003). These theories focus on persistent periodical disturbances but not transient disturbances. The main contribution of this paper is to consider both kinds of disturbances in a multi-electrical energy source and propose a novel control structure based on the singular perturbation theory (Khalil & Grizzle, 2002; Kokotović, Khalil, & O'Reilly, 1986). The system is divided into a fast system and a slow system. The slow system, called the degenerated system, is a PCH system and the controller can be achieved through interconnection and damping assignment (IDA) (Ortega & Garcia-Canseco, 2004).

The paper is organized as follows: Section 2 gives the origin of the disturbances, the control objective, and the system model. Section 3 introduces the system and defines static solutions and dynamic solutions. The contributed controller is presented in Section 4. Experimental results are given in Section 5. Finally, conclusions are drawn in Section 6.

2. Problem statement and system modelling

Fig. 1 gives the configuration of the battery/UC hybrid energy storage system applied in HEV. The propulsion system consists of an ICE and an electric machine, providing propulsion to the load vehicle. The electric machine is connected to the DC bus with an inverter (DC–AC converter). Cauet et al. (2013) present an active control method of the DC–AC converter, aiming to control the torque of the electric machine, so as to compensate the torque ripple of the ICE, to achieve a smooth rotational speed on the crankshaft. The torque disturbances are composed of harmonics for each speed operating point. Their compensation by the electrical motor generate harmonic currents. These currents can damage the battery. Fast accelerations and decelerations of the vehicle likewise product transient currents. The most important objective of the DC/DC controller is to separate the high frequency and low frequency disturbances. In this case, the fast transient are generated by the Ultracapacity and the low transient by the battery.

This paper focuses on the hybrid energy storage system connected to the DC bus with two DC–DC converters. This structure provides the flexibility to achieve the control objective. In Hilairet et al. (2013), the propulsion system is considered as a combination of a resistive load and an inductive load. In this paper, the whole propulsion system is considered as an exosystem. Thus, the influence of the exosystem to the hybrid energy storage system can be regarded as a measured exogenous current, denoted by $d(t)$. This current may be positive or negative. Positive current indicates that the electric machine operates in generator mode; while negative current implies that the electric machine works in motor mode.

Consider the exogenous current $d(t)$ as a combination of a constant component $\bar{d}$ and a variable component $\tilde{d}(t)$, i.e., $d(t) = \bar{d} + \tilde{d}(t)$. $\tilde{d}(t)$ is regarded as an exogenous disturbance which could be transient and persistent. The former is due to the instantaneous load power demand during vehicular acceleration and deceleration, and has been widely studied in the literature; the latter is due to the torque ripples compensation. The ripples are then transferred to the DC part. Consider the electrical part in Fig. 1. From energy conservation point of view, neglecting the losses in the circuit, the power on the DC bus ($P_{dc} = V_{dc}I_{dc}$) is totally delivered to the electric machine ($P_{pmsm} = T_{pmsm}\omega_m$). This is equivalent to:

$$V_{dc}I_{dc} \approx T_{pmsm}\omega_m$$

where V_{dc} and I_{dc} are the voltage and current on the DC bus respectively. T_{pmsm} is the electrical torque, and ω_m is the rotational speed on the crankshaft. In order to achieve a smooth rotational speed (constant ω_m), T_{pmsm} is assigned to compensate the torque ripples of the ICE. Thus, the ripples are transferred to the DC bus. Without proper controller of the DC converters, these ripples will not only cause an oscillating DC bus voltage but also introduce ripple current in the battery. Batteries, having high specific energy but low specific power, wear down quickly exposing to such substantial and persistent current disturbances.

Therefore, it is necessary to reject the disturbances through a powerful active control. The control objective is summarized as follows:

- to absorb the disturbances causing battery wear by the UC side converter. Mathematically, the current through the ultracapacitor side converter I_{L_2} is expected to be equal to the current disturbance $\tilde{d}(t)$, i.e., $I_{L_2} = \tilde{d}(t)$;
- to maintain a constant voltage in the DC bus; and
- to maintain the state of charge of the UC around its nominal value.

Mathematically, disturbances $\tilde{d}$ could take the following two forms:

- Persistent disturbance, $d(t)$, is a quasi-harmonic disturbance, and defined as $d(t) = \sum_{i=1}^{N} a_i(t)e^{j\phi_i(t)}$, where a_i and ϕ_i change with the dynamics of ω_m which are slower than the battery

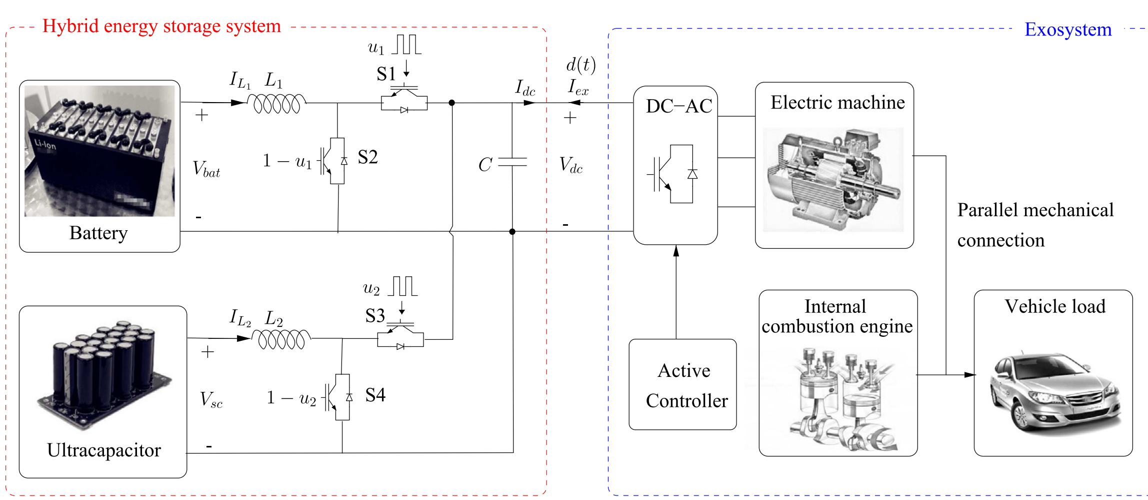

Fig. 1. Battery/UC hybrid energy storage system in hybrid electric vehicles.