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Dynamic modeling platform for series hybrid electric vehicles

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Abstract: This paper introduces a simulation model that can be used to develop and test designs and control systems for hybrid electric vehicles (HEVs). The work involves a novel simulating platform, developed in Simulink, where each component of a series HEV is developed using a first-principles approach in a modular fashion, validated by available experimental data and then integrated to form a coupled nonlinear dynamic model. The vehicle model is capable to act as a platform for the design of supervisory control systems (SCSs) that optimize the energy flow in the powertrain. Simulations with two distinct SCSs and two driving cycles are used to analyze the vehicle performance under varying driving and operating conditions. The results demonstrate the applicability of the model for realistic prediction of both vehicle behavior and component energy losses, design optimization and control system design.

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1. INTRODUCTION

Due to environmental concerns, alternatives to the conventional vehicle are sought and the Hybrid Electric Vehicle (HEV) has emerged as a viable part of the solution. To facilitate this transition and to ensure a cost effective and rapid development of new HEV designs, it is greatly beneficial to employ modeling and simulation tools to explore and optimize designs. By now, there have been numerous studies on the subject of modeling and simulation of HEVs, however the academic literature has mainly focused on the modeling of particular HEV components, rather than the integration of entire vehicle models Van Mierlo et al. (2004); Liu and Peng (2008); Doucette and McCulloch (2011). The latter modeling capability is provided by various commercial modeling software tools, such as ADVISOR, AVL CRUISE, PSAT, PSIM and others, that are readily available.

Notwithstanding the activity in this area, it is believed that currently available modeling platforms do not yet include sufficient modeling detail or flexibility, nor are they sufficiently validated, to satisfy the objectives for which they are built. These include: (a) to help identify which aspects of the design, from component to system level, need to be modified for optimal overall operation, for example in terms of fuel economy, emissions and acceleration, (b) to study the transient behavior of each component and how it interacts with the integrated vehicle system, and (c) to improve performance by designing clever control schemes both for individual components and for the supervision of the integrated powertrain to enable optimal energy flow management. Existing models often rely on static look-up tables and performance maps that omit important transient characteristics, or on simple power-request dynamics that do not allow for the accurate scaling or for the adjustment of critical design parameters.

The present work aims to create a high-fidelity modeling and control tool that is capable of both fast computation and accurate dynamic simulation of HEVs. The task involves the modeling and control of the individual subsystems of the vehicle and its powertrain, and their integration into a coherent system model, presently of series powertrain architecture. The aim is to develop experimentally validated flexible component models in the form of equations derived from first principles, in an object-oriented manner, so that they can be used broadly in the construction of system models of any powertrain topologies beyond the series one. A key issue is therefore the accurate description of the interdependencies between the subsystems. A further important aspect of the present task is to develop SCSs that manage the energy flow in the overall system to propel the vehicle, and to achieve enhanced system efficiency and other objectives.

The paper is organized as follows. In Section 2 the component models of the HEV and their integration to an overall system model are described. Key characteristics of the models are descriptions for the hybrid-electric drive powertrain, regenerative braking, vehicle dynamics, and component-level controls. Section 3 describes the system level supervisory controllers used to regulate the energy flow through the vehicle components. Simulations of two driving cycles are conducted and the results are presented and discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. COMPONENT MATHEMATICAL MODELING

The hybrid vehicle considered in this work utilizes a series powertrain topology and represents a class of passenger vehicles that are appropriate for urban and extra-urban transportation. Its general structure, including the powertrain, is shown in Figure 1.

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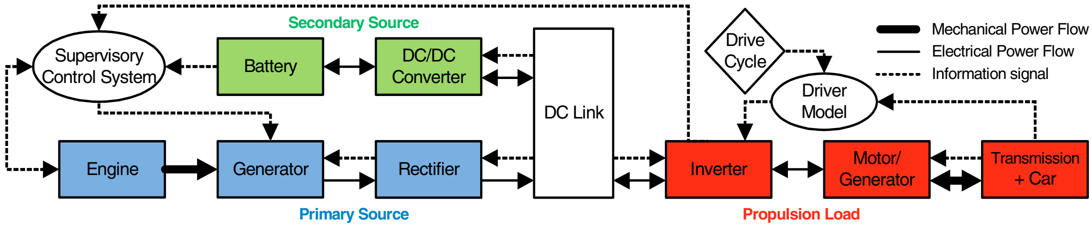

Fig. 1. Overall structure of series hybrid vehicle powertrain and main body. Thin and thick arrows correspond to electrical and mechanical energy flow respectively, while the direction of the arrows shows the direction of the flow.

The powertrain comprises: a common DC-link of 700 V, on which there are connected the Primary Source (PS) – a diesel internal combustion engine (ICE) and a Permanent Magnet Synchronous Generator (PMSG) with the associated AC/DC converter (rectifier); the Secondary Source (SS) – a battery with the associated DC/DC converter; and, the Propulsion Load (PL) – a Permanent Magnet Synchronous Motor (PMSM) with the associated DC/AC converter (inverter), together with the car. The car includes the body masses, transmission, suspension, tires and aerodynamics. The supervisory controller decides the power flow between the various powertrain components, and acts in response to the commands of a driver model that is used to enable the following of speed demands corresponding to specific driving cycles. The component models are first constructed in causal form in Simulink, with appropriate choice of inputs and outputs, and are subsequently interconnected via their inputs and outputs, and control feedback loops, to obtain the overall model. The modeling work presented here is an evolution of the work presented in Evangelou and Shukla (2012).

2.1 Propulsion Load

Car Accurate car response requires accurate representation of the longitudinal car behavior. The model built describes the longitudinal car dynamics and it is based on the multibody model presented in Thommyppillai et al. (2009), capable of general motions. The main ingredients of the model are a main body with forward and vertical translation, and pitch rotation, suspension, spinning wheels, rear wheel connection to the motor shaft via continuously variable transmission (CVT), aerodynamic lift and drag forces proportional to the square of the speed, vertically compliant and slipping tyres, tyre rolling resistance proportional to tire normal load, and regenerative braking. The parameter values used in the model are representative of a contemporary European family saloon and are taken from Thommyppillai et al. (2009), where the total mass is 1475.6 kg, the pitch inertia is 2152.1 kgm^2, and the drag coefficient is 0.35.

Permanent Magnet Synchronous Motor (PMSM) In the present work a surface mounted PMSM has been used. The associated 3-phase circuit diagram of the star-connected PMSM can be seen on the right part of Figure 2. ω_{sm} is the inverter frequency in (electrical) rad/s. The inverter frequency and the rotor speed, ω_{rm}, are related according to $\omega_{sm} = p_m \omega_{rm}$ in which p_m is the number of pole pairs per phase in the stator. The 3-phase dynamic equations can be expressed in terms of the standard 2-phase rotor

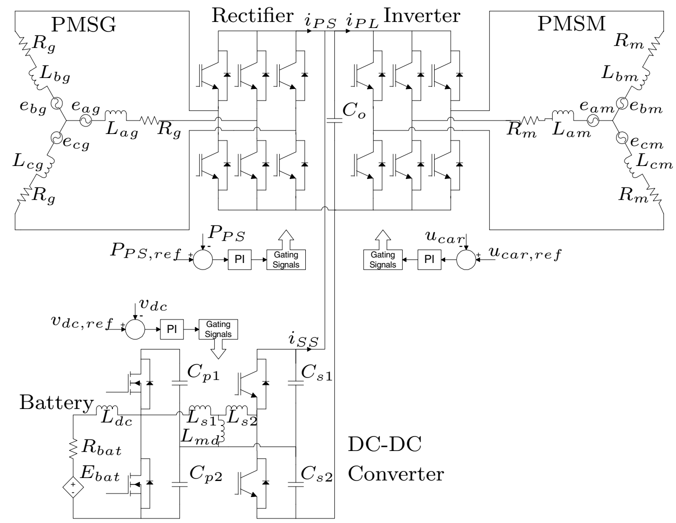

Fig. 2. Circuit diagram showing the electrical connection of the generator (PMSG), AC/DC rectifier, battery, DC/DC converter, DC/AC inverter and motor (PMSM). Symbols R, L and e represent phase resistances, inductances and induced emfs respectively. Subscripts a, b and c correspond to the individual phases, and subscripts g, m and ref correspond to 'generator', 'motor' and 'reference'. E_{bat} and R_{bat} correspond to the battery emf and internal resistance, while L_{dc}, L_{s1}, L_{s2}, L_{md}, C_{p1}, C_{p2}, C_{s1} and C_{s2} are inductances and capacitances associated with the DC/DC converter. i_{PS}, i_{SS} and i_{PL} denote the primary source (generator-branch), secondary source (battery-branch) and propulsion load (motor-branch) dc currents. C_0 is the DC-link capacitor, v_{dc} is the DC-link voltage, P_{PS} is the primary source power and u_{car} is the forward speed of the car. The signals related to the control of v_{dc}, P_{PS} and u_{car} are also shown.

d-*q* rotating reference frame Pillay and Krishnan (1989) as follows:

$$\frac{di_{dm}}{dt} = (v_{dm} - R_m i_{dm} + \omega_{sm} L_{qm} i_{qm})/L_{dm}, \quad (1)$$

$$\frac{di_{qm}}{dt} = (v_{qm} - R_m i_{qm} - \omega_{sm}(L_{dm} i_{dm} + \lambda_{fm}))/L_{qm}, \quad (2)$$

where i_{dm} and i_{qm} are the d- (direct) and q- (quadrature) axis components of stator current, v_{dm} and v_{qm} are the d- and q-axis components of stator voltage, L_{dm} and L_{qm} are the d- and q-axis stator inductances, and R_m is the stator resistance. The electromagnetic torque produced by the motor is given by Pillay and Krishnan (1989)

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