Modeling and Simulation of a Hybrid-Electric Vehicle Drivetrain

Gregory A. Hubbard
Graduate Student, Massachusetts Institute of Technology
Control Systems Development Engineer
Allison Transmission Division of General Motors Corporation

Kamal Youcef-Toumi
Associate Professor of Mechanical Engineering
Massachusetts Institute of Technology

ABSTRACT

The drivetrain of a hybrid-electric vehicle is modeled and simulated from a system level approach. The need for accurate dynamic models for developing control algorithms is motivated.

Detailed models capable of describing both transient and steady-state operation of each of the key drivetrain components are constructed. Bond graphs are the tool of choice for modeling because they focus on mechanisms of energy generation, storage, and dissipation. Further, they permit integration of submodels, give insight into component interaction, and allow straightforward derivation of governing equations. The following component models are presented: transmission, vehicle chassis/body, three-phase AC induction motor, lead-acid battery, and four cycle, four stroke, spark ignited internal combustion engine. Simulation results for these components are presented.

INTRODUCTION

As problems of air pollution and dependency on fossil fuels persist, the need for modes of transportation that alleviate these concerns grows. The hybrid-electric vehicle (HEV) offers improvements over conventional vehicles with today's technologies. The HEV blends energy generating, energy storing, and energy distributing components to achieve performance in fuel economy, emissions, acceleration, maximum speed, and range that no single element drivetrain can yet match. An HEV matching reliability and cost of conventional vehicles could capture significant market share.

Simply connecting components together does not necessarily result in an improved vehicle drivetrain. Thorough characterization of each component's idiosyncrasies is required if an optimal drivetrain is to be configured. Furthermore, supervisory control that interprets the driver's tractive effort request and manages the power flow between the components is needed. Dynamic models are used to design component and supervisory control algorithms [1].

The bond graph tool is well-suited for describing the dynamic vehicle processes. A bond graph is a pictorial representation of the power and energy phenomena in a physical system. A key benefit of the bond graph is that it describes analogous energy processes in different energy domains identically. This permits the HEV engineer to focus on general energy terms rather than the particular constitutive laws of a specific technology when characterizing physical behavior. Bond graphs of each component may be linked to others, permitting analysis of the interaction between subsystems.

VEHICLE CONFIGURATION

The vehicle under examination is a nine meter (30 ft) long urban transit bus. The bus has a wet weight, the weight of the vehicle including maximum fuel capacity, oil, batteries, and all other equipment needed for operation without passengers or driver, of 9525 kg (21,000 lb.). The bus is capable of seating 31 people, at an assumed average weight of 68 kg (150 lb.) each. The gross vehicle weight (GVW) includes the wet weight plus the maximum amount of passengers and cargo the bus can carry. For this vehicle, the GVW is 13,600 kg (30,000 lb.). The bus has a frontal cross-sectional area which is 2.74 m (9 ft) high and 2.44 m (8 ft) wide for an area of 6.69 m² (72 ft²). The aerodynamic dimensionless drag coefficient for the modernly styled bus is 0.50. The tire radius is 0.475 m (18.7 in).

The hybrid-electric drivetrain is now described. The drivetrain is that described by Mayrhofer, Kriegler, and Albrecht and presented in Figure 1 [2]. Each N represents an independent angular velocity. The C's are clutches used to achieve multiple powertrain configurations. Pure electric, series hybrid, and parallel hybrid are possible. This study is limited to the case where the planetary geartrain operates as a continuously-variable transmission (CVT), with clutches C1 and C2 locked and C3 and C4 open.

The advantage of CVT operation lies in allowing the internal combustion (IC) engine, linked to the sun gear, to operate at a speed that is independent of the velocity of the transmission output. This operation is permits the IC engine to always operate at the speed that gives either the highest efficiency, lowest exhaust emissions, or a compromise of these two for a given operating load. Electric motor 1 adds the additional benefit of permitting the IC engine to operate at the speed and load combination that consumes the least fuel or produces the fewest emissions.

The planetary gear train functions as a CVT by permitting each component, sun gear, ring gear, and carrier, to be free to rotate. CVT operation is possible because the planetary set is, in control systems terms, a two input system. Kinematically, it is a two degree of freedom system. Here, the sun gear operates at constant speed, while the ring gear velocity achieves the correct transmission ratio from sun input to carrier output. Motor 2 attains the ring gear velocity commanded by the supervisory controller.

COMPONENT MODELING

Bond graph models for each of the drivetrain components were constructed and integrated to produce the complete vehicle model. First the model for the internal combustion engine is described. Then, models for the transmission, vehicle chassis/body, electric motors, and lead-acid batteries are summarized. Each component dynamic model captures the energy storage, dissipation, and generation characteristics during both steady-state and transient operation. Pertinent simulation results are discussed.
Internal Combustion Engine

The General Motors Quad 4 engine was chosen for analysis because its power range matches the HEV mean power demand and detailed design information for it is available in the public domain [3]. The dynamic model for the internal combustion engine builds on the work of Heywood and Moskwa [4,5]. The engine model is subdivided into mechanical and thermodynamic sections. The mechanical model assumes a rigid crankshaft, an empirical energy dissipation function for cam losses from Armstrong and Buuck, and an empirical energy dissipation function for bearing losses from Bishop and Heywood [6,7,4]. One state equation describing the flywheel velocity incorporates all significant inertias reflected via slider-crank kinematic equations to the flywheel.

The thermodynamic section of the engine model is a zero dimensional model employing the filling and emptying method for engine plenums. The combustion chamber consists of two zones: a burned and an unburned region. All gas mixtures are assumed to be ideal gases. Separate control volumes are considered for the following: intake manifold, unburned and burned combustion chamber regions, and the exhaust manifold.

A bond graph is constructed for the thermodynamic processes and is presented in Figure 2. The throttle valve, intake manifold, exhaust manifold, intake valve, unburned cylinder zone, burned zone, and exhaust valve for one cylinder are included. The R-fields represent flow through restrictions: valves modeled as isentropic nozzles. The input to each R-field is the effective discharge area, C₂A (m²). The input for the throttle valve comes from the engine low-level controller. Between the R-fields are zero junctions, one for the temperature and one for the pressure of each plenum. A C-field with thermal and hydraulic bonds captures the energy conservation of each plenum. Heywood derives the following formula for the time rate of change of temperature in the control volume:

\[ \dot{h} = \frac{B'}{A'} \left[ m \left( 1 - \frac{h}{B'} \right) - \frac{\dot{V}}{B'} \frac{C'_r}{V} + \frac{1}{B'm} \left( \sum_{i=1}^{L} m_i h_i - \sum_{i=1}^{L} m_i h_a + Q \right) \right] \]  

where \( h \) is the specific enthalpy of the gas, \( \dot{V} \) is the time rate of change of the plenum volume, \( V \) is the volume of the plenum, \( \dot{V} \) is the time rate of change of the fuel/air equivalence ratio, and \( \rho \) is the gas density. \( A', B', \) and \( C' \) are parameters describing partial derivatives of the gas properties. Specific assumptions for the computation of these parameters for the control volumes in the engine model are described by Hubbard [8].

In the center of the bond graph, the Wiebe heat release model determines the heat from combustion and the rate of mass burning from the unburned to the burned zone as a function of crank angle [4]. Figure 3 depicts this Wiebe function for a spark advance of 30° BTDC, and combustion duration of 80°. The cylinder models include a flow source for the PdV work done on the piston by the gas. The pressure acting on the piston drives the engine’s mechanical model.

Simulation results for the IC engine bond graph model are presented in Figures 4, 5, and 6. The engine operates at 4000 rpm and is driving a 187 N-m load. Figure 4 shows the mass flow rate of air into the combustion chamber from the intake manifold through the inlet valve. The characteristics of the simulated flow agree with empirical data for a similar engine [4]. When air mass begins to flow through the opening intake valve, it is flowing from the high pressure combustion cylinder to the lower pressure intake manifold. The air flow depends not only on the pressures in the cylinder and exhaust manifold but also the effective intake valve area as a function of lift.

The flow rate through the exhaust valve is shown in Figure 5. Because the effective exhaust manifold outlet area and the atmospheric pressure are assumed constant, the flow rate variation is a result of pressure and temperature fluctuations in the exhaust manifold. The exhaust manifold pressure oscillates within the entry of burned gas products from the cylinders. The cylinder pressure result is given in Figure 6. The peak pressure magnitude near 3500 kPA agrees with the load conditions from the intake manifold pressure and the quantity of fuel burned [9]. It is shown that these results may be extended to compute instantaneous IC engine efficiency [8].

Transmission and Vehicle Chassis/Body

The transmission directs energy between the drivetrain components. The bond graph model shown in Figure 7 is described below. Descriptions of energy dissipation for bearings by Shipley and for gear meshes by Özgüven and Houser are included [10,11]. Eight independent states in the transmission and one independent state in the vehicle chassis/bodies are contributed to the system.

In this HEV configuration, the IC engine operates at a constant nominal speed, \( f_{c0} \), and supplies a constant torque, \( e_{c0} \), consistent with the engine’s minimum brake-specific fuel consumption (BSFC) point. The minimum BSFC point is the engine’s peak steady state efficiency operating point. The first electric motor (bond 10) is responsible for maintaining the desired constant engine operating mode and operates at speed, \( f_e \), which is directly proportional to \( f_{t4} \) through the transformer, gear mesh \( TF_{c0} \). It must balance any torque debit or credit in the shaft represented by \( e_{t1} \). The second electric motor (bond 26) elicits the desired vehicle velocity by determining the velocity of the ring gear, \( f_{21} \), through the gear mesh \( TF_{223} \). The ring structure denotes the planetary gear kinematic constraint described in the VEHICLE CONFIGURATION section.

AC Induction Motors

The three-phase AC induction motors transmit energy between the battery-fed inverter and the transmission. The field-orientation principle is used in motor control simulations for optimal torque production. In 1959, Kovacs and Racz introduced the concept of vector quantities in AC machines [12]. Trzynadlowski described a dynamic model founded on Kovacs and Racz [13]. This dynamic model permits analysis with nonsinusoidal currents. The model is based on a fictitious two phase, two pole motor. It is termed the dq-model for its orthogonal axes: the direct, \( d \), and quadrature, \( q \).

The bond graph model describing the transformation of energy from the electrical domain through the magnetic domain to the mechanical domain is shown in Figure 8. In the bond graph, \( v_{u0} \) and \( v_{u0} \) are the stator voltages driven by the battery fed inverter. Energy is stored in inductances: \( L_{in} \), the leakage inductance in the stator, \( L_{ir} \), the leakage in the rotor, and \( L_m \), the magnetizing inductance. The copper losses in the stator are given by \( R_s \); those in the rotor are \( R_r \). The flux linkages are designated by \( \lambda_{ds} \) and \( \lambda_{qr} \). The state equations from the bond graph are equivalent to those given by Trzynadlowski:

\[
\begin{bmatrix}
\frac{d\lambda_{ds}}{dt} \\
\frac{d\lambda_{qr}}{dt} \\
\frac{d\phi}{dt} \\
\frac{d\psi}{dt}
\end{bmatrix} = \begin{bmatrix}
-R_{s} & -R_{s} & -R_{s} & -R_{s} & -R_{s} & -R_{s} \\
-R_{s} & -R_{s} & -R_{s} & -R_{s} & -R_{s} & -R_{s} \\
0 & 0 & L_{r} & -L_{m} & 0 & 0 \\
0 & 0 & -L_{m} & 0 & L_{r} & 0 \\
0 & 0 & 0 & 0 & L_{m} & -L_{r}
\end{bmatrix} \begin{bmatrix}
\lambda_{ds} \\
\lambda_{qr} \\
\phi \\
\psi
\end{bmatrix}
\]
From the torque developed by the fictitious two pole, the torque for a real, three-phase motor may be derived:

\[
T = \frac{P}{2} \frac{2}{3} T_{dq} = \frac{P}{3} L_{m} (v_{qs} i_{dr} - i_{ds} v_{qs})
\]  

The two AC induction motors are driven by DC to AC fast switching, low loss IGBT. Switching at 20kHz, the inverter dynamics are ignored. But a constant resistance voltage drop across the inverter is assumed. A hysteresis current controller is simulated to determine the voltage switching to elicit the desired current waveforms [8].

Lead-Acid Batteries

The battery pack stores or discharges energy based on the motor requirements. The lead-acid battery model builds on the work described by the landmark paper by Shepherd and that by Ekdunge [14,15]. Ekdunge’s model includes detailed descriptions of battery electrochemistry, but simplifies the analysis by using integral mean values for parameters such as sulfuric acid concentration. The purpose of the model is to describe the energy dissipation, generation and storage characteristics of the lead-acid battery. The bond graph described by the landmark paper by Shepherd and that by Ekdunge values for parameters such as sulfuric acid concentration. The electrochemistry, but simplifies the analysis by using integral mean values for parameters such as sulfuric acid concentration. The purpose of the model is to describe the energy dissipation, generation and storage characteristics of the lead-acid battery. The bond graph shown in Figure 9 depicts the elements for battery dynamics. The causal input to the model is the current from the electric motor models. The output is the voltage imposed on the motors.

The battery cell voltage is expressed as:

\[
E_{cell} = E_0 - IR_{electrolyte} - R_{a,1}(I) - R_{n,1}(I)
\]

where \(E_0\) is the equilibrium cell potential, \(I\) is the battery current, \(R_{electrolyte}\) is the resistance of the electrolyte, and \(R_{a,1}\) and \(R_{n,1}\) are the overpotentials at the positive and negative electrodes, respectively. The overpotentials are nonlinear functions of the cell current characterized by Tafel equations described by Ekdunge and Bode [15,16]. Hubbard expands the model to include charging [8].

Next, the results of a lead-acid battery simulation are presented. The scenario for the simulation is that the battery is discharged at 60 A for 30 minutes, charged at 60 A for 30 minutes, then left in open circuit for one hour. Figure 10 shows the sulfuric acid concentration during the simulation. The positive electrode consumes sulfuric acid during charge and returns it during charge faster than the negative electrode, as explained by diffusion process kinetics equations [15]. In open circuit, the acid diffuses from higher concentration regions to those of lower concentration. This lead-acid battery model describes transient and steady-state characteristics.

CONCLUSIONS

The need for control algorithms to exploit the components of a hybrid-electric vehicle drivetrain motivates the development of accurate transient and steady-state models. Dynamic models for each of the drivetrain components have been presented, including the internal combustion engine, transmission, vehicle chassis/body, AC induction motors, and lead-acid battery pack. Descriptive simulation results have also been shown. The choice of bond graphs for modeling was instrumental because the bond graph focuses modeling effort on mechanisms of energy generation, storage, dissipation, and transfer, and it provides a map to the governing equations. These dynamic models form the foundation for schemes to size the drivetrain components and for low-level and supervisory control methods [1].

REFERENCES

Figure 2: Bond Graph for Two Zone, Four Stroke, Spark Ignited IC Engine Model

Figure 3: Wiebe Function for the Fraction of Fuel/Air Mixture Burned

Figure 4: Air Mass Flow through Intake Valve

Figure 5: Mass Flow Rate of Air through Cylinder Exhaust Valve, Cylinder 1

Figure 6: Cylinder Pressure during IC Engine Simulation
Figure 7: Transmission and Vehicle Chassis/Body Bond Graph Model

Figure 8: Bond Graph Representation of AC Induction Motor in Simplified $dq$ Axes

Figure 9: Bond Graph Representations of the Lead-Acid Battery Cell (a) and Complete Battery (b)

Figure 10: Sulfuric Acid Depletion during Discharge, Replenishment during Charge, and Diffusion Process.