A Parallel Energy-Sharing Control for the Fuel cell-Battery-Ultracapacitor Hybrid Vehicles

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Abstract: - This paper proposes a parallel energy-sharing control for fuel cell electric vehicles (FCEVs) application. The hybrid source consists of a fuel cells (FCs) generator, battery packs and Ultracapacitor (UC) modules. In the proposed parallel energy-sharing control, each source is connected to the direct current (DC) bus via power electronics converters. A total of six control loops are applied in the supervisory system in order to regulate the DC bus voltage, control of current flow and at the same time to monitor the state of charge (SOC) of each energy storage device. Simulations as well as experimental test bench are carried out to verify on the proposed energy control system.

Key-Words: - Fuel cell, battery, Ultracapacitor, Hybrid source, Fuel cell hybrid vehicle, Energy management control and Parallel energy-sharing control.

1. Introduction

Due to the rapid escalating of gasoline prices, depletion of fossil fuels and environmental concerns, most of the automotive industries have intensified in the development and commercialization of minimum-and-zero emission vehicles. Electric vehicles (EVs) powered by battery is one of the early approaches to green technology. However, the major problems that are normally associated with the Battery Electric Vehicles (BEVs) are its relatively short travel journey and long charging period. Due to these barriers, one of the alternative solutions in replacing of battery as primary energy source in the EV is to use of FC generator. This type of vehicle is known as fuel cell electric vehicle (FCEV).

Application of FCs in vehicle is one of the promising solutions to provide a high energy efficient, quiet, less pollutant and electric vehicle with longer driving range (as long as the fuel supply is available). The Polymer electrolyte membrane Fuel Cell (PEMFC) is commonly utilized in the FCEV due to its relatively small size, light weight and simple structure [1-3]. PEMFC generates electricity through the chemical reaction between hydrogen and oxygen. Hence, the by-products from it contains of heat and water. However, there are problems when one tries to use FC alone to power the vehicle, such as its relatively short lifespan, poor dynamic response, difficulty during FC cold start-up, high cost, and inability to capture of braking energy during vehicle deceleration or downhill [3-5]. Moreover, peak power demand from the FC could lead to fuel starvation phenomenon and shorten its lifespan. For these reasons, hybridization of FC with energy storage units (ESUs) is necessary in order to overcome these problems as well to reduce the vehicle size and cost [4].

ESUs can compose of the battery modules, UC modules or combination of both (combined ESUs).The comparative study performed in [3,4,8,9] indicate that FC-battery-UC hybrid vehicle could lead to a more practical solution, higher fuel economy and extends battery lifespan. From the literatures, most of the proposed energy management strategies applied in the FC hybrid source are of series configurations[3,4,9].In series configuration, the energy dense source is used to charge on the power dense source, and the power dense source is used to regulate the DC bus and to response of peak power demand.

This paper proposed a parallel energy-sharing control for the FCEV combining of FC generator, battery and UC modules. The aim of this paper is to discuss on the control structures and the design of the proposed parallel energy-sharing algorithm. With parallel energy-sharing control, the load demand can be simultaneously provided by all energy sources, however, with different contribution depending on the characteristics of energy sources and the control strategy. In other words, parallel energy control can provide higher degree of energy sharing and greater output power during steady state. ESUs can be used to compensate power requirement once the load demand is larger than the maximum power available from the FC generator. Consequently, the overall volume of the hybrid sources can be downsized and optimized. The battery, on the other hand, can be operated in a narrow charge-discharge cycle and work in idle condition during steady state provided that the based power demand can be fulfilled by the FC.

2. Proposed Energy Management Based on Characteristics of Vehicle Loads and Energy Sources

Energy management is one of the most important factors to ensure the optimization in efficiency, dynamic performance as well as reliability of a FCHV. This is true especially with the utilization of combined ESUs (battery and UC). In order to optimally used of each source and avoid them from hazardous, the proposed algorithm in this paper is developed based on the characteristics of vehicle load components, FC, UC and battery. These are discussed as follows.

- *FCHV load components* can be categorized into two types: constant load and transient load. Constant load consists of based load (on-board electric load and air conditioning), rolling resistance, aerodynamic drag and gravitational load during uphill or downhill. These loads are almost constant and they should be supplied from the FC. On the other hand, transient load is associated with the power needed during acceleration, deceleration or braking. These loads cause a quick power transient response and should be compensated by the energy buffer or storage units.

- *Fuel cell (FC)* shows a slow transient response and has a relatively high internal resistance. In addition, FC system has the disadvantages of slow start-up and this often cited as a major opposition to the use of FC in domestic vehicle especially with the used of fuel reformer [10]. However, FC is able to supply the power continuously as long as the reactants are available. Hence, it could functions as a power generator in the hybrid source by constantly supplying the average or required steady state power. The power flow during this mode is as shown in Fig. 1(a). Depends on the speed of vehicle and state-of-charge (SOC) of ESUs, the FC is used to charge on them while they are in low energy content. A power slope limiter is needed to avoid FC from any peak transient response which could effect to a permanent damage on it (FC starvation phenomenon).

- *Ultracapacitor (UC)* has a very high capacitance density and able to provide a large amount of power (high specific power) within a relatively short period (low specific energy). Moreover, UC is a robust device. It has an extremely long lifecycle, low maintenance and low internal resistance. So, during the design of energy management system, the UC can functions as main energy buffer during peak power transient period. Nevertheless, UC is known to have a relatively low energy density and fast self-discharge characteristics. Application of UC solely as ESU in the FCHEV may face vehicle start-up problem after it has been left for a number of weeks. Therefore, during the start-up stage, power must generally come from energy dense sources such as battery.

- *Battery* has an advantage of high specific energy but relatively low in specific power. The power response is faster than FC, but slower than UC. Furthermore, battery has a limited lifespan (300-2000 cycles) [10,11]. It depends on a lot of factors such as: types of the battery, depth of discharge cycles, discharge rate, cell operating temperature, charging regime, number of overcharge and others. Hence, to optimize the lifespan of battery, it is recommended that the battery current slope must be limited within a safety range in order to reduce the peak transient stress toward it. So, the peak power response can be come from the UC. As discussed early, the main power during the start-up stage must mostly comes from the battery as depicted in the Fig. 1(c).
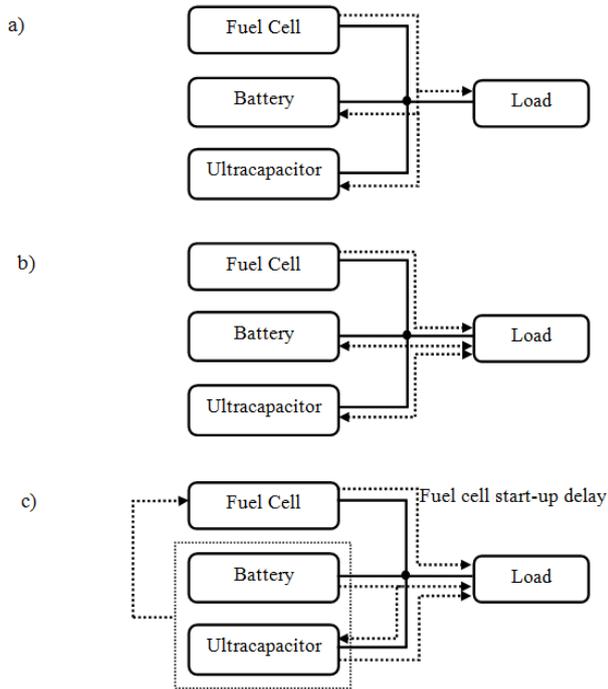
Figure 1   Mode of power flow in the hybrid system: a) during steady state, b) during transient, c) during start-up

3. Proposed Energy Control Strategy

A parallel energy-sharing method is proposed to control of the power flow between the DC bus, primary energy source (FC) and ESUs (UC and battery). The DC bus provides a regulated DC source that is used to supply the motor drive system and vehicle accessories. A parallel active connection is used for the connection between all energy sources and the DC bus as depicted in Fig. 2. In the proposed configuration, FC is connected to the DC bus via a single quadrant boost converter to step-up the voltage and blocks the regenerative power from flowing back into the FC. The battery and UC are connected via the bi-directional power flow half-bridge converters.

The control structure of the proposed parallel energy-sharing control shown in Fig. 3 contained a total of six control loops (all using PI-controllers): a DC bus voltage control loop, three inner current control loops, an UC voltage control loop and a battery charging control loop. These are discussed as follows:

A.   DC bus voltage control loop

The DC bus voltage controlled by the DC bus voltage control loop is used to provide a regulated

voltage source to vehicle drive system. A proportional-integral (PI) controller is used in the voltage control loop to attain a stable and fast dynamic response of DC bus voltage. The required load current (I_{load}) generated via the DC bus voltage controller will then be part of the current reference for the three inner current control loops. The three inner current control loops are used to control the currents for FC, battery and UC respectively.

B.   UC current control loop

A PI controller is used in the UC current control loop to control of UC current flow. UC current reference variable is generated by subtracting the load current (I_{load}) with the output current from battery and FC. This is to ensure that UC will only supply the peak current during transient and back to zero (idle state) once the load current is in steady state condition. However, in order to maximize the usage of UC within the hybrid system, UC voltage control loop is added to control of its energy content in reference to the speed of vehicle as discussed next.

C.   UC voltage control loop

In order to optimize the fuel economy of hybrid source vehicle, energy in UC must be monitored and fully be utilized. By doing so, it can ensure the UC always has sufficient volume to accept most of the kinetic energy during vehicle deceleration and also keep a sufficient energy for vehicle acceleration at the same time. Let the kinetic energy for vehicle is given by equation (1).

$$E_{K.E} = \frac{1}{2} M.(v)^2 \tag{1}$$

Where $E_{K.E}$ is the kinetic energy of vehicle, M is the mass of vehicle and v is the speed of vehicle. Since, the kinetic energy during vehicle deceleration must mostly captured by the UC, it can assumed that the varying in UC energy content equal to the vehicle kinetic energy. So, relation between the vehicle kinetic energy and UC terminal voltage is derived in equation (2).

$$\Delta E_{UC} = \frac{1}{2} C_{UC}.(V_{UCmax,}{}^2 - V_{UC}{}^2) \tag{2}$$

Where ΔE_{UC} is the varying energy content in UC, V_{UC} is the terminal voltage of UC, $V_{UC,max}$ is the maximum voltage of UC and C_{UC} is the capacitance of UC. From equation (1) and equation (2), the

terminal voltage of UC can now be related with the vehicle speed as given in equation (3).

$$V_{UC}(v) \leq \sqrt{V_{UC,max}^2 - \frac{M}{C_{UC}}v^2} \qquad (3)$$

The UC voltage loop is designed to monitor and control of UC terminal voltage accordingly to the vehicle speed as derived in equation (3). A PI controller is used to control the UC terminal voltage. To ensure that UC always has an adequate energy for vehicle accelerations, UC charging command (I_{UC-C}) from the PI controller is added to the current loops of battery and FC in order to get charge on UC when needed. Conversely, the UC

needs to discharge to afford a sufficient volume for vehicle kinetic energy during deceleration. This can be realized by summing up the UC discharge command (I_{UC-D}) to the UC current control loop. The UC discharge command is generated by inversed the outputs signal from the UC voltage control loop. To avoid the battery being charged by the UC, the maximum value of I_{UC-D} is limited at the load current demand. Thus, this can prevent the unnecessary power losses as the battery is designed to charge on the UC at the origin.
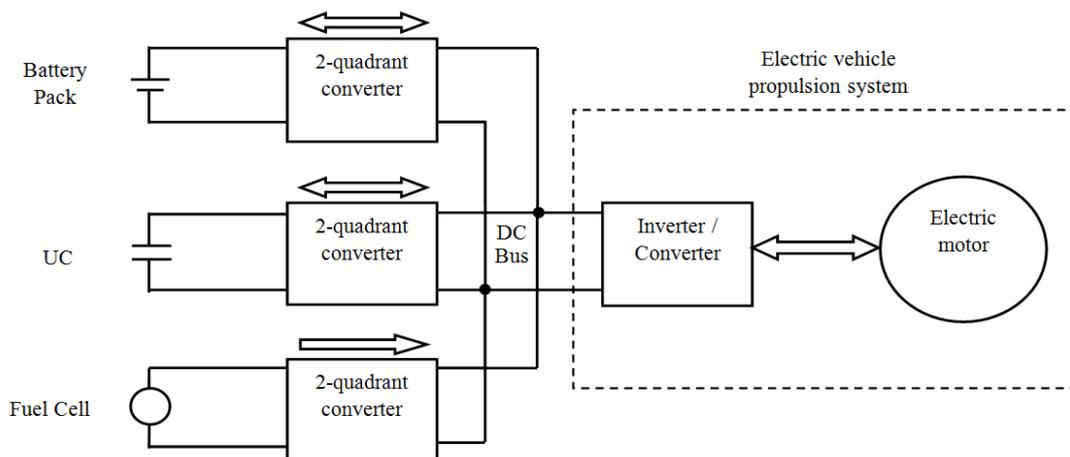
Figure 2   Proposed parallel energy sharing system
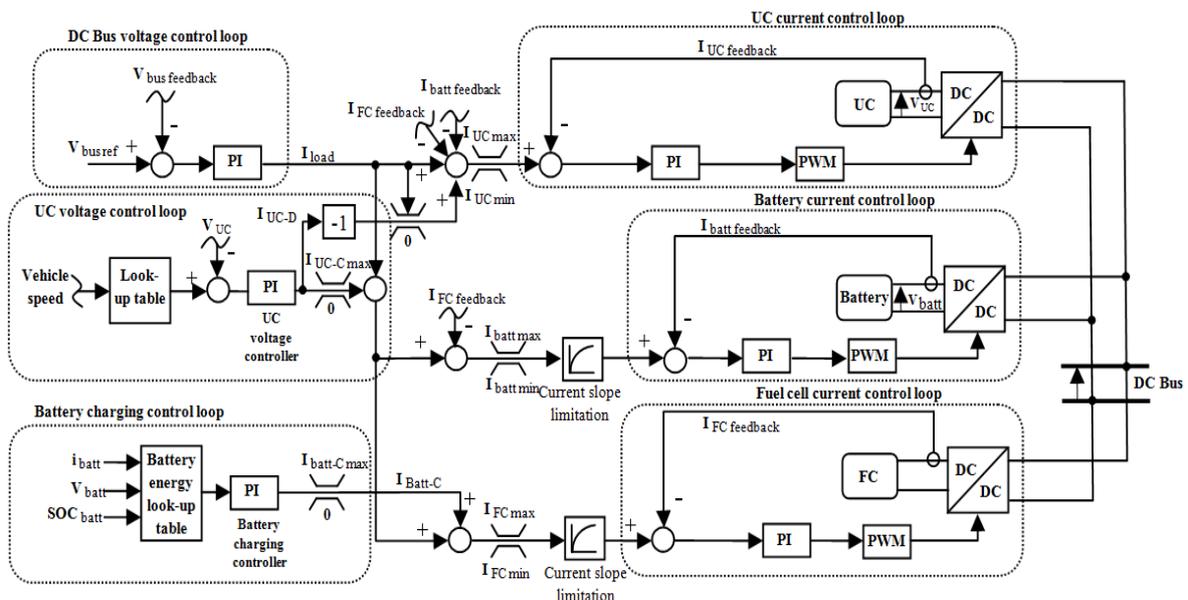
Figure 3   Control structure for the proposed parallel-energy sharing system

D. Battery current control loop

In the proposed parallel of energy management system, battery is used to supply the energy that required during FC start-up stage (i.e. the compressor of the FC, the heater, the FC monitoring system and others), pre-charge the UC during vehicle start up, balance on load demand when FC is limited at its maximum power and compensate some power during vehicle acceleration or deceleration. To ensure a safety operation for the battery, the battery current reference must be limit within a safety range (e.g.: $-0.4Q_{Batt}$ to $0.5Q_{Batt}$). Besides, a current slope limiter is added in the control loop to reduce on power stress towards the battery especially during burst power response. The battery current control loop is controlled by a PI controller.

E. FC current control loop

As the main energy source in the hybrid system, FC current control loop is designed to supply the steady state load power demand and charge on the ESUs when need is arise. The FC current reference must limited within an allowable range (the maximum FC current can be set to the corresponding FC rated value and the minimum FC current is set to be zero). On top of that, the FC current slope is limited at a safety rate to ensure of a secure operation (by introducing a low pass filter). A PI controller is used in the control loop to achieve a zero steady state error response.

F. Battery voltage control loop

It is not an easy task to accurately measure and predict the SOC of a battery. Battery capacity depends on numerous factors as mentioned before. Nevertheless, an approximation for the battery energy content can evaluated through a function of battery terminal voltage, battery current flow and battery initial SOC as given in equation (4). The initial SOC of battery can be obtained based on its open circuited terminal voltage [8].

$$E_{Batt}(t) = SOC_{Batt}(0).Q_{Batt}.V_{Batt}.3600 - \int_0^t v_{Batt}(t).i_{Batt}(t).dt \qquad (4)$$

Where E_{Batt} is the battery energy content, Q_{Batt} is the capacity of the battery (in amp-hour). A simple charging method is implemented to charge the battery, which is based on the constant current-constant voltage (CCCV) method. In the proposed energy control system, battery is only charged by the FC. A battery charging current command (I_{Batt-C}) is added to the current reference signal for FC current control loop. The charging signal is limited between a maximum current of $0.4Q_{Batt}$, and a minimum current of 0A.

G. Summary for the proposed parallel energy-sharing control system

Based on the discussion above, the reference signals for each control loop are summarized as below:

$$V_{bus\ ref} = \text{constant} \qquad (5)$$

$$I_{UC\ ref} = I_{load} - (I_{FC\ feedback} + I_{Batt\ feedback}) + I_{UC-D} \qquad (6)$$

$$I_{Batt\ ref} = I_{load} + I_{UC-C} - I_{FC\ feedback} \qquad (7)$$

$$I_{FC\ ref} = I_{load} + I_{Batt-C} + I_{UC-C} \qquad (8)$$

Where $V_{bus\ ref}$ is the dc bus voltage, $I_{UC\ ref}$, $I_{Batt\ ref}$ and $I_{FC\ ref}$ are the current loop reference signals for UC, battery and FC unit respectively. I_{load} is the load current demand, I_{UC-C} and I_{UC-D} is the UC charge and discharge signal that generated from the UC voltage control loop, $I_{FC\ feedback}$ and $I_{Batt\ feedback}$ are the current feedback signals for the FC and battery respectively, and I_{Batt-C} is the battery charging command.

4 Experimental results

Simulations as well as experiments are carried out to verify the viability of the proposed method. The simulations are carried out using of MATLAB/Simulink simulation package. For the experimental set-up, the batteries are composed by 4 series connected units of 12V and 45AH calcium-calcium battery. The UC considered is a BMOD0165 EO48 BO1 BOOSTCAP from Maxwell with 165F capacity and 48V voltage rating. The FC behavior is emulated by a dc power supply HP6675A. These devices were allocated according to the availability in the laboratory. The control algorithm is implemented using dSPACE DS1104 controller board with an overall sampling period of 100µs. Fig. 4 shows the laboratory-scale experimental test bench used to verify the proposed scheme.

Figure 4   Picture of experimental set-up

The DC bus voltage is set to 80V and a shunt DC motor rated at 0.25hp 120V 3000r.p.m. is then connected to the DC bus via H-bridge converter to represent the vehicle propulsion system. A loaded generator-set is then coupled with the DC motor. Before the proposed hybrid system is loaded with the motor drive system, a pulse response using resistive load at 36ohm is applied toward the system to ensure system's functionality. Te resistive load results a pulse current load demand steps from

0A to 2.222A and drop to 0A again as illustrated in Fig. 5 below. The UC and battery modules are full-of-charge and load power is zero at initial.

At t = 10 s, the resistive load is turned on and the constant load power step up from 0A to 2.2222A. From the results, one can observe the following:

- The UC module supplies most of the transient power required.
- The slope of current drawn from the battery and FC are limited at a time constant of 1.5s and 5s, respectively. Hence, the UC power provides the fastest dynamics; the battery power is in the middle dynamics; and the FC power is the slowest dynamics.
- Synchronously, the UC power, after the sharp discharge, decreases slowly to a constant discharge current at around 1.5A.
- Since, the UC is full-of-charge at initial, which is higher than the designed limit (87.5%). So, during the steady-state, the constant load power is supplied by the FC and UC module. The UC module is keep discharged and the battery is at idle condition.
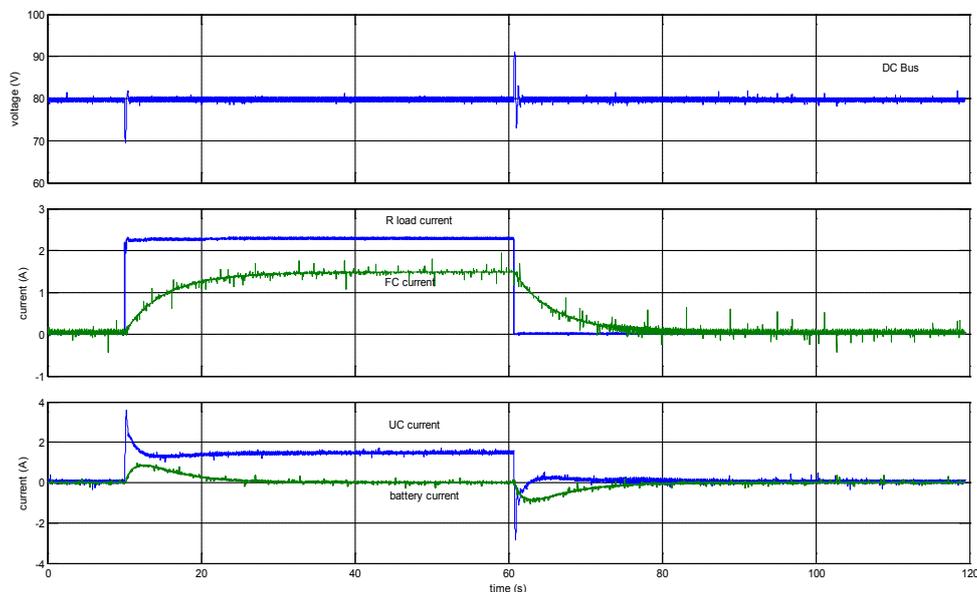
Figure 5   Pulse response using resistive load

At t = 60 s, the resistive load is turned off and the constant load power step down from 2.222A to 0A. From the results, one can observe the following:

- The UC module response most of the transient power.
- The power due to the slow response of FC are recuperated mostly by the UC and

followed by the battery within a limited current slope.

- The UC power provides the fastest dynamics, followed by the battery power and FC power.

During the steady state, the load power is zero and output power from the FC, battery, and UC are also zero.

To further verify on the proposed energy control, the DC motor-generator coupling set is then connects to the DC bus. An ideal start-stop drive cycle is loaded toward the proposed hybrid system and the results are highlighted and discussed during the motor acceleration, deceleration and steady state. At the initial, the battery is fully charged and the SOC of UC is set at 87.5% (V_{UC} =42 V).
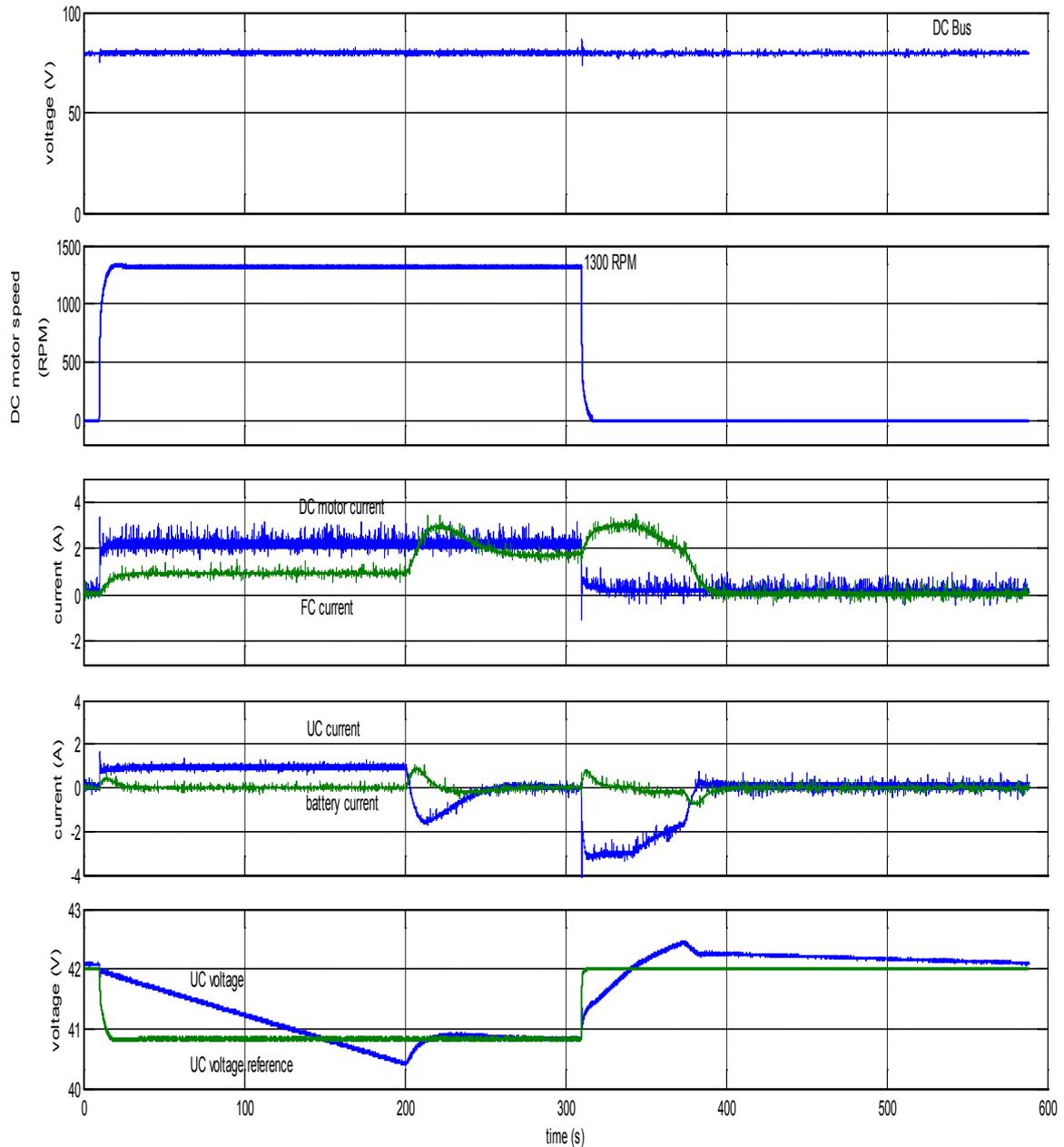
Figure 6 An ideal start-stop drive cycle response for the proposed hybrid system
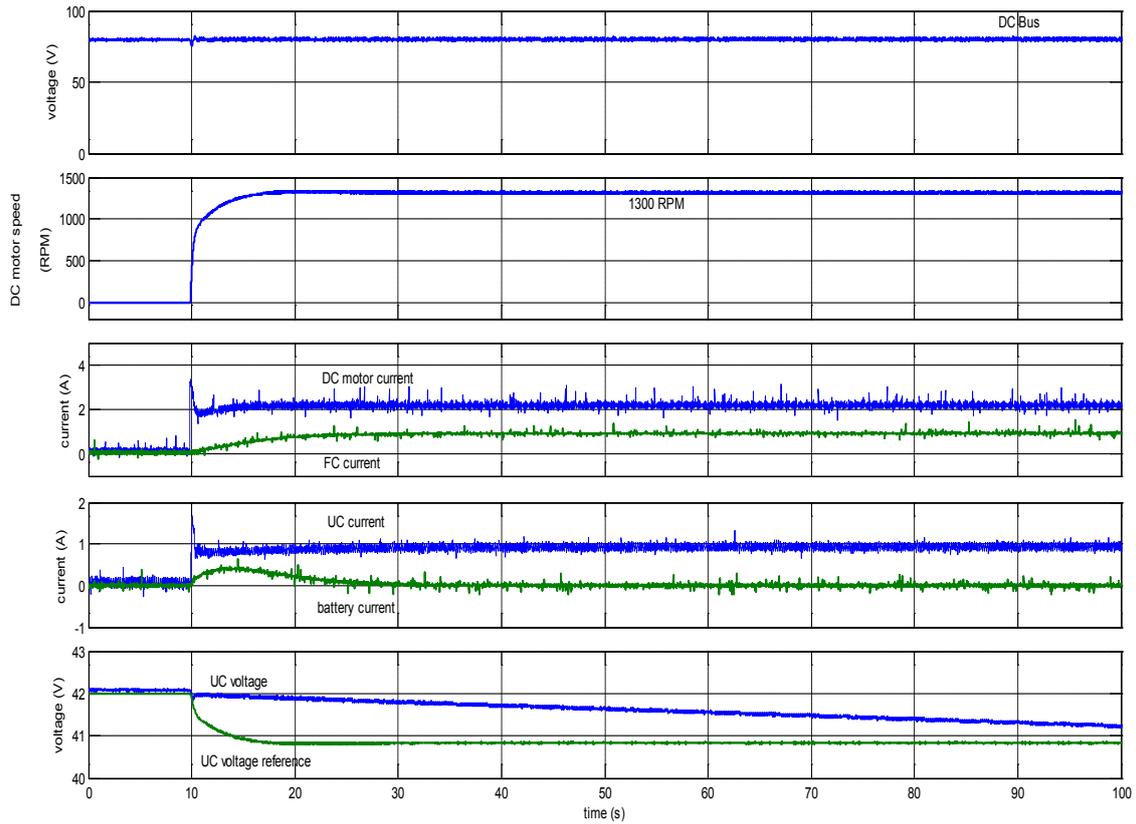
Figure 7 Response during motor acceleration (zoom in view)
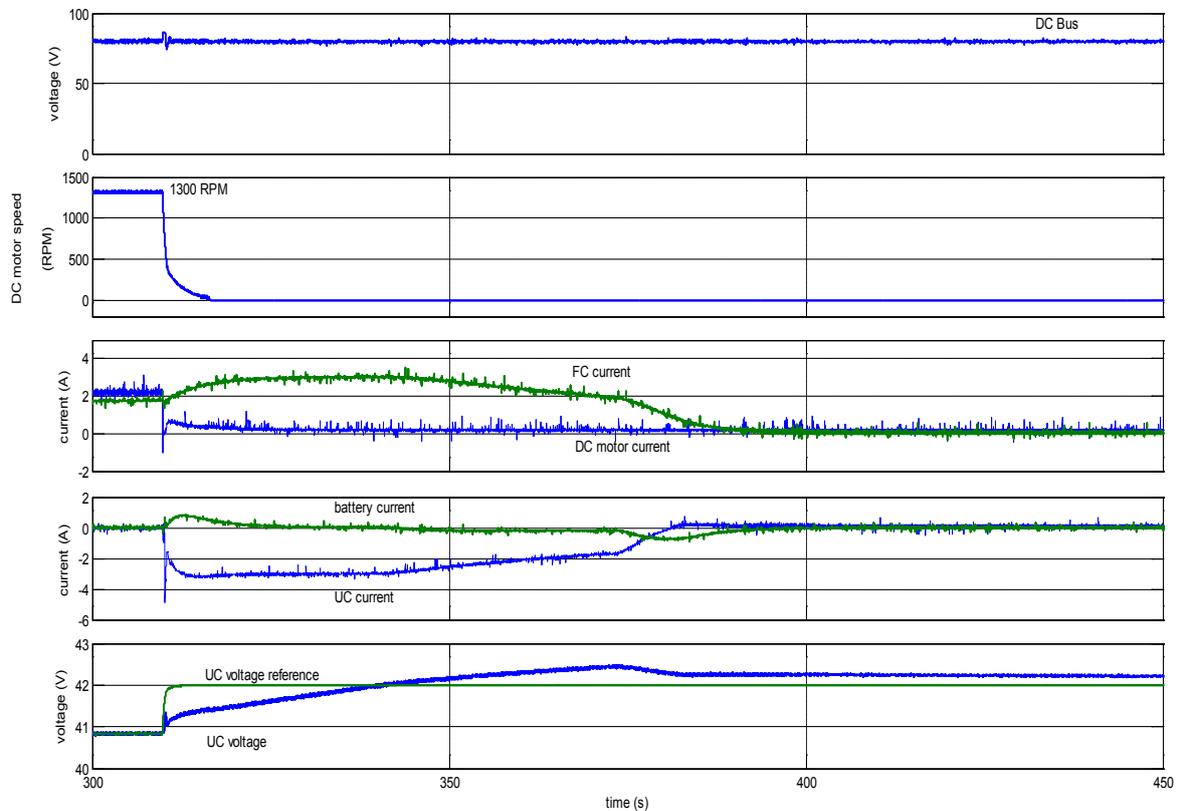
Figure 8   Response during motor deceleration (zoom in view)

Fig. 6 shows the experimental results for an ideal start-stop cycle whereby the DC motor is accelerates at $t=10s$ from stand still condition to steady speed condition (1300 rpm) and then decelerates at $t=310s$ to stand still condition.

Fig. 7 shows the response during motor acceleration in zoom in view. As the DC motor started to accelerate, the following conditions are observed:

- During motor acceleration, the UC module supplies most of the peak power demand followed by the battery and FC within a limited current slope.
- So, the UC power provides the fastest dynamics; the battery power is in the middle dynamics; and the FC power is the slowest dynamics.
- Synchronously, the UC power, after a sharp discharge during motor acceleration, decreases slowly to a constant discharge current at around 1A.
- Based on the speed of the DC motor, the UC module is keep discharging up to it reference voltage to make room for regenerative energy from the DC motor.
- The steady-state load current is approximately 2A, which is totally supplied by the FC and UC sources. The battery is back to idle state after the transient response.

Fig. 8 shows the response during motor deceleration in zoom in view. When the DC motor starts to decelerate, it can be observed that the regenerative braking energy from the DC motor is supplies back to the dc bus. One can observe that:

- First, the sharp braking power is recuperated by the UC and at the same time, the UC is also getting charged from the FC and battery.
- Second, the FC and battery are supply power to charge the UC. The battery is then back to idle condition and the UC charging power is fully comes from the FC.
- Third, when the UC module is charged up to its reference voltage, the FC power slowly reduces to zero.
- Fourth, the slow power response of the FC will then recuperated by the battery when the UC is charged up to its reference voltage.

Refers to Fig. 6, during the steady state, one can observe the following:
 i.   Steady state speed
   - During the steady state speed, the UC is discharged accordingly to the speed of

motor to make room for regenerative power.
- However, if the UC voltage is lower than its reference voltage, the UC will get charged from the battery followed by the FC.
- Once the UC is attained to its reference voltage, the FC is supplies all of the constant load power. At this time, the Battery and UC are in the idle condition.
 ii.   Stand still condition
   - At the stand still (zero speed) condition, the FC and battery are charge on the UC up to its reference voltage.
   - The FC, battery and UC are in idle condition when there are no load demands.

5. Conclusions

This paper mainly discusses on the designs and control structures for the proposed parallel energy-sharing control in FCHVs application. The hybrid source in this paper consists of FC generator, battery and UC modules. Through the proposed energy control system, it avoids of peak power stress toward the FC and battery. Hence, the UC is used to provide peak power demand and to recuperate most of the braking power at the same time. Voltage of the UC is controlled accordingly to vehicle speed in order to ensure sufficient energy for vehicle acceleration and also adequate volume for vehicle braking. The proposed method does not guarantee perfect results in all situations, but provides a satisfactory energy management method in control the overall FCHV system. The validity of the proposed energy control scheme is supported by simulation and experimental results under average and peak power response.

References:

[1] A. Emadi, Y.J.Lee, K.Rajashekara, Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles, *IEEE Trans. on Industrial Electronics*, Vol. 55, No. 6, 2008, pp. 2237-2245.

[2] K.P.Adzakpa, K.Agbossou, Y.Dube, M.Dostie, M.Fournier, A.Poulin, PEM Fuel Cells Modeling and Analysis Through Current and Voltage Transient Behaviors, *IEEE Trans. on Energy Conversion*, Vol.23, No. 2, 2008, pp.581-591.

[3] P.Thounthong, S.Real, B.Davat, Energy management of fuel cell/ battery/ supercapacitor hybrid power source for vehicle applications, *Journal of Power Sources*, Vol. 193, No. 1 2009, pp. 376-385.

[4] WenzhongGao , Performance Comparison of a Fuel Cell-Battery Hybrid Powertrain and a Fuel Cell-Ultracapacitor Hybrid Powertrain, *IEEE Trans. on Vehicular Technology*, Vol. 54, No.3, 2005, pp. 143-150.

[5] Jennifer Bauman and Mehrdad Kazerani, A Comparative Study of Fuel Cell-Battery, Fuel cell-Ultracapacitor, and Fuel Cell-Battery-Ultracapacitor Vehicles, *IEEE Transactions On Vehicular Technology*, Vol. 57, No. 2, 2008, pp. 760.

[6] N. Schofield, H. T. Yap and C. M. Bingham , Hybrid Energy Sources for Electric and Fuel cell Vehicle Propulsion, *IEEE Transactions on Energy Conversion,* Vol. 23, No. 2, 2005, pp. 522-529.

[7] E. Schaltz, A. Khaligh and P. O. Rasmussen, Investigation of Battery/ Ultracapacitor Energy Storage Rating for a Fuel Cell Hybrid Electric Vehicle, *IEEE 2008 Vehicle Power and Propulsion Conference*, 3-5 Sept. 2008, Harbin, pp.1-6.

[8] A. A. Ferreira, J. A. Pomilio, G. Spiazzi and L. de Araujo Silva, Energy Management Fuzzy Logic Supervisory for Electric Vehicle Power Supplies System, *IEEE Transactions on Power Electronics*, Vol. 23, No. 1, 2008, pp. 107-115.

[9] Phatiphat Thounthong, Stephane Real and Bernard Davat, Control Strategy of Fuel cell/ Supercapacitors Hybrid Power Sources for Electric Vehicle, *Journal of Power Sources*, Vol. 158, No. 1, 2006, pp. 806-814.

[10] C. M. Jefferson and R. H. Barnard, *Hybrid Vehicle Propulsion*. Southampton, UK: WIT Pr., 2002.

[11] M.Ehsani, Y.Gao, and A. Emadi. *Modern Electric, Hybrid Electric and Fuel Cell Vehicle-Fundamentals, Theory and Design* (Second Edition). Boca Raton: CRC press, 2010.