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Hybrid electric vehicle fuel minimization by DC-DC converter dual-phase-shift control

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ABSTRACT

The paper introduces an advanced DC-link variable voltage control methodology that improves significantly the fuel economy of series Hybrid Electric Vehicles (HEVs). The DC-link connects a rectifier, a Dual Active Bridge (DAB) DC-DC converter and an inverter, interfacing respectively the two sources and the load in a series HEV powertrain. The introduced Dual Phase Shift (DPS) proportional voltage conversion ratio control scheme is realized by manipulating the phase shifts of the gating signals in the DAB converter, to regulate the amount of DAB converter power flow in and out of the DC-link. Dynamic converter efficiency models are utilized to account for switching, conduction, copper and core losses. The control methodology is proposed on the basis of improving the individual efficiency of the DAB converter but with its parameters tuned to minimize the powertrain fuel consumption. Since DPS control has one additional degree of freedom as compared to Single Phase Shift (SPS) voltage control schemes, a Lagrange Multiplier optimization method is applied to minimize the leakage inductance peak current, the main cause for switching and conduction losses. The DPS control scheme is tested in simulations with a full HEV model and two associated conventional supervisory control algorithms, together with a tuned SPS proportional voltage conversion ratio control scheme, against a conventional PI control in which the DC-link voltage follows a constant reference. Nonlinear coupling difficulties associated with the integration of varying DC-link voltage in the powertrain are also exposed and addressed.

1. Introduction

Transport is a significant contributor of carbon emissions, only coming second to Energy (Committee on Climate Change, 2015). The vast majority of these emissions come from road transport and are currently on the rise (Edenhofer, 2014). The hybrid electric vehicle (HEV) has been identified as critical for achieving sustainable transportation, by decreasing consumption of fossil fuels (Bose, 2013). According to Khaligh, Rahimi, and Emadi (2008) there is a strong potential to enhance the sustainable impact of HEVs by improving their efficiency, with significant advances already achieved in the last decade by smart supervisory control systems that manage the powertrain energy flow (Wirasingha & Emadi, 2011). The present paper represents an attempt to contribute to this goal by proposing DC-link voltage controls to operate series HEV powertrains more efficiently and improve their fuel economy.

Various HEV topologies exist. A DC-DC converter is included in architectures in which the DC-link and electric energy store (generally a chemical battery) operate at different voltages, to act as the interface between them. Many types of DC-DC converters have already been employed in this context, ranging from standard boost (Estima & Cardoso, 2012), three-level (Dusmez, Hasanzadeh & Khaligh, 2014), isolated dual half- and full-bridge (DAB) (Al-Sheikh et al., 2014; Inoue & Akagi, 2007; Krismer & Kolar, 2012; Li et al. 2003; Rathore & Prasanna, 2013) and other converters (Amjadi & Williamson, 2010). The DAB converter, included in the present research, has become popular due to its advantages in power controllability, bi-directionality, soft-switching ability and high efficiency (Zhao, Song, Liu, & Sun, 2014). Operation under soft-switching has particularly received wide attention in an attempt to achieve energy loss minimization (Chen, Rong, & Lu, 2010; Ma et al., 2009). The loss reduction is achieved by zero-voltage-switching (ZVS) or zero-current-switching (ZCS) in all the

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Abbreviation: DAB, Dual Active Bridge; DPS, Dual Phase Shift; HEV, Hybrid Electric Vehicle; ICE, Internal Combustion Engine; PFC, Power Follower Control; PL, Propulsion Load; PMSG, Permanent Magnet Synchronous Generator; PMSM, Permanent Magnet Synchronous Motor; PS, Primary Source of energy; SCS, Supervisory Control System; SOC, State Of Charge; SPS, Single Phase Shift; SS, Secondary Source of energy; TCS, Thermostat Control Strategy

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converter switches, but this comes at the expense of additional components and more complex control. Furthermore, the reduction is obtained mainly in the switching losses which is only one of the loss mechanisms in the converter.

The simplicity and ease of implementation of the single phase-shift (SPS) control has established it as the classical control methodology of DAB converters. In this scheme, the average power flow through the converter can be regulated directly by the phase shift input. However, operation under SPS control is marred by circulating currents and reactive power, which increase the energy losses (Bai & Mi, 2008). Various other control algorithms, involving different phase-shift and modulation strategies, have been proposed in the literature with the aim of increasing the DAB converter efficiency (Krismer et al., 2006; Oggier, García & Oliva, 2011; Zhou & Khambadkone, 2009). These schemes, however, have disadvantages related to implementation complexity, limited power range and limited operating range. Dual phase-shift (DPS) control, which manipulates two phase-shifts as control inputs, has emerged as a suitable algorithm to eliminate reactive power and increase efficiency (Bai & Mi, 2008; Wen & Su, 2015; Zhao, Song, & Liu, 2013).

Beyond the provision of the interface, the deployment of a DC-DC converter in a series HEV powertrain facilitates the controlled variation of the DC-link voltage by manipulating the converter electronic switches via their gating signals. Studies on DC-link control already exist, with a precursor of such work found in Estima and Cardoso (2012). This work compares two single source electric drive systems in which a battery either supplies an inverter directly or does so via a bidirectional boost converter, to power a Permanent Magnet Synchronous Motor (PMSM). The presence of the boost converter enables control of the DC-link voltage, and it is shown that when the voltage is changed in proportion with the PMSM speed, overall efficiency improvements result.

In Song and Wang (2014) a more complex dual source topology is considered corresponding to series HEV powertrains. It comprises a DC-link with a three-phase rectifier interfaced engine-generator set, a bidirectional DC-DC converter interfaced battery, and a three-phase inverter interfaced motor. The work proposes improved operation reliability by implementing DC-link voltage control which maintains a constant inverter modulation index. The principle followed is that reliability deteriorates with increasing converter energy losses, hence the underlining objective of the DC-link control is to reduce these losses. However, while the constant modulation index objective is beneficial to the inverter losses, it is not necessarily the optimal rule for DC-DC converter loss reduction. Furthermore, Song and Wang (2014) does not account for the rectifier losses and the effect of the voltage control on these losses.

A similar series HEV powertrain, with a DAB DC-DC converter, is treated in Roche, Shabbir and Evangelou (2016) with the objective to reduce the losses in all the electronic converters. This work develops a process to choose the most appropriate nominal DC-link voltage for maximized inverter and rectifier efficiencies. It also designs a DC-link voltage control that pushes the DAB converter in boost/buck operation when the battery charges/discharges, such that it avoids hard switching losses persistently in its whole operating range. Thus it achieves substantially higher converter efficiency than conventional constant voltage control schemes. Nevertheless, this study does not consider the impact of the varying DC-link voltage on the overall efficiency of the powertrain and hence on the fuel economy.

The present research develops a novel, efficient and powerful DC-link voltage control algorithm for a series HEV that optimizes the overall system efficiency, by dual-phase-shift control of the DAB DC-DC converter. In order to provide the appropriate context for comparison the research also contributes a single-phase-shift algorithm for DC-link control, based on the approach in Roche et al. (2016), which has further been adapted and optimized for overall system efficiency. System efficiency is quantified by utilizing the concept of equivalent fuel consumption which accounts for both the real fuel and battery charge consumption. Both control schemes developed are compared with a conventional PI constant DC-link voltage control scheme in extensive simulations with a comprehensive HEV mathematical model. The investigation in this paper represents an application of DPS control in a significantly more complex setting than in existing literature, which essentially considered DPS control of a DAB DC-DC converter utilized at simple boundary conditions of constant input voltage and constant power out to a resistive load (Kim, Rosekeit, Sul, & De Doncker, 2011; Wang, Wu & Lee, 2013; Wen & Su, 2015; Zhao et al., 2013).

The paper structure is as follows. Section 2 describes: (a) the basis HEV model that is used to conduct the research, (b) the supervisory control strategies employed to simulate the HEV model, (c) the modeling of the inverter and rectifier power loss respectively for varying PMSM and Permanent Magnet Synchronous Generator (PMSG) operating conditions, and (d) the operating mode dependent DAB converter switching, conduction, copper and core loss modeling. Section 3 describes the DC-link control schemes developed and tested in this work: the constant voltage PI control, and the SPS and DPS proportional voltage conversion ratio control schemes. Simulation results are presented in Section 4, including a description of the tuning of the voltage controls, and a comparison of their characteristics and performance in terms of power profile, evolution of DC-link voltage and modulation indexes, converter losses and fuel economy. Conclusions are drawn in Section 5.

2. Modeling

The HEV model utilized in this paper is high-fidelity. It corresponds to a general-purpose passenger car and is based on that presented in Roche et al. (2016) and Shabbir (2016), with earlier versions of the model found in Evangelou and Shabbir (2016) and Evangelou and Shukla (2012). As in the basis model, the present model characterizes the dynamic efficiency for both the inverter and rectifier by including modulation-index dependent conduction and switching losses. The DAB converter design employed in this work reduces the emphasis on soft switching and hence a corresponding concise loss model is utilized, which has been developed in Evangelou & Rehman-Shaikh and is based on the model in Zhao et al. (2013). The HEV model, supervisory control schemes, and inverter, rectifier and DC-DC converter dynamic efficiency models employed are summarized in this section.

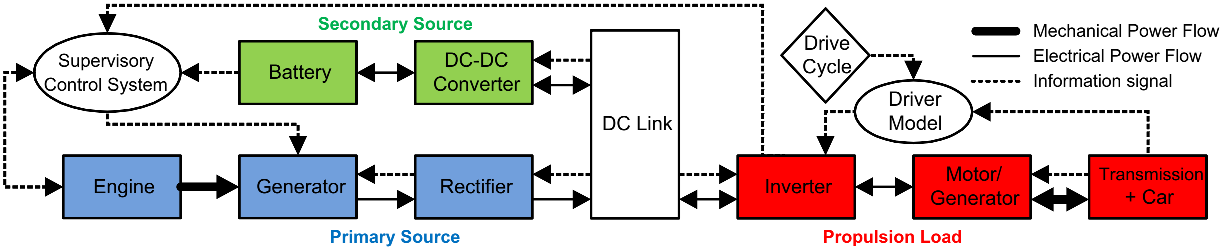

Fig. 1. High level block diagram of the series HEV powertrain used in this work (Evangelou & Shabbir, 2016).