ELECTRICAL ARCHITECTURES FOR HYBRID VEHICLES: IMPLICATIONS FOR MODELLING AND CONTROL

James Marco

Department of Automotive Engineering,
School of Engineering, Cranfield University,
Bedfordshire, UK.

Contained within this paper is a discussion into the modelling and control of the electrical architecture for a HEV. Two configurations of electrical architecture are discussed; a system in which the bus voltage is allowed to vary during vehicle acceleration and regenerative braking and secondly, a fixed bus voltage system in which the voltage is held constant by the inclusion of a bi-directional DC-DC converter. The relative merits of each solution are discussed. Consideration is given to the component sizing of the energy storage device, the associated control system complexity and finally the performance of the HEV.

Keywords: Dynamic Modelling, Electrical Simulation, Feedback Control, Power Management, Automotive Control, Hybrid Vehicles

1. INTRODUCTION

The development of fuel cell vehicles (FCV) and hybrid electric vehicles (HEV) is an active area of research for a number of automotive manufacturers, subsystem suppliers and academic institutions worldwide. In order to ascertain the most cost-effective and innovative solution, researchers are concurrently investigating different powertrain architectures, different hybridisation strategies and the integration of different subsystem technologies (Emadi 2005, Naylor 2006).

In recent years, considerable attention has been given to the integration of both fuel cells and batteries with ultracapacitors. A number of different hybrid configurations employing ultracapacitors have been presented within the literature. The difference between each topology relates mainly to whether the primary source of energy is a fuel cell or a battery and to the degree and location of the power electronics within the powertrain; in particular, whether the main vehicle bus voltage is fixed to a constant value allowed to vary with the terminal voltage of the ultracapacitor.

The work presented in this paper aims to bring together and compare the modelling, simulation and control requirements for the two options of electrical architecture; a fixed bus voltage and a floating bus voltage electrical system. The two examples presented are based on a fuel cell hybrid vehicle employing ultracapacitors. However, the modelling and control strategies presented are mainly generic and can be applied to a number of different hybrid vehicle configurations and energy storage technologies.

Critical to realising the objective of an energy efficient vehicle is the design of a control system for the vehicle's electrical architecture that properly allocates power between the steady-state energy source (SES), i.e. the fuel cell and the peak energy source (PES), i.e. the ultracapacitor. Irrespective of the exact topology of the electrical architecture, the control objectives are generally the same; to regulate the state of charge (SOC) of the PES and to limit the rate and absolute magnitude of the demand placed on the SES.

The design of simulation models that represent both the dynamics of the vehicle and it's electrical architecture is a challenging task; such models are highly non-linear, stiff and execution of the model states is not only a function of time but also of discrete events. As a result, a fundamental understanding of the dynamics of the system is a pre-requisite to accurate numerical simulation and control system design.

This paper is structured as follows; Section 2 introduces the modelling and control of the floating bus electrical architecture. Section 3 introduces the modelling and control of the electrical architecture when a bi-directional DC-DC converter is added to maintain a constant value of bus voltage. Finally in Section 4, both options of electrical architecture are evaluated. Consideration is given to the component sizing of the energy storage device, the associated control system complexity and the performance of the HEV

2. A CONTROL SYSTEM FOR A HEV USING A FLOATING BUS ARCHITECTURE

A detailed discussion into the modelling and control system design process is presented in (Marco and Vaughan, 2007a).

2.1 Plant Model Development

The equivalent electrical circuit for the high voltage system is presented in Fig. 1. The circuit is made-up of a fuel cell stack, a DC-DC boost converter and an ultracapacitor connected in parallel to the output stage of the power electronics. As it can be seen from the figure, when energy is drawn and fedback to the ultracapacitor, the value of bus voltage will vary. The state and algebraic equations for the plant model are presented in (Marco and Vaughan, 2007a). and will not be repeated here.

The fuel cell representation presented in Fig.1 was originally proposed by (Standaert 1996) and has subsequently been employed in a number of recent studies (Xin, 2005). The resistor – capacitor (R_{fc}-C_{fc}) network represents both the activation losses and the resistive losses within the fuel cell system.

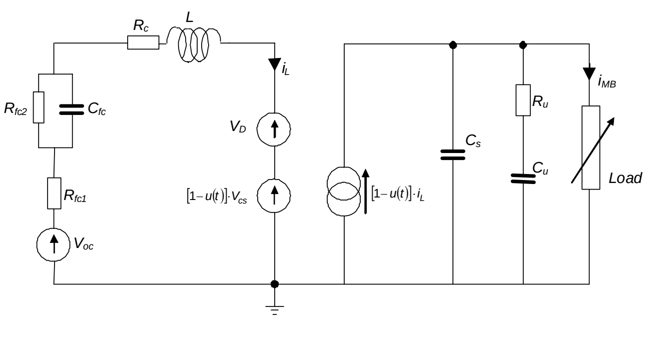

Fig. 1. Equivalent circuit diagram for the floating bus architecture model (high bandwidth model)

Fig.1 presents a small-signal, averaged model of a DC-DC boost converter. The model has two states; one associated with the input inductance (L) and the second with the output smoothing capacitor (C_s). The power electronic switching device, an Insulated Gate Bipolar Transistor (IGBT), is replaced by a continuous-time control signal, u(t) with the constraint; $0 \geq u(t) \leq 1$. The conduction losses associated with the IGBT and the power diode can be represented by a constant reverse voltage (V_D) within the circuit. Results presented in (Maksimovic 2001) show that converter dynamics up to approximately one-tenth of the switching frequency of the IGBT are accurately captured by a model of this type. Since the switching frequency for the IGBT is in the order 20kHz, the simplified representation is deemed to be sufficiently representative for system design purposes.

An accurate model of the complete ultracapacitor subsystem is obtained from a first-order resistor-capacitor circuit, where C_u defines the total capacitance of the ultracapacitor and R_u the effective series resistance (ESR) of the ultracapacitor.

Simulation and analysis of the plant model identifies that the dynamics of the system are dominated by the ultracapacitor and the resistor-inductor network on the fuel cell side of the converter. The activation losses within the fuel cell and the power electronics' smoothing capacitor result in two very high resonant modes. As a result, the model is not appropriate for control system design purposes in which the simulation must be executed for many hundreds of seconds as different control and vehicle parameters are varied. Removing these two high frequency modes from the system, results in the simplified reduced-order model, shown in Fig. 2. The dynamics of the simplified model can now be represented by two bilinear, first-order differential equations. The reduced order model can be simulated with an integration time interval in the order of 10ms.

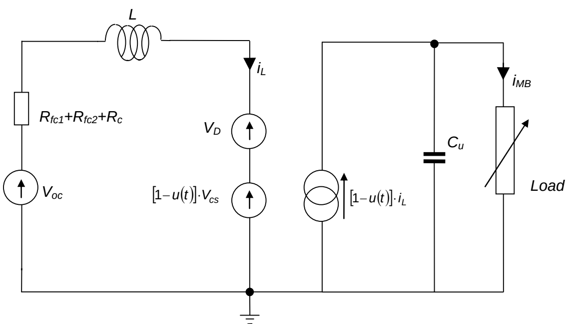

Fig. 2. Equivalent circuit diagram for the floating bus architecture model (low bandwidth model)

2.2 Control System Design

Fig. 3 presents the structure of the high voltage bus management control system. It comprises of two nested control loops; an inner current loop and a slower outer voltage control loop. Based on the linearised equations for Fig. 2, the system can be described as a stable, Type 0 system. A proportional + integral (P+I) algorithm was added to the forward path dynamics $G_p(s)$. In addition a saturation is also added to the forward path of the control loop such that in accordance with the definition of $u(t)$ the control signal is bound between zero and unity.

With respect to the outer voltage control loop, since any large voltage transients above the upper limit would potentially damage both the power electronic switch and also the individual cells that comprise the ultracapacitor, the primary control objective for the voltage loop is for it to be over or critically damped. In addition, the bandwidth of the voltage control loop should be sufficiently low so as to ensure that the two nested loops do not detrimentally interact with one another. Simple proportional control was used for $G_v(s)$. The primary reason for the use of proportional control is that the dynamics of the ultracapacitor result in a pole very close to the origin of the s-domain, which means that the system inherently contains integral corrective action. In addition, the use of proportional control results in a system that can be very easily calibrated as one method of changing the operating characteristics of the vehicle.

Because the control signal within the voltage loop is a current demand to the boost converter, a low value of $G_v(s)$, results in a low value of current being drawn from the fuel cell stack. The ultracapacitor is therefore forced to meet more of the load requirements; resulting in a higher depth of discharge and a longer recharge time for the device.

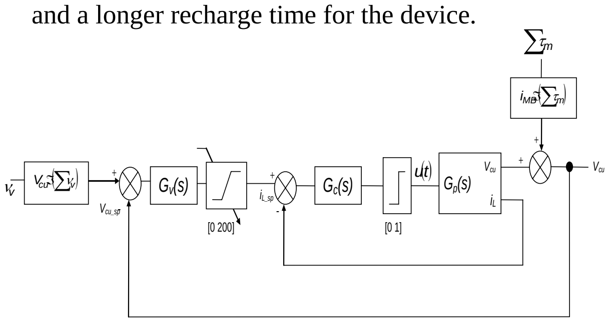

Fig. 3. High voltage bus management strategy for the floating bus architecture

Low values of $G_v(s)$ also reduce the ability of the control system to regulate the value of bus voltage with respect to either a change in the set-point to the control loop or the presence of an external disturbance. Conversely, high values of $G_v(s)$ result in higher demands being placed on the fuel cell system

2.3 Control System Verification

Contained within (Marco and Vaughan, 2007a) is a detailed simulation exercise in which the control system is integrated within a full non-linear hybrid powertrain model and exercised over a number of different legislative and real world drive-cycles. Fig. 4 presents the example simulation results from that study. The Figure shows the performance of the hybrid powertrain over the US06 drive-cycle.

The results presented above and in (Marco and Vaughan, 2007a) show that the transient response of the fuel cell system and the ultracapacitor should therefore be the primary considerations when calibrating $G_v(s)$.

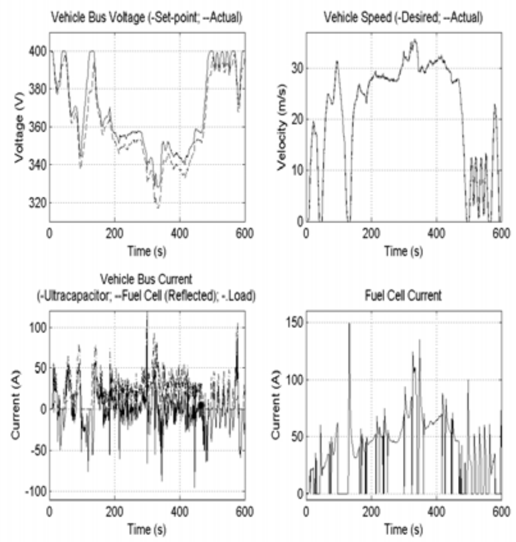

Fig. 4. Performance of the high voltage bus management system over US06

The hybridisation of the powertrain improves the energy utilisation and range of the vehicle, not through the control calibration, but through using the ultracapacitor as a transient power buffer to the fuel cell. As a result, a smaller, more lightweight fuel cell solution may be employed without compromising the performance of the vehicle. This fact is analogous to principle of engine downsizing within a hybrid powertrain employing an internal combustion engine. As discussed in (Marco 2005), reducing the weight of the hybrid powertrain facilitates additional mass de-compounding gains to be realised, which in turn can further improve the energy efficiency of the vehicle.

3. A CONTROL SYSTEM FOR A HEV USING A FIXED BUS ARCHITECTURE

The aim of this section is to introduce the modelling and control for a HEV electrical architecture in which a bi-directional DC-DC converter is employed in series with the energy storage device to maintain a fixed value of bus voltage during vehicle acceleration and regenerative braking. This section summarises the modelling and control methodology introduced in (Marco, 2008)

3.1 Plant Model Development

Fig. 5 shows the reduced order, simplified plant model for the system. With respect to Section 2, the main difference is the inclusion of the two additional power electronic devices between the ultracapacitor and the high voltage bus. The bi-directional converter manages the flow of current to and from the ultracapacitor. The two power electronics have two modes of operation; with u_3 held off and u_2 actuated the system behaves as a boost converter in which current is sourced from the ultracapacitor. Conversely, with u_2 held off and u_3 actuated the power electronics operate as a buck converter in which the polarity of the current is reversed.

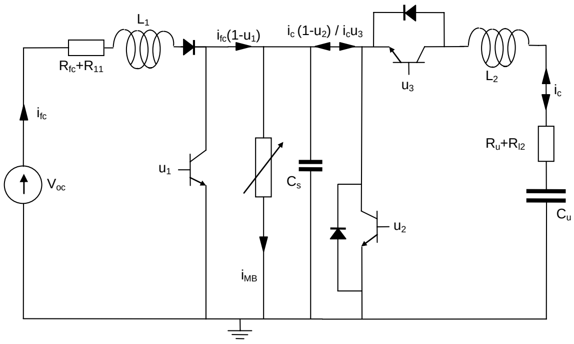

Fig. 5. Equivalent circuit diagram for the fixed bus architecture model (low bandwidth model)

The smoothing capacitor (C_s) that would normally be in parallel with the ultracapacitor has been neglected since the capacitance value of the latter is many orders of magnitude greater than that associated with C_s.

As with the electrical architecture models introduced in Section 2, the mathematical equations that define the dynamics of Fig. 5 are highly stiff and non-linear. Unlike the previous models however, Fig. 5 represents a hybrid model in which execution of the model states is not only a function of time, but also of the operating mode of the power electronics. Because of the resulting discontinuities within the system, experimentation conducted in (Marco, 2008) has shown that a variable step, variable order, numerical integration algorithm cannot be used to solve the model equations during simulation. As a result, a fixed step low order algorithm must be employed in order to achieve the desired levels simulation accuracy and run time.

3.2 Control System Design

The control system for the vehicle comprises of two main functions, one for the fuel cell and boost converter and one for the ultracapacitor combined with the bi-directional converter. The fuel cell is controlled by a single current control loop around the fuel cell stack. The primary objective of the feedback loop is to manage the magnitude and rate at which current is drawn from the fuel cell. High transient current demands placed on the fuel cell can lead to oxygen starvation and potentially permanent damage to the system. These control objectives are realised through a low-pass filter in series with a saturation as part of the pre-filtering strategy for the set-point to the control loop. The breakpoint frequency for the filter is defined as a calibration within the strategy. As is it can be seen from Fig. 6, the set-point signal applied to the fuel cell current control loop comprises of two separate components.

The first component, $i_{fc\_\tau m}$, is derived as a function of the torque demand sent to the electrical machines. Feed-forward control, based on a reference model of the vehicle's powertrain is required to estimate the current that is needed to meet the torque demand requested by the driver. The second component, i_{fc_c}, represents the demand signal from the SOC control algorithm that uses excess current from the fuel cell to regulate the SOC of the ultracapacitor.

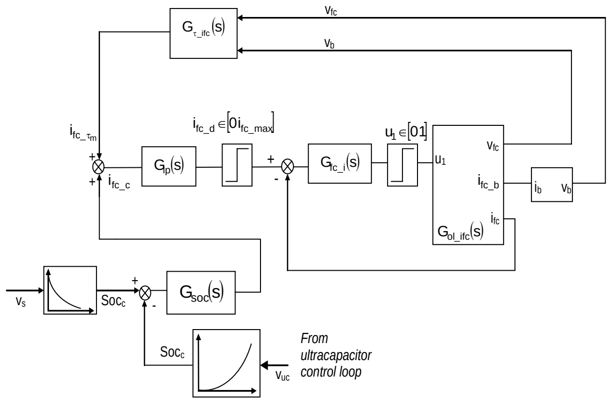

Fig. 6. Fuel cell control loop for the HEV electrical architecture

By examining the characteristic polynomial of the transfer function that defines the closed loop fuel cell control system, it can be seen that the dynamics are dominated by the pole of the low-pass filter and a pole at the origin of the S-domain due to the inherent integral action associated with the ultracapacitor. Simple proportional control within the SOC control loop can therefore be employed.

With respect to the current that is sunk and sourced from the ultracapacitor, as shown in Fig. 7 two nested control loops are required to manage the ultracapacitor subsystem. The main function of the bus voltage control loop is to maintain a constant vehicle bus voltage. The control loop generates a current set-point that is limited to the maximum switching current of the IGBTs. Because the dynamics of the bi-directional converter are different and dependant on the operating mode of the system (buck or boost) simulation experiments conducted in (Marco, 2008) have shown that two separate current loops are required; one for each switch u_2 and u_3. The same generic P+I algorithm can be employed within each loop; the difference between the two relates to the required calibration of the controller gains.

3.3 Control System Verification

Verification of the vehicle's control system followed the same process as that discussed in Section 2.3. The control system was integrated within a full non-linear model of the hybrid powertrain. The emphasis of the study presented in (Marco, 2008) is to understand the effects of varying the calibration of the breakpoint frequency of the pre-filter on the efficiency of the powertrain and the transient demands placed on the fuel cell stack.

Fig. 8 presents the performance sensitivity of the HEV for variations in the gain associated with the

SOC control loop. The figure depicts the absolute error within the SOC control loop, the integral of the SOC error within the control loop, the maximum value of fuel cell current during the drive-cycle and finally the predicted range of the vehicle over the drive-cycle. The first two metrics relate to the ability of the control system to manage the SOC of the ultracapacitor, whereas the latter relates to the hydrogen consumed by the vehicle and the dynamic load that is applied to the fuel cell.

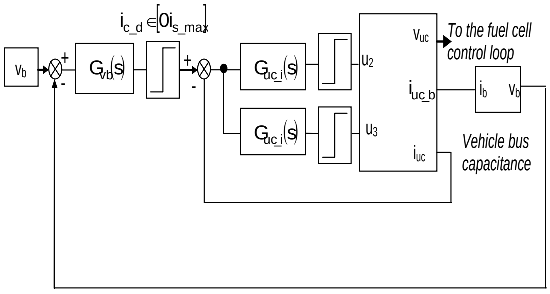

Fig. 7.Ultracapacitor control loop lop for the HEV electrical architecture

In all cases, consideration is given to the performance of the vehicle over four drive-cycles; the North American Urban Dynamometer Schedule (UDDS) and three real-world cycles captured specifically to verify the energy management control system.

With respect to Fig. 8, with lower values of gain, the SOC error is too high which implies that, for a given vehicle speed, the voltage in the ultracapacitor will not be at the desired value to either assist in the acceleration of the vehicle or to recapture energy during regenerative braking. For higher values of gain, there is little further improvement in the management of the ultracapacitor. However with higher values of gain within the control loop, the fuel cell current is increased further with a corresponding increase in the hydrogen consumed by the fuel cell and a reduction in the driving range of the vehicle.

4. DISCUSSION INTO THE SELECTION OF ELECTRICAL ARCHITECTURE

The aim of this section is to highlight the relative merits and compromises associated with the selection of either a floating bus or a fixed bus electrical architecture for a HEV. The discussion focuses on three main areas; component sizing of the energy storage medium, the associated control system complexity that is required to manage the system and finally the performance of the vehicle.

4.1 Component Sizing

With respect to the floating bus solution, the need for the ultracapacitor to connect directly to the high voltage bus means that, for a given cell technology, the size of the energy storage pack is fixed. Cell voltages in the order of 2.5V are common, which implies that a string length of 160 cells would be required for a 400V system.

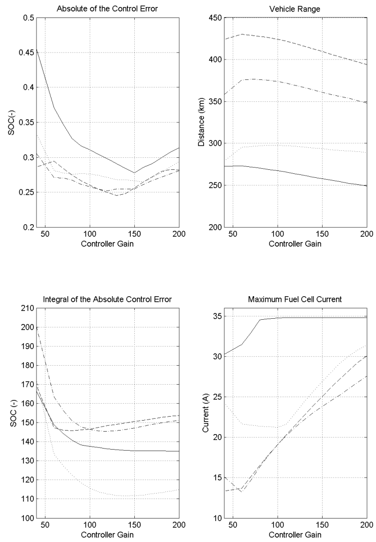

Fig. 8. Performance sensitivity of the SOC control control loop to variations in the controller gain

Large string lengths require active balancing of the cells to ensure that the performance of the pack does not degrade. Furthermore, the large mass and volume of the pack may be prohibitive for integration within certain vehicles. The main advantage of this topology relates to the simplicity of the required control system and the improved ability of the vehicle to recapture energy through regenerative braking. Both facets are discussed further in the following subsections.

With the fixed bus architecture, the power electronics essentially decouple the PES from the bus voltage. As a result, it is possible to optimise the string length, through simulation, with respect to the required performance of the vehicle. Such studies require a whole systems approach, since as the string length varies the ESR, mass, volume and operating current will also vary and affect the performance of the vehicle.

4.3 Control System Complexity

From Sections 2 and 3, the main conclusion that can be drawn is that the more power electronics employed within the electrical architecture of the vehicle, the greater the level of control system content and complexity. In general, for each electronic switch, at least one feedback control loop is required. In some cases two nested feedback loops; an outer voltage control loop and an inner current control loop will be necessary.

As discussed in (Marco, 2008) the control of the power electronic subsystems will often require their own dedicated hardware. The high bandwidth of the control loops can be in the order of $1.3{\times}10^4$ rads^{-1}. Such a high bandwidth (and therefore sample time) requires a prohibitively fast transmission rate if the control system is to be distributed throughout the vehicle. Experimental analysis found that CAN bus utilisation of 70% would be required to distribute the control of the bi-directional DC-DC converter between different hardware modules. It is widely accepted that CAN bus utilisation at this level can result in indeterministic behaviour.

With respect to the floating bus architecture presented in Section 2, the main advantage of this approach is the simplicity of the control solution for the energy management system. The system is inherently single-input-single-output (SISO) and therefore classical control techniques are highly applicable. With simple proportional control for the outer voltage control loop, the system is very easy to calibrate. The power management characteristics of the vehicle can be varied from that of a load-follower to a load averaging strategy simply by varying the magnitude of one variable.

The fixed bus voltage option presented in Section 3 requires five feedback control loops, each with its own control terms. The control systems design is once again based on classical control theory. The hybrid nature of the electrical system means that additional supervisory control constructs are required to identify the different modes of vehicle operation and change the control strategy of the power electronics accordingly. Because of the increased number of control loops and control terms, calibration of the overall strategy is a much more challenging task than that associated with the calibration of the floating bus control system.

4.3 Vehicle Performance

One of the main considerations for the inclusion of power electronics between the ultracapacitor and the high voltage bus is the current limit associated with the power electronic switches. Typical maximum values of switching current are in the order of 200A. In a number of scenarios the current associated with the regenerative braking manoeuvre is in excess of this value. As a result, in order to protect the power electronics from excessive loads the control system must limit the amount of regenerative braking, which in turn limits the ability of the vehicle to recapture energy. When the ultracapacitor is directly connected to the high voltage bus, this restriction does not apply. As a result, higher levels of energy recapture under braking are possible (Marco and Vaughan, 2007b). It should be noted that this limitation is particularly applicable to a ultracapacitor PES. If the PES was a battery then the PES itself may require a current limit due to the comparatively high ESR of the technology.

5. CONCLUSIONS

Contained within this paper is a discussion into the modelling and control of the electrical architecture for a HEV. Two configurations for the electrical architecture were introduced; a floating bus system in which the value of the bus is allowed to vary with the SOC of the PES and secondly, a fixed bus voltage system in which the value of bus voltage is held constant by the inclusion of a bi-directional DC-DC converter between the PES and the bus. The relative merits of each solution were discussed. Consideration was given to the component sizing of the PES, the associated control system complexity that is required to manage the system and finally the performance of the vehicle. The control system design and modelling activities presented are based on a hybrid FCV using ultracapacitor technology. However, the modelling and control strategies presented are mainly generic and can be applied to a number of different hybrid vehicle configurations and energy storage technologies.

ACKNOWLEDGEMENTS

The research presented within this paper forms part of the following programmes; LIFECar which is part funded by the DTI through the Technology Partnership Programme, HYRBAN which is jointly funded by the BOC Foundation and OSCar Automotive and finally, WREN which is wholly funded by the EPSRC.

REFERENCES

Emadi A., et al., (2005), Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations, IEEE *Transactions on Vehicular Technology*, Volume **54**, Number 3, pp 763-770.

Maksimovic D., Thottuvelil V.J., (2001), Modelling and simulation of power electronic converters. In: Proceedings of the IEEE, Volume 89, Issue 6, pp 898-112.

Marco J., Vaughan N.D, (2007a), The Control-Orientated Design and Simulation of a High Voltage Bus Management Strategy for use within Hybrid Electric Vehicles, International *Journal of Vehicle Systems Modelling and Testing*, Volume **2**, Number 4, pp 345-368.

Marco J., Vaughan N.D., (2007b), Defining Performance Metrics for Hybrid Electric Vehicles, Society of Automotive Engineers Technical Paper Series, SAE Automotive World Congress, Paper Number: 2007-01-0287.

Marco J., (2008), The Modelling, Control and Simulation of the Electrical Architecture for an Urban Hybrid Fuel Cell Vehicle, Submitted to the *Journal of Simulation Modelling Practice and Theory*.

Naylor S.M., et al., (2006), Fuel cell drive train topologies – computer analysis of potential systems. In: *3rd IET International Conference on Power Electronics, Machines and Drives*, Ireland.

Standaert F., et al., (1996), Analytical Fuel Cell Modelling, *Journal of Power Systems*, Volume **63,** pp 221-234.

Xin K., et al., (2005), A hybrid model with combined steady-state and dynamic characteristics of PEM fuel cell stack. In: *14th IAS Annual Meeting, Industrial IEEE Annual Conference*, Volume **3**, pp 1618 – 1625.