Application of Virtual Test Bed in Design and Testing of Hybrid Electric Vehicles

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ABSTRACT

This paper describes a virtual prototype of a Hybrid Electric Vehicle (HEV) developed within the Virtual Test Bed (VTB) environment which is simulation software for modeling, simulation, and virtual prototyping of multi-disciplinary systems. The main models used in the HEV system, including power sources, converters, controllers and vehicle driving train, are described first, then the HEV system was constructed based on these models. Finally, the system is tested for optimization of power sharing among the energy components and the vehicle dynamic response for given driving cycles. A full motion animation of the HEV is also demonstrated.

1. INTRODUCTION

Hybrid electric vehicles (HEVs) [1] combine one or more energy conversion technologies (e.g., heat engines, fuel cells, generators, or motors) with one or more energy storage technologies (e.g., fuel, batteries, super capacitors, or flywheels). The combination of generation, storage, and electric propulsion provides a load-leveling effect that offers the possibility to greatly reduce emissions and fuel consumption. The main object of this paper is to describe a virtual prototype of an HEV that is based on a fuel cell power source with both batteries and supercapacitors for energy storage. The virtual prototype is constructed in the environment of the Virtual Test Bed (VTB).

Simulation of an HEV is a complex process involving many technical disciplines. The interdisciplinary nature of the problem makes it difficult to define a simulation model using only the common simulation tools, such as SPICE, Pspice, Matlab/Simulink, etc. The Advanced Vehicle Simulator (ADVISOR), developed by the National Renewable Energy Laboratory (NREL), is helpful in the exploration of hybrid vehicles [2, 3], but it does not allow detailed study of the system dynamics. We use here a tool called the VTB [4, 5]. The philosophy of the VTB environment is consistent with that of the VHDL-AMS language [6] that defines several forms of connections between simulation objects – those in which power flow is conserved at points of connection between simulation objects, and those in which only signals or data are exchanged between objects. The VTB embraces multi-disciplinary systems and it offers a combination of both topological and mathematical expressions for formulation of models, thus providing a comprehensive and efficient system modeling environment. Another important feature of the VTB is the advanced visualizations of simulation results, yielding full-motion animation of mechanical components, or imaginative mappings of computed results onto the system topology. Because of these capabilities VTB can assist in integrating the knowledge of experts from many disciplines, allowing study of the dynamic behaviors of complex interdisciplinary systems.

The HEV described in this paper is composed of a mechanical train that includes all the mechanical parts of the vehicle, including the motor that converts energy between electrical and mechanical, a fuel cell system as the primary source of power, battery and super capacitor stacks to meet high and intense power demands respectively, DC/DC converters to control power flow between the components, and a supervisory controller to control and balance the whole system. Fig. 1 shows the block diagram of the HEV.

![Fig. 1. Block diagram of hybrid electric vehicle](image)

In the following sections, we first describe the main models used in this system, then construct the HEV system, and finally, test the system and present the results.

2. COMPONENT MODELING FOR HEV

All the models for the system were constructed using the resistive-companion (RC) modeling approach [7]. The main components are described as follows.

2.1. Fuel Cell Model

Fuel cell system provides the average power requirements of the vehicle. This power should be
large enough to overcome air drag and other losses (about 15 Kw) during steady cruising. For each cell of a fuel cell stack, a simplified voltage-current relation can be expressed as:

\[ V_{cell} = E_{f_0} - b \cdot \log(I / A_{f_c}) - R_{f_c} \cdot I - m \cdot e^{(nI / A_{f_c})} \]  

(1)

Where \( E_{f_0} \) is the standard potential of the H2-O2 reaction, \( b \) is the Tafel slope in mV, \( A_{f_c} \) is the active area of the membrane electrode assembly, and \( R_{f_c} \) is the internal ohmic resistance. \( m \) and \( n \) are constants of the empirical equation and can be obtained by a nonlinear regression analysis [8, 9]. Fuel cell parameters are listed in Table 1, and Fig. 2 shows the fuel cell V-I curve. Beyond this static characteristic, the stack model also includes the effects of inlet gas pressure, thermal transient response, and so forth.

Table 1. Parameters of fuel cell

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{f_0} )</td>
<td>1000 mV</td>
</tr>
<tr>
<td>( B )</td>
<td>25 mV</td>
</tr>
<tr>
<td>( A_{f_c} )</td>
<td>292 cm²</td>
</tr>
<tr>
<td>( R_{f_c} )</td>
<td>0.000819 Ω</td>
</tr>
<tr>
<td>( M )</td>
<td>0.0475 mV</td>
</tr>
<tr>
<td>( N )</td>
<td>0.0065 cm²mA⁻¹</td>
</tr>
</tbody>
</table>

2.2. Battery Model

A lithium-ion battery is used in this system due to its high energy density and long lifetime. Many detailed physics-based models have been built to study the internal dynamics of the lithium-ion battery [10-15], but generally these models are not suitable for system level design exercises. On the other hand, simple dynamic models based on capacitor/resistor networks [16, 17], that can be used in a circuit simulator are generally too simplified. The battery model used in this paper is based on reference [18]. The model accounts for nonlinear equilibrium potentials, rate- and temperature-dependencies, thermal effects and response to transient power demand.

Fig. 3 shows the battery model equivalent circuit. The battery consists of a nonlinear voltage source in series with an internal resistance, and an \( R_C \) network that represents the first order transient response of the battery.

\[ E(t), V(t), I(t), R, C \]

![Battery equivalent circuit](image)

The equilibrium potential of the battery (open-circuit voltage) depends on the temperature and the amount of active material available in the electrodes, which can be specified in terms of the state of discharge (SOD). The discharge capacity of the battery depends on the discharge rate and the temperature. The expressions for the potential, the terminal voltage and the state of discharge are given by equations (2), (3) and (4).

\[ E(t) = E_0 + R_C \cdot I(t) \]  

(2)

\[ V(t) = V_0 + R_C \cdot I(t) + \alpha(T) \cdot \Delta V + \beta(T) \cdot \Delta I \]  

(3)

\[ SOD(t) = \frac{Q_s}{Q_0} \cdot \text{SOD}(t) \cdot \Delta V \]  

(4)

Where \( c_k \) is the coefficient of the \( k \)th order term in the polynomial representation of the reference curve, and \( Q_s \) is the battery capacity referred to the cutoff voltage for the reference curve. SOD is the state of discharge. For \( k=0, E=E_0 \) is the open-circuit voltage at the beginning of discharge at the reference temperature for the reference curve.

Battery current and battery heat generation are calculated from equations (5) and (6). When the current and temperature are obtained from these two equations in every time step, they will affect the coefficients \( \alpha(T) \) and \( \beta(T) \) in the next time step, and the battery potential and SOD will be affected further.

\[ \frac{dI(t)}{dt} = \frac{1}{R_C} \cdot \left[ I(t) - \frac{E(t) + R_C \cdot I(t) - R_{RES}}{R_C} \right] + C \cdot \frac{d}{dt}(E(t)) - \frac{d}{dt}(E(t) \cdot T(t)) - R_{RES} \cdot I(t) \]  

(5)

\[ \frac{dT(t)}{dt} = \frac{C_p \cdot T(t)}{C_m} + \frac{m \cdot c_p}{h_c} \cdot \left[ I(t) - \frac{E(t) + R_C \cdot I(t) - R_{RES}}{R_C} \right] \]  

(6)

Here \( C \) is battery transient capacitor, \( m \) is battery mass, \( c_p \) is battery heat capacity and \( h_c \) is heat transfer coefficient.

2.3. Super capacitor Model

The supercapacitor provides peak power during acceleration or serves as the immediate repository for electric energy regenerated during braking. A typical super capacitor is constituted of two porous
carbon electrodes impregnated with electrolyte and separated by a porous insulating membrane. Due to the usage of porous high-surface-area materials such as activated carbons, the behavior of the supercapacitor is not simply described. Existing models range from a simple single Resister/Capacitor network to complex ladder networks [19-24]. The equivalent circuit of super capacitor model [19] used in this paper is shown in Fig. 4. The reason we use this circuit is first, it physically mimics the distributed nature of the charge stored in a porous electrode; second, it can be easily combined with various loads and used to find analytical or numerical solution, and third, its performance fits the experimental data. Fig. 5 shows a comparison of the frequency response of the equivalent circuit model with measured data.

![Fig. 4. Super capacitor equivalent circuit](image)

![Fig. 5. Comparison between simulation results and test data for Maxwell PC100 100F capacitor: Real part of complex resistance (star is test data and solid line is simulation results), imaginary part of complex resistance (square is experimental data and is line for simulation results)](image)

The parameters of the super capacitor equivalent circuit are shown in Table 2.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>L</th>
<th>65 nL</th>
</tr>
</thead>
<tbody>
<tr>
<td>R₁</td>
<td>6.62 mΩ</td>
<td>C₁</td>
<td>28.1 mF</td>
</tr>
<tr>
<td>R₂</td>
<td>1.7 mΩ</td>
<td>C₂</td>
<td>2.05 F</td>
</tr>
<tr>
<td>R₃</td>
<td>1.47 mΩ</td>
<td>C₃</td>
<td>18.9 F</td>
</tr>
<tr>
<td>R₄</td>
<td>4.94 mΩ</td>
<td>C₄</td>
<td>53.2 F</td>
</tr>
<tr>
<td>R₅</td>
<td>29.6 mΩ</td>
<td>C₅</td>
<td>31.7 F</td>
</tr>
</tbody>
</table>

2.4. Driving Train

The model of the drive train integrates the propulsion motor and the chassis system. The motor model is based on a simplified representation similar to that of a DC motor. This motor powers the vehicle during acceleration and also serves as a generator during vehicle braking. Since our focus is on the electric power sharing and control, all of the mechanical parts and driving conditions, such as vehicle mass, wheels, body size, air drag coefficient and rolling resistance coefficient, etc, are integrated together into this one model. The parameter values of the motor and vehicle are listed in Table 3 and Table 4 respectively. All the parameters of the driving train can be changed through the model parameter dialog box. The parameters shown below are those for a small electric racing vehicle similar to the Formula Lightning class.

<table>
<thead>
<tr>
<th>Table 3. DC Motor Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Voltage</td>
</tr>
<tr>
<td>Rated Speed</td>
</tr>
<tr>
<td>Armature Resistance</td>
</tr>
<tr>
<td>Armature Inductance</td>
</tr>
<tr>
<td>Rotor Inertia</td>
</tr>
<tr>
<td>Drag Coefficient</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4 Vehicle parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Mass</td>
</tr>
<tr>
<td>Wheel Radius</td>
</tr>
<tr>
<td>Wheel Rotor Inertia</td>
</tr>
<tr>
<td>Wheel Rolling Resistance Coefficient</td>
</tr>
<tr>
<td>Aerodynamic Drag Coefficient</td>
</tr>
<tr>
<td>Air Density</td>
</tr>
<tr>
<td>Frontal Area of The Vehicle</td>
</tr>
<tr>
<td>Distance Between Front and Real Wheel</td>
</tr>
<tr>
<td>Distance Between Left and Right Wheel</td>
</tr>
</tbody>
</table>

2.5. DC Power Converter.

The fuel cell, driving train and the supercapacitor are connected to the DC bus through DC-DC converters. The converter connecting the fuel cell is a buck converter and only allows energy to flow out of the fuel cell. The converters for the driving train and super capacitor are bi-directional, allowing power to flow in or out of the components according to the vehicle driving commands. We use switching average models of the converters. Fig. 6 shows the circuit diagram of the power converter model and the model equations are presented as equation (7), (8) and (9). The values of inductances and capacitor are given in Table 5.
2.6. Controller

Two level control is adopted in this system. At the local level, generic controllers respond to local measured variables and to the commands delivered by the supervisory controller. The supervisory controller balances and controls the whole system.

- Read the driver's command;
- Command the driving train controller to deliver the appropriate power to the motor to respond to driver's request;
- Command the capacitor converter to supply/absorb additional power if necessary;
- Command the fuel cell converter to supply appropriate power if necessary;
- Charge the battery and super capacitor if necessary;
- Protect the battery from overcharge, overdischarge and limit the battery current to a safe maximum value;
- Protect the supercapacitor from overcharge or overdischarge;
- Limit the fuel cell current to its maximum save value

2.7. Other Components

Driver speed and steering controls are integrated into the simulation model to allow the simulationist to “drive” the vehicle interactively. Also a Fuel cell power limiter is used to limit the fuel cell current variation rate.

3. SYSTEM SIMULATIONS AND RESULTS

3.1. System Schematic

The system schematic of the HEV is shown in Fig. 7. All the component parameters can be easily accessed and changed in the model parameter dialog boxes by double clicked on the model icon in VTB schematic editor.

3.2. Response to driving commands

In the example driving simulation shown in Fig. 8,
the vehicle is first accelerated to 26.8m/s (60 mil/h) in 20 seconds, then cruises for 15 seconds at this speed, and finally decelerates and stops in another 15 seconds.

Power sharing among different components is shown in Fig. 10. The driving train draws the maximum power (about 220 Kw) at the 10th second; about 57% (125Kw) is obtained from the supercapacitor stack. During cruise, the fuel cell supplies about 50Kw and battery supplies about 15Kw to keep the vehicle at a high speed (about 60mil/h). During vehicle deceleration, the driving train regenerates energy and feeds it back to the DC bus. At the 41st second, the peak regenerated power is about 120Kw. Most of this energy is absorbed by the supercapacitor stack. The fuel cell, battery and supercapacitor work well in a group and have a good power sharing.

Fig. 9 shows the current distribution on the DC bus to different components. The fuel cell stack current is positive and it increases/decreases slowly according to the internal limiter. It reaches its maximum value of about 180 amps (about 50Kw) at the 20th second and begins to decrease at the 35th second. The battery stack delivers most of the current during the first 3 seconds then it reaches its current limit. During the cruising period the battery stack still supplies some current since the fuel cell has reached its limit, yet more power is required to maintain the high vehicle speed. Finally, the battery is recharged during braking. The supercapacitor delivers peak current to the vehicle during the acceleration and accepts almost all the regenerated current during braking. During the cruising period, supercapacitor current is nearly zero since the function of supercapacitor is to supply and accept large power surges rather than to supply steady state power.

Fig. 11 shows the voltage variation during this maneuver. The bus voltage remains at about 300V. The supercapacitor voltage decreases during acceleration and increases during deceleration. The fuel cell stack has a high open circuit voltage but drops down heavily with a full load.

3.3. Animation of HEV

An important feature of the VTB is its advanced visualization system, which allows full motion animation of the mechanical components. The
visualization can operate either interactively or off-line. During an interactive session, the simulation output data is streamed to the visualization subsystem. On the other hand, data generated in an off-line simulation is first stored in the form of a text file [4]. This aspect of the VTB has been utilized to achieve the full motion animation of the HEV. Fig. 12 shows a screen shot of the 3D visualization in action. The trace of the vehicle path that is visible in the figure is a result of an arbitrary driving command provided by the user.

Fig. 12. 3D visualization of the performance of Hmmwv electric vehicle, including dashboard instruments, and steering wheel for user interaction

4. CONCLUSIONS
A virtual prototype for a HEV is developed within the VTB environment including construction of all the component models. The advanced visualization capabilities yield a fully interactive animation of the HEV driving experience.

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