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Integrated modeling and analysis of dynamics for electric vehicle powertrains

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ABSTRACT

Powertrain of an electric vehicle (EV) is a compound system with an electrical sub-system, such as batteries, inverters, and electrical motors, as well as a mechanical sub-system, including transmissions, differential, and wheels. Since the electrical systems directly affect the vehicle driving performance and dynamics of an EV, integrated modeling considering both the mechanical and electrical systems is essential to assess ultimate kinetic and dynamic characteristics of an EV in terms of input electrical quantities. In this paper, an entire analytic model for the powertrain of EVs is developed to describe EV dynamics with respect to electrical signals, in consideration of both mechanical and electrical systems. Theoretical models based on mathematical expressions, combining the mechanical power system and the electrical power systems, are derived for predicting the final vehicle driving performance as a function of electrical quantities. In addition, a Matlab model of an EV is developed to verify the derived mathematical analysis model. Based on the theoretical model of the powertrain, a variety of relationships between electrical quantities and vehicle dynamics, such as velocity, acceleration, and forces of the EVs, are finally investigated and analyzed.

1. Introduction

Recent issues of exhausting fossil fuels and global warming caused by internal combustion engine (ICE) vehicles have led to considerable efforts to develop EVs as environment-friendly vehicles utilizing electrical energy sources (Butler, Ehsani, & Kamath, 1999; García, Torreglosa, Fernández, & Jurado, 2013). There is a large difference between the drivetrain system of EVs and ICE vehicles. In contrast with conventional ICE vehicles, the powertrain systems of EVs run electric motors through electrical energy stored in batteries. Accordingly, EVs are equipped with power electronics circuits, such as DC–DC converters and DC–AC inverters. Permanent magnet synchronous motors (PMSMs) applied to EVs has recently become more common, due to their various advantages, such as light weight, easy control, high power factor, and high torque density. In particular, interior PMSMs of compact size, high efficiency and with small torque ripples, have been commonly used for EVs (Murakami, Kataoka, Honda, Morimoto, & Takeda, 2001; Na, Park, Kim, & Kwak, 2011). Electrical energy is transformed to mechanical energy through the electrical motors, in order to provide mechanical power to drive the wheels. Since the powertrain system of an EV is a complex system with both the electrical and the mechanical sub-systems, it is necessary to model and analyze the powertrain systems of the EV in consideration of the two sub-systems, to clearly address the vehicle dynamics. In particular, integrated modeling and analysis of the entire EV powertrain system is required to discover how a variety of vehicle dynamic characteristics are related with electrical quantities (Gao, Mi, & Emadi, 2007). However, analytic studies on EV powertrains have been mostly focused on modeling and analysis of mechanical power system without taking electrical systems into consideration (Ehsani, Rahman, & Toliyat, 1997; Kroeze & Krein, 2008; Mapelli, Tarsitano, & Mauri, 2010; Nair & Rajagopal, 2010; Onoda & Emadi, 2004; Powell, Bailey, & Cikanek, 1998). Systematic analysis integrating the electrical and the mechanical sub-systems until now have been missing in the literature. Generic EV models have been designed by utilizing computer-aided simulation tools, such as Matlab/Simulink without deriving mathematical analysis (Kroeze & Krein, 2008; Nair & Rajagopal, 2010). Some theoretical analyses of EV powertrains have been, without investigating explicit correlations between vehicle dynamics and electrical quantities, implemented based on models for mechanical components (Ehsani et al., 1997; Mapelli et al., 2010; Powell et al., 1998).

This paper constructs behavior models based on mathematical approaches for respective electrical and mechanical sub-systems. With numerical analysis for the two sub-systems, integrated analytic expressions combining the two sub-systems are, through

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theoretical derivations, derived to obtain theoretical closed-form expressions. The theoretical model constructed in this paper can describe evident relationships between electrical quantities and vehicle dynamics such as velocity, acceleration, and forces of the EV. Having derived integrated theoretical models, the paper then constructs a Matlab/Simulink model for an entire EV powertrain to validate the developed mathematical analysis models. Confirming that the results from the two models are consistent for a standard vehicle speed profile, a variety of influences on vehicle dynamics, including velocity, acceleration, and forces of the EV, of electrical quantities are, in detail, presented and analyzed in this paper. The scientific innovation of this paper is developing the generic EV model based on detailed and accurate analytic models with the correlation between the electric input signals and the mechanical final output variables, which has not been covered in existing research. With theoretical analysis for respective electrical and mechanical sub-systems, integrated models of the EV powertrain with the PMSM type are derived by combining the two subsystems through mathematical derivations. Furthermore, the derived analytic models have been validated, in comparison with the simulation model developed with the Matlab/Simulink libraries, by testing with the FTP-75 driving cycle. The developed analysis models directly relates the dynamic vehicle behaviors with the electrical signals, including the motor phase currents and the angular rotor speed, which are already measured by the electrical sensors and realized for the motor controls of the EV powertrains. As a result, final EV dynamics, such as the wheel speed, the wheel torque, the vertical forces on front and rear wheel, the tractive force, and the speed/acceleration in the vehicle tractive direction, can be easily monitored and predicted using the proposed analysis models and the real-time electric signals.

2. Modeling of an electric vehicle powertrain

Depending on the mechanical structures as well as the number of motors, and, EV powertrain systems can be generally classified into six possible configurations, as illustrated in Fig. 1. According to the number of motors employed in the drivetrains, the six arrangements of the EV powertrains in Fig. 1 can be categorized with two classes: one-motor and two-motor based powertrains, which are summarized in Table 1.

Fig. 1(a)–(c) illustrate one-motor based EV powertrains, where single motor delivers driving power to wheels through mechanical constituents. The one-motor based EV powertrains have been favored, since they can maximize the utilization of existing mechanical systems in conventional ICE vehicles. As a result, the EV driveling configurations with one-motor based structure have been mostly employed for EV systems due to their structural similarity with the ICE vehicles. The differentials splitting generated torque to the wheels are essential, which enables the wheels to be driven at different speeds when vehicles turn corners (Chan, 2002). The two-motor based EV powertrains can shorten mechanical transmission paths from the electric motor to the driving wheel, as shown in Fig. 1(d)–(f). Individual motors with dedicated converters are used to provide speed and toque for respective wheels, which results in no requirements for differentials. Therefore, simplified structures in mechanical systems of the two-motor based EV drivelines are obtained at the cost of increased complexity of electrical components and controllers. The one-motor based EV drivelines have mostly been adopted in commercial EVs, while the two-motor based powertrains have been utilized for small-scale demonstrations. Thus, this paper deals with modeling and analysis of the one-motor based EV system.

The entire powertrain of the EVs shown as Fig. 1(a) is, in detail, represented in Fig. 2 with the both electrical and mechanical sub-systems, in the direction of power transmission. The electrical sub-system consists of electronic controller, power converters including a DC–AC inverter and DC–DC converter, batteries, and a PMSM. Speed profiles are obtained by driver's commands resulted from the brake and accelerator pedals operated by drivers. The speed profiles of the EVs are converted to the speed command and the torque command of the electrical motor. The electronic controller generates gating signals of the inverter to control desired speed and torque of the motor, by adjusting the magnitude and the frequency of the currents through the motor. The electrical power of the PMSM controlled by the power converter is delivered to the mechanical system via the clutch, which links the electrical and the mechanical sub-systems. The mechanical sub-system is comprised of a clutch, gearbox (transmission), differential, axle shaft, and wheels for generating driving force. Through all the mechanical constituents, final EV dynamic outputs are created as forms of a tractive force F_x, a vertical force F_z of vehicles, a vehicle speed v_x, and a vehicle acceleration a_x. Due to the direct coupling of the two sub-systems and the sequential power transmission in EVs, an integrated electro-mechanical model combining the electrical and the mechanical sub-systems enables the eventual vehicle

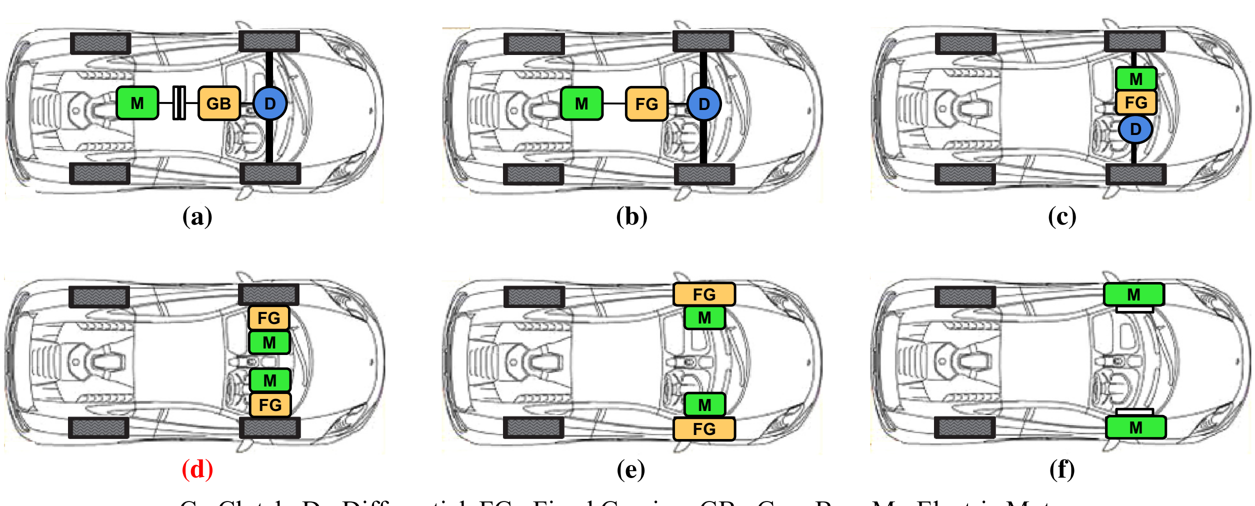

Fig. 1. Six types of EV configurations. One-motor based EV powertrains: (a) Conventional. (b) No transmission (RF). (c) No transmission (FF). Two-motor based EV powertrains: (d) No differential. (e) In-wheel with FG. (f) In-wheel without FG.