Power Management Strategy Based on Game Theory for Fuel Cell Hybrid Electric Vehicles

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Abstract—**In this paper, we present an integrated system approach based on game theory for automotive electrical power and energy management systems. We apply this approach to a case study fuel cell hybrid electric vehicle (FC-HEV) by using the Simulink-based simulator ADVISOR. The case study fuel cell vehicle is rated with 80kW peak and 25kW average propulsion power, and consists of a fuel cell stack, a battery pack, an ultra capacitor, and two 35kW induction motors. In this control strategy, the game 'players' are the individual power sources, and the 'strategies' of players are their alternating states. The objective of the players is to maximize their payoff, where the payoff is a function of the powertrain efficiency and vehicle performance. Simulation results indicate that the optimal power and energy management strategy can improve both fuel economy and performance.**

Keywords- **Hybrid Electric Vehicle (HEV), Fuel Cell Electric Vehicle, Power Management Strategy, Energy Management Strategy, Game Theory.**

I. INTRODUCTION

With the emergence of various electric and hybrid drivetrains and the increasing power demand of non-propulsion automotive loads, on-board power and energy management strategy is becoming increasingly necessary [1]. The primary function of automotive electric power management is to prioritize real-time power requests from the loads, and allocate power resources available from the generation and storage devices in an optimized manner for maximum vehicle efficiency and performance [2-3]. Good power and energy management strategies can help reduce the weight, size, and cost, and improve the performance of the vehicle. Figure 1 shows an example of a fuel cell hybrid vehicle architecture, which consists of a fuel cell stack (FC), a battery pack, an ultra capacitor (UC), an inverter, and two induction motors. The same electrical architecture will also be used in our case study for developing new power management strategies.

Game theory offers one solution for developing a power and energy management control strategy [4-5]. At the basis of game theory is the concept of a decision, where a choice leads to an outcome. That outcome is rewarded in terms of payoff in utility. Utility maps non-numerical winnings (or losses) into numerical values, so that all different forms of winnings may be converted into common units. Play in the game space is governed by a set of rules that dictate what is and is not allowed during play. Envision this translation into the automotive environment where the decision becomes how much power to supply at a given moment in time and the payoff is both in terms of system efficiency (i.e. fuel economy) and performance parameters (e.g. acceleration). The rules are operating conditions of components, for example. It is by association that the automotive power distribution and management strategy becomes a game.

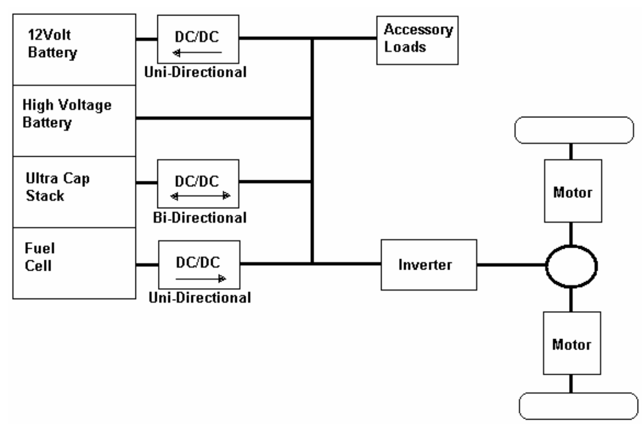

Fig. 1. Power/energy management system of a fuel cell hybrid vehicle.

The game theory control strategy contests one player, represented by the power-supplying components of the drivetrain, versus nature, which is the power consuming opposing player, comprised of propulsion (i.e. acceleration, traction, grade, and aerodynamic drag) and components being recharged. The n-tuple of components are each represented by their own power management controller (PMC), which communicates necessary information, such as operating parameters, to the governing controller, or the master PMC (MPMC).

For game theory control strategy, each criteria of interest comprising one component of payoff, is represented via a utility function for each device in the powertrain, which is mapped to the utility function based on its impact to payoff as defined by the n-tuple of controllers. For example, regions of high efficiency for a component will be mapped to high utility, since maximizing system efficiency is critical. Once all the utility functions are developed, the system will be loaded by power, and the game theory control strategy can predict how best to meet that load, given the current operating conditions of the system.

II. Utility Functions

By definition, utility is used for multiple unique payoffs, and so, in order to keep the unique functions in a common unit, they must have similar ranges and magnitudes of components that amount to their relative system importance. For example, if the fuel cell is sized to be twice as large as the battery, its utilities should be twice that of the battery utilities, unless the control system designer wishes to weight use of the battery more heavily.

A. *Efficiency Utility*

Since efficiency is a numerical payoff, it is easy to correlate to utility. Higher efficiency is a more favorable payoff. The most fundamental concept of efficiency utility is to understand that any operating conditions that support higher component efficiencies should be mapped to higher utility. Efficiency utility should be the dependent variable as a function of the opposing player's strategy, i.e. power. Efficiencies for each component can be then calculated dynamically once they are fit to a curve as a function of power.

B. *Performance Utility*

For the purposes of our simulation, performance was limited to analysis of acceleration. However, performance utility can be extended to any parameter that the control strategy designer deems an important indicator of performance. For the analysis of acceleration, once again, higher acceleration is a more favorable payoff. Hence, operating conditions of components that yield greater acceleration, or support regions of operation that yield higher acceleration, should describe higher utility. Map these individual operating points to a function of power to construct the performance utility function for a particular component.

For example, the fuel cell operating at greatest power output supports the largest vehicle acceleration, ignoring wheel slip. The fuel cell air compressor does not have a direct impact on acceleration, but maximum compression ratio generates maximum fuel cell power, therefore, greater compression ratios would be mapped to higher acceleration utility.

C. *Composite Utility*

Once each major component impacting energy and power efficiency is mapped to at least one efficiency and acceleration function, then the MPMC must synthesize the composite utility for a given moment in time. In order to do this, the MPMC must have a method to determine each criteria's importance with respect to one another, which for our simulation was the importance of efficiency with respect to acceleration. This can be accomplished by hard coding specific operating conditions that trigger execution of one specific definition of utility. Or, the MPMC can be allowed to use operating information to dynamically determine the relative importance of each criterion. In our modeling work to be described later, this is accomplished by using differences in throttle position sensing (or accelerator pedal position sensing) over a time interval to calculate the instantaneous acceleration. As a linear function of maximum possible vehicle acceleration, this was converted to a percentage vehicle acceleration, and used to scale the efficiency utility function. The remainder of the percentage on a scale from zero to one, was used to reduce the magnitude of the efficiency utility. Thus, the efficiency and performance utility for all components can then be summed to develop the composite (system) utility.

III. Vehicle Model Description

The SIMULINK-based modeling tool ADVISOR [6] is extensively used in this study. ADVISOR is supplied with a default fuel cell-energy storage subsystem (ESS) hybrid vehicle model. It is this model that forms the basis for the simulation.

After all the added components, the vehicle mass was raised to 1191kg. Each component model was modified to specify a particular component in our vehicle design of a system with an 80kW fuel cell, battery pack, and ultra capacitor pack. The motor was resized to be two 35kW electric motors. Specifics of these modifications are discussed below, under respective headings. The primary modification to the base model was the addition of the ultra cap model.

A. *Fuel Cell Model*

The fuel cell attempts to maintain a target state of charge (SOC) for the ESS, which is the average of the SOC operating band (40-80%, target is 60% SOC). The fuel cell is required to provide the bus requested power plus the additional required for the ESS to maintain the target SOC. The greater the ESS deviates from target SOC, the larger the power amount that is requested from the ESS.

Coolant temperature is assumed to asymptotically approach maximum when the fuel cell is on, and asymptotically approach ambient temperature when the fuel cell is off. The change in temperature is a function based on the temperature of the fuel cell and the rate of change of the function is a function of vehicle speed and ambient temperature (20 degrees Celsius).

The fuel cell thermal model can be thought of as a box housed in the engine compartment of the vehicle, where thermal conductivities exist between the interior and exterior of the fuel cell, the exterior of the fuel cell and the underside of the hood, and the hood and ambient atmosphere.

B. *ESS Model*

Power is taken first from the fuel cell, and the balance required to drive the vehicle load, beyond the limitation of what the fuel cell can provide for that time interval, is removed from the energy storage subsystem.

The ESS is modeled as a SOC-dependent voltage in series with an SOC and current dependent internal resistance. The convention of positive current is discharge current. Discharge power from the ESS is limited to keep the bus above the minimum controller voltage. Charge and discharge power to/from the ESS is limited to keep the bus within the ESS voltage limits.

The energy storage subsystem has losses associated with a charging columbic efficiency. The ESS is treated as a lumped thermal mass with active air cooling. The fan is on whenever the battery temperature is greater than the set temperature (35 degrees Celsius). The fan speed is set to a constant speed.

C. Ultra Cap (UC) Model

The pack of ultra capacitors is modeled as a lumped energy storage device, with an internal resistance and pack capacitance. The ultra caps are very similar to the ESS model, with the exception of SOC being a function of UC voltage. The voltage and SOC do not change instantaneously with each time step. Rather, the capacitive nature of the pack causes the voltage to change as a function of a RC time constant.

The UC Pack has losses incorporated due to internal resistance. This internal resistance generates heat. The pack is assumed to be air cooled, and will begin to asymptotically approach ambient temperature if left unused.

D. DC-DC Converter Model

The efficiencies of the DC-DC models are incorporated into the components they support, i.e. the fuel cell and the UC stack.

E. Motor Model

The maximum of required or available bus power (bus voltage x current) is calculated imposing the current limit of the motor upon the calculation as a constraint. The motor is turned off when the average velocity of the motor over one time step is zero.

F. Inverter Model

Since all components' power must flow through the inverter, the inverter model is incorporated into the motor model as efficiency, and is therefore, not a separate model.

G. Transmission Model

The transmission is modeled even though its ratio is set 1:1. The gearbox model includes losses, rotational inertia, and the potential for gear reduction. The torque loss is zero when the gears are stationary and when applied at the input of the gear reduction. The inertia torque is that required to accelerate the final drive's inertia from the input side. The efficiency associated with output torque is estimated assuming it is the same as the efficiency for requested input torque at the available input torque and speed.

H. Accessory Loads

The base control scheme calls for a constant accessory load of 700 watts. The base scheme was modified to accommodate the inclusion of the high voltage accessory loads, i.e. the adaptive suspension system, the electric air conditioning, the electric power steering, the fuel cell air compressor and coolant pump. Based on the power requirements for all these devices, the peak accessory load was 30kW peak, 9.86kW average. Hence, accessory load profiles were derived for all test drive profiles to be run.

The fuel cell dependent components have loads based on fuel cell operating conditions, and are therefore, functions of the fuel cell output power. The power steering is dependent upon vehicle speed, and therefore is a function of speed. The other two vehicle loads (active suspension and electric A/C) are independent of the profile (and most modeled parameters), and are therefore, preset into a defined schedule.

I. Vehicle Model

The force required to move the vehicle down the road is a combination of aerodynamic, rolling resistance, grade, and acceleration at any given time interval. This force is resolved into propulsion power and added to accessory loads to comprise the power requested of the power generation and/or energy storage devices. The simulation is fed with a drive cycle of vehicle speed versus time, from which all necessary parameters are derived. Using the road load equation, the speed is resolved into a power request as described above.

The maximum time step average vehicle speed is requested based upon tire traction. The drivetrain only requests as much force as the front tires can transmit to the road. This force is based on tire slip characteristics and the "acceleration-dependent weight" imposed upon the front axle. This "acceleration-dependent weight" is simply a modification of mass carried on the drive axle based upon buck and yaw, which become increasingly significant at higher acceleration and deceleration levels.

IV. SIMULATION RESULTS

Three common drive cycles were simulated: US06, Federal Test Procedure (FTP), and Constant 60 Miles Per Hour (MPH). A fourth drive cycle is a simple step input of 220 MPH held for two minutes to model acceleration performance.

Figure 2 compares the simulated fuel cell power output between the default basic control strategy and the new game theory based control strategy for the FTP drive cycle. Notice that the basic control, designated by the light line, prompts the system for more fuel cell power, whereas the game theory control accepts more power from the more efficient batteries. Figure 3 shows the percentage use of fuel cell and battery for the basic control strategy for same drive cycle. From this plot it is apparent that the basic control strategy is heavily biased toward fuel cell dependence.

Figure 4 compares the maximum acceleration response profiles for the step input between the default basic control and game theory control strategies. The line marked by (1) represents the requested 220 MPH profile. The line marked by (4) indicates the basic control strategy response prior to component upsizing. (3) specifies the gain in speed response due to component upsizing, and (4) is the vehicle response when components are controlled with the game theory strategy. The game theory control allows for gain in performance where the vehicle is component power limited, not wheel slip limited.

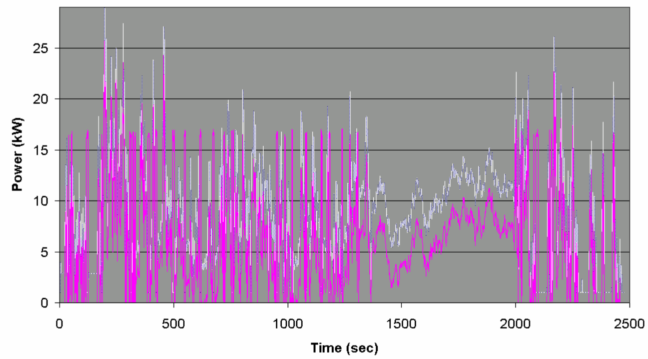

Fig. 2. Fuel cell power output for the basic control strategy (light line) and the new game theory control strategy (dark line) for the FTP drive cycle.

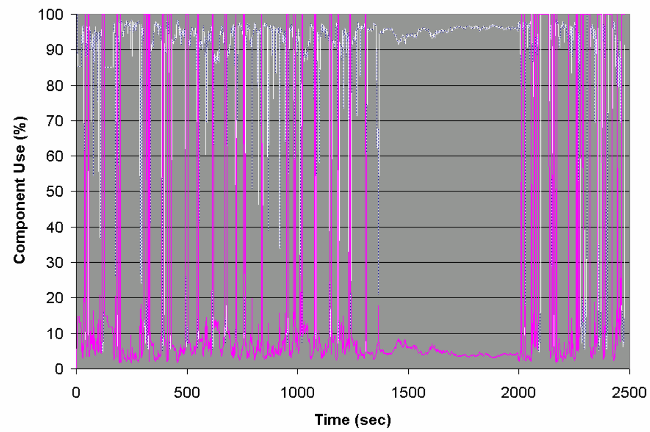

Fig. 3. Percentage use of fuel cell (light line) and battery (dark line) for the basic control strategy over the FTP drive cycle.

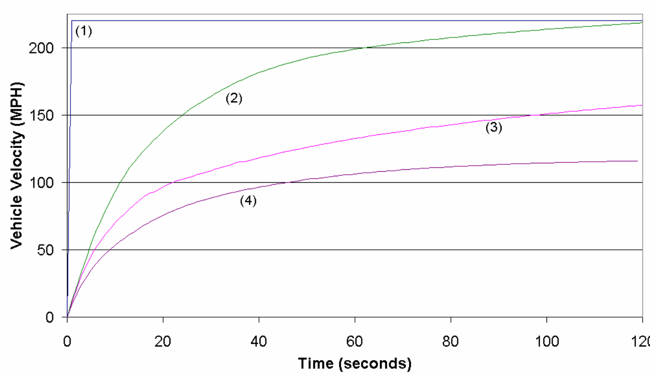

Fig. 4. Maximum Acceleration Response Profiles

A. Adjusted Miles Per Gallon Gasoline Equivalent (AMPGGe)

Fuel economy is compared in terms of conventional units as a common frame of reference. In order to have a balanced profile, SOC is adjusted to have initial SOC for both the ESS and the UC systems to match final SOC at the end of the simulation. There are a number of ways this can be accomplished.

- Modify the control strategy.
- Iterate the simulation, altering the profile until SOC matches.
- Recharge or discharge at the end of the profile, until initial SOC is achieved.
- Restrict operation within the cycle to ensure that the SOC ends within tolerance.

There are other ways to accomplish an energy balance for a simulation, but all those encountered during research involve ambiguity with respect to what efficiency the energy is recaptured at, leaving a bandwidth that resultant fuel economy can reside in. Hence, a median recharge efficiency of 60% was selected for all AMPGGe numbers. This is defended by the presumption that some energy will be recaptured at efficiencies greater and some at less than 60%. Under that assumption, the simulations produced the following results:

TABLE I. AMPGGE, CONTROL STRATEGY COMPARISON

Cycle	Control Strategy	
	Basic	***Game Theory***
US06	55.73	60.56
FTP	29.27	29.44
C60	56.21	58.88

All units in MPG, assuming 60% recharge efficiency

This fuel rate is multiplied by the simulation time step to achieve a net total quantity of grams of hydrogen (H_2) consumed for a particular profile. This quantity is then converted to equivalent gallons of gasoline using density of both gasoline and H_2, as well as the lower heating values of the fuels. This is used to get the energy per unit volume of gasoline (kWh/gal) and energy per unit mass of H_2 (kWh/gram). The density of gasoline is approximately 749g/liter; the density of H_2 is approximately 0.0899kg/m^3; the lower heating value of gasoline is approximately 42.6MJ/kg; the lower heating value of H_2 is approximately 120MJ/kg. This yields the following 33.694kWh/gallon gasoline and 33.2kWh/gram of H_2. The conversion between mass of H_2 and gasoline gallons is given by the following equation:

$$A = B*C*D \ldots (1)$$

A = Equivalent gallons of gasoline used by the fuel cell
B = grams of hydrogen used during the cycle
C = constant (0.1196MJ per gram of hydrogen)
D = constant (1 gallon of gas has 121.3MJ)

The net SOC dictates how much energy is removed from/supplied to an energy storage device over the course of any given profile. Power supplied added to power lost at any given time interval gives an input power profile for the ESS. Hence, an integral of this value for any energy storage device over the course of an entire profile will yield the net energy consumed or regained by the energy storage device:

E = D*INTEGRAL((F+G)/H)dt, over the entire profile…(2)

E = Equivalent gallons of gasoline used by energy storage device
F = Power out during the profile
G = Power lost during the profile
H = Recharge efficiency
D = constant (1 gallon of gas has 121.3MJ)

Therefore, AMPGGe can be calculated as:

I = J/(A+E(ESS)+E(UC))…(3)

I = AMPGGe
J = Distance traveled over entire profile
A = Equivalent gallons of gasoline used by the fuel cell
E(ESS) = Equivalent gallons of gasoline used by the batteries
E(UC) = Equivalent gallons of gasoline used by the ultra caps

B. Acceleration Simulation

Table II compares some common references for vehicle acceleration between the two control strategies. If acceleration is the only indicator of vehicle performance, by using the game theory control strategy, the vehicle was able to achieve better vehicle performance. The game theory control strategy throughout this process weighted the acceleration as heavily as possible, disregarding efficiency utility to supply as much power as possible, at the expense of efficiency.

TABLE II. ACCELERATION TIMES BETWEEN VEHICLE SPEEDS

Speed	Control Strategy	
	Basic	***Game Theory***
0 to 60	10.65	8.61
40to 60	3.44	2.01
0 to 85	17.48	11.77

All speeds in MPH; all times in seconds

V. DISCUSSIONS AND CONCLUSIONS

Accurate control of the power generation and/or energy storage devices that comprise a hybrid vehicle is imperative for successful system performance and output. The energy storage and supply devices will be unique to a particular architecture, just as the architecture itself is unique, and thus, the solution as to how to provide, recapture, or dissipate energy at any given time instant for an architecture will also be unique. The proposed control solution needs to be specific with respect to the architecture and will require an in-depth analysis of the interfaces that exist between components for the architecture. The power distribution control strategy answers the question as to what component will supply or recapture the energy and/or power for a given time interval, and this answer comes from observing component to component interaction. Careful observation must be made regarding the operating points of each individual component in the system that is involved in the path through which power must flow in order to answer a power request, regardless of whether that request is positive or negative (supply or storage). In short, a power distribution control strategy that does not account for the entire power flow path is incomplete, and may be operating the system in a manner that is less efficient or that provides lower than the maximum potential system performance. The latter statement is what allows the game theory approach to achieve its benefits.

The game theory control strategy, by design, is tailored very specifically to a particular architecture and the specific components that comprise said architecture. Without explicit and tight change control on the vehicle platform, and without in-depth knowledge of the relationships that exist between component variables, the game theory control strategy becomes less effective. This does not mean that it cannot find a place or use in the vehicle design environment that currently exists in the automotive industry. In the automotive industry, the game theory approach is best applied as a post-production software change for the power control strategy, as opposed to a first generation, brand new vehicle platform implementation. Many vehicles have lifecycle runs that last decades, where little is changed on the vehicle from year-to-year. One could feasibly take this game theory approach and apply it to such a vehicle (one with a stable architecture) to realize what benefits it could provide to successive model years of that vehicle.

The game theory based strategy does not account for the impact of driveability on power distribution (i.e. scaling back charge power to allow for smooth deceleration). This impact is not beyond the scope of this control strategy, but the case study did not account for it. Typically, the method for most efficiently recapturing regenerative power to an energy storage device does not coincide with the smoothest method of decelerating the vehicle. Often, the regenerative power must be limited, i.e. more must be wasted in the friction brakes, to preserve the smooth ride that a customer expects from a vehicle. This could be rolled into the ESS utility function.

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