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A Parallel Energy-Sharing Control Strategy for Fuel Cell Hybrid Vehicle

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Abstrak

Makalah ini menghadirkan strategi kendali berbagi-energi parallel untuk aplikasi kendaraan hibrida fuel cell (FCHV). Catudaya hibrida terdiri dari pembangkit fuel cell (FC) dan unit penyimpang energy (ESU) yang mengkombinasikan modul baterai dan kapasitor ultra. Bus arus DC digunakan untuk antar muka antara catudaya dan sistem pendorong kendaraan elektrik (EV). Catudaya dan sistem pendorong ini dikoneksikan ke bus DC konversi elektronika daya. Terdapat enam kalang kendali didesain pada sistem supervisi untuk mengatur tegangan bus DC, mengendalikan aliran arus listrik dan pada waktu yang sama memonitor kondisi pengisian dari masing-masing piranti penyimpan energi. Pengendali proposional integral (PI) diterapkan untuk mengatur keluaran dari tiap-tiap kalang kendali mengacu kepada sinyal referensinya. Sistem kendali energy yang diusulkan disimulasikan pada lingkungan MATLAB/Simulink. Hasil penelitian mengindikasikan bahwa sistem kendali berbagi-energi paralel yang diusulkan mampu menyediakan tanggapan kendaraan hibrida yang praktis terhadap tanggapan traksi kendaraan elektrik dan pada waktu yang sama mampu menghindarkan FC dan baterai dari beban lebih.

Kata kunci*: baterai, fuel cell, kapacitor ultra, kendaraan elektrik, sumber hibrida*

Abstract

This paper presents a parallel energy-sharing control strategy for the application of fuel cell hybrid vehicles (FCHVs). The hybrid source discussed consists of a fuel cells (FCs) generator and energy storage units (ESUs) which composed by the battery and ultracapacitor (UC) modules. A direct current (DC) bus is used to interface between the energy sources and the electric vehicles (EV) propulsion system (loads). Energy sources are connected to the DC bus using of power electronics converters. A total of six control loops are designed in the supervisory system in order to regulate the DC bus voltage, control of current flow and to monitor the state of charge (SOC) of each energy storage device at the same time. Proportional plus integral (PI) controllers are employed to regulate the output from each control loop referring to their reference signals. The proposed energy control system is simulated in MATLAB/Simulink environment. Results indicated that the proposed parallel energy-sharing control system is capable to provide a practical hybrid vehicle in respond to the vehicle traction response and avoids the FC and battery from overstressed at the same time.

Keywords*: battery, fuel cell, hybrid source, hybrid vehicle, ultracapacitor*

1. Introduction

With the escalating number of vehicles on road, energy shortage and environmental concern, lots of research and development have been conducted to explore for other alternative energy sources in replacing the fossil fuel in vehicular application. The FC has been widely considered as one of the most potential solutions due to its high energy density, zero emissions and sustainable fuels [1]. In contrast to the battery powered electric vehicle (BEV), fuel cell vehicle (FCV) offers a longer driving range as long as the fuel supply is presented. However, there are still a lot of obstacles when employing the FC alone to power a traction system. These included of 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 [2-4]. Moreover, peak power demands from the FC could lead to fuel starvation phenomenon and hazardous to its lifespan. To this end, the energy storage units (ESUs) are considered as the

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most significant device to optimize the performance of FCV. In addition, a proper sizing of ESUs in the FCV possibly could greatly reduce vehicle size and cost [3].

The ESUs could compose by battery modules, UC modules or combination of both (combined-ESUs). The ESUs must be sized such that they are able to provide an adequate peak power and sufficient energy to propel the vehicle when the need is arise. Many recent works have been presented such as the hybridization of FC/UC hybrid source [3,5-7], FC/battery hybrid source [3,5,6,8] as well as FC/battery/UC hybrid source [2,9,10] for vehicular application. From the comparative studies performed in [3,4], results showed that by an appropriate sizing of combined-ESUs (battery and UC) in the FCHV, it could lead to a more practical and efficient traction system. The combined-ESUs are capable to provide a high specific power and high energy density's storage unit at the same time. However, the hybridization of combined-ESUs with FC generator would complicate the energy management control in the hybrid source system.

This paper focuses on the energy management and power flow control. From the literatures, most of the proposed energy management strategies that applied in the FC-battery-UC hybrid source are in series configuration [2,3]. In the series configuration of energy management, the power-flow is controlled using a series connection such that the energy dense sources are used to deliver the required power to charge the power dense source, and the power dense source is used to regulate the DC bus and to response peak power demand at the same time.

A parallel energy-sharing control method is presented here. However, the detailed model of converters and power sizing for the FC generator and ESUs are beyond the scopes of this study. Through the proposed energy management system, the power-flow between the multiple energy sources (FC, battery and UC) and the DC bus are being controlled in a parallel mode. By the proposed energy management control system, the DC bus is regulated by all energy sources simultaneously with different contribution depending on the characteristics of energy sources and also the defined energy control rules. The EV propulsion system can then be connected to the DC bus via inverter or converter depending on the electric motor types.

Arrangement of this paper is as follows: section 2 discusses on the design of energy management system while section 3 discusses on the control structures. The simulation results and discussion are presented in Section 4 and finally the conclusion is presented in Section 5.

2. Energy Management Design

Energy management is one of the most important factors to optimize the efficiency, dynamic performance as well as reliability of a hybrid system. This is true especially with the utilization of FC generator and combined-ESUs (battery and UC). In order to optimally use of each energy source and avoid them from hazardous, the proposed energy management system in this paper is developed based on the characteristics of vehicle load components and each energy source (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 generator. 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 relatively high internal resistance. In addition, FC system has the disadvantages of slow start-up which often cited as one of the major opposition to the use of FC in domestic vehicle especially with the use of fuel reformer [11]. However, FC is able to supply power continuously as long as the reactants are available. Thus, the FC is serves as a power generator in the hybrid system by continuously supplying the average or required steady state power. The power flow during this mode is as shown in Figure 1(a). Depends on the speed of vehicle and state-of-charge (SOC) of the ESUs, the FC is also used to charge on them while they are in low energy content. A power slope limiter is needed to avoid the FC from any peak transient response which could damage on it (fuel cell starvation phenomenon).

- Ultracapacitor (*UC)* has a very high capacitance density and is 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. Consequently, the UC functions as main energy buffer during peak power transient period. The mode of power flow during transient stage is as shown in Figure 1(b). Nevertheless, UC is known to have a relatively low energy density and fast self-discharge characteristic. The hybrid traction system using of UC as the only-ESU may face start-up problem once the charge in the UC is depleted due to self-discharged process [3]. In this stage, one should not rely on the FC to power the vehicle, supply the initial acceleration power and charge on the UC at the same time. Furthermore, the FC system usually requires some few minutes to stabilize after start-up. Therefore, during the start-up stage, the main power should be comes from other source (i.e. 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 limited lifespan (300-2000 cycles) [1,11]. 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 of peak power transient stresses toward it. In this case, the peak power response could come from the UC. As discussed early, the main power during start-up stage must mostly comes from the battery as depicted in Figure 1(c).

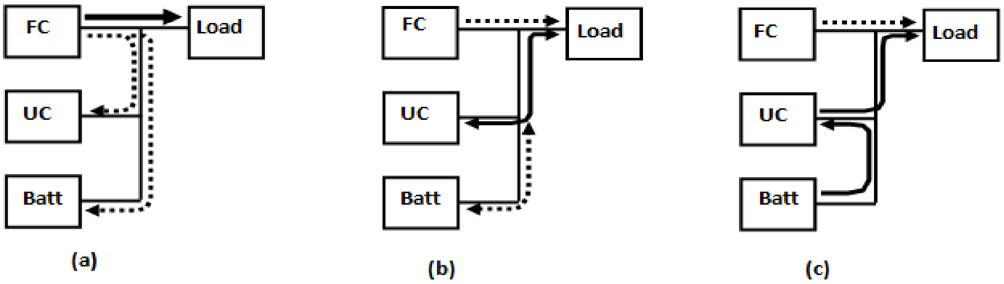

Figure 1. Three modes of hybrid source operation during (a) steady state, (b) transient, and (c) vehicle start-up (solid arrow: main power flow, dotted arrows: secondary power flow).

3. Research Method

In order to accomplish the mode of power flow as discussed above, a parallel energy-sharing control system is created to control the power flow between the DC bus, FC generator and ESUs (UC and battery). The vehicle traction system and accessories are supplied through the DC bus at a regulated voltage. To enable the control of power flow from each source, DC/DC converters are employed to interface between the sources and the DC bus as depicted in Figure 2. In order to step-up the output voltage from the FC generator and blocks regenerative power at the same time, a single quadrant boost converter is employed to connect the FC to the DC bus. On the other hand, the battery and UC are connected to the DC bus via bi-directional half-bridge converters such that they are able to be charged-up or discharged.

The control structure of the proposed parallel energy management control is as shown in Figure 3. It contains 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. The DC bus voltage control loop is used to regulate the DC bus voltage which generates a current reference (I_{load}) to the three inner current control loops. The three inner current loops are then used to control the currents for the FC, battery and UC respectively. In order to limit the slope of reference current for the battery and FC within their safe values, low pass filters with time constants τ_1 and τ_2 are used respectively. The final value of current reference for the UC is obtained by subtracting the reference current generated by the DC voltage loop with the output current from battery and FC; this is to ensure that only the UC current reference contains the demanding peak transient elements of the load current reference. To enable the battery to operate in a narrow charge-discharge cycle, the battery current reference is subtracted with the FC output current. By doing so, the peak power demand from the FC is avoided and at the same time only the FC will supply the continuous steady state power.

In the proposed control strategy, the UC is used mainly for two reasons: to provide the peak power requirement during acceleration and to absorb the vehicle kinetic energy during regenerative braking. It is therefore important to ensure that the UC is always ready to provide the peak power as well as to absorb the braking power. For this reason, the SOC of the UC is made dependent on the vehicle speed such that the available capacity of the UC is proportional to the vehicle kinetic energy. For instance, if the vehicle is moving fast (i.e. large kinetic energy), more room is made available in the UC for regenerative braking and vice versa. Thus the UC voltage is given by (1).

$$V_{UC}(\upsilon) \le \sqrt{{V_{UC,max}}^2 - \frac{M}{C_{UC}}\upsilon^2} \qquad (1)$$

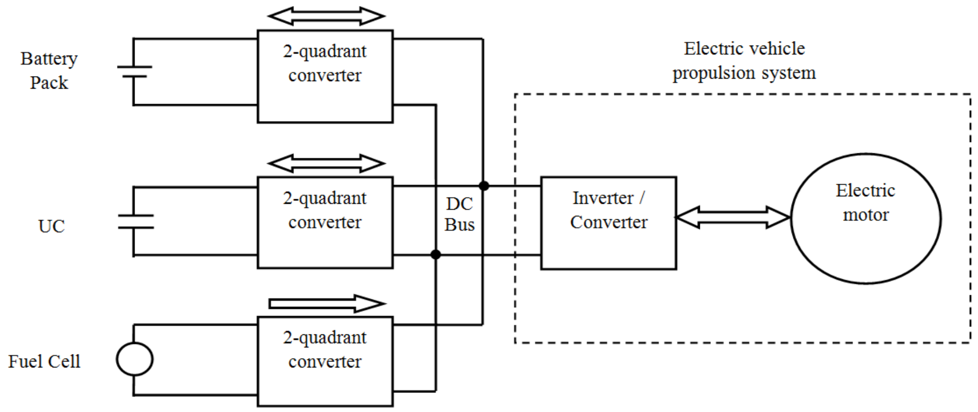

Figure 2. The proposed parallel energy-sharing system

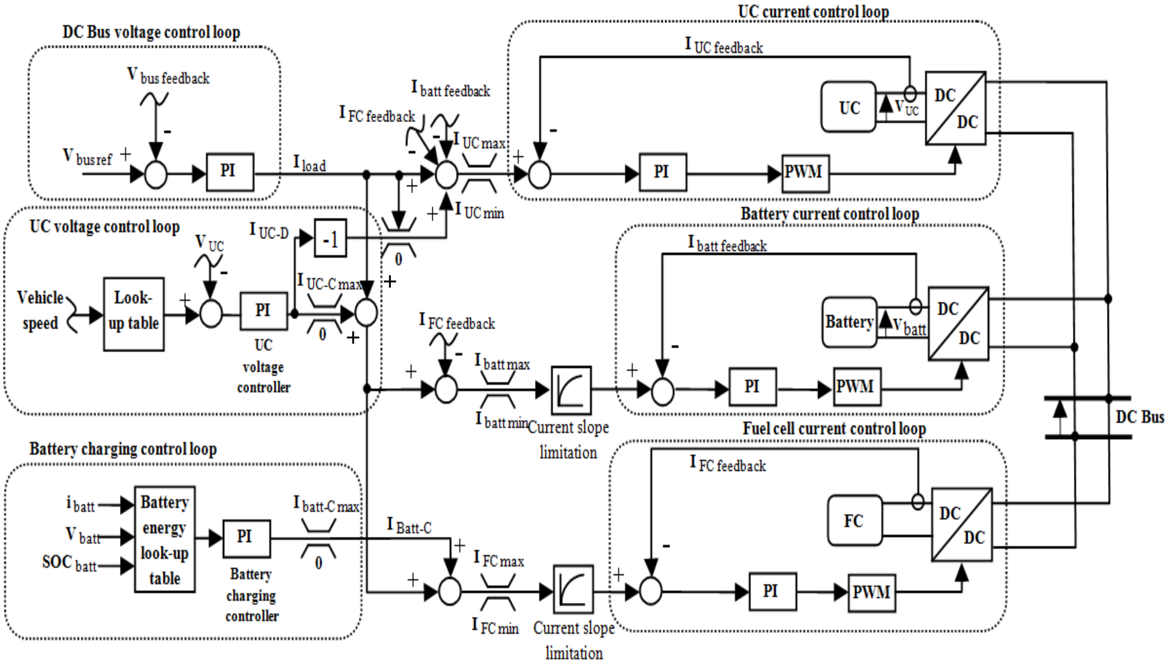

Figure 3. Proposed parallel energy-sharing control system for fuel cell-battery-ultracapacitor hybrid power source.

In (1), V_{UC} is the terminal voltage of the UC, $V_{UC,max}$ is the allowable maximum voltage of the UC, M is the mass of the vehicle, v is the speed of vehicle and C_{UC} is the capacitance of the UC. To ensure that the UC always has an adequate energy from the battery and FC for vehicle accelerations, UC charging command ($I_{UC\text{-}C}$) is added to the battery and FC current references. Conversely, UC need to be discharged to provide sufficient volume for the vehicle kinetic energy during regenerative braking. This can be realized by summing up the UC discharge command ($I_{UC\text{-}D}$) to the UC current control loop. To avoid battery being charged by UC, the UC discharge command is limited to load current demand.

In the proposed energy control system, battery is only charged by the FC and is controlled through the battery charging control loop. A simple charging method is implemented to charge on the battery, which is based on constant current-constant voltage (CCCV) method. The initial SOC of the battery can be obtained based on its open-circuit terminal voltage [9]. The battery charging command ($I_{Batt\text{-}C}$) is generated from the control loop and added to the current reference of FC current control loop in order to charge of it.

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

$$V_{bus\ ref} = constant \tag{2}$$

$$I_{UC\ ref} = I_{load} - (I_{FC\ feedback} + I_{Batt\ feedback}) + I_{UC\text{-}D} \tag{3}$$

$$I_{Batt\ ref} = I_{load} + I_{UC\text{-}C} - I_{FC\ feedback} \tag{4}$$

$$I_{FC\ ref} = I_{load} + I_{Batt\text{-}C} + I_{UC\text{-}C} \tag{5}$$

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 the UC, battery and FC respectively. I_{load} is the load current demand, $I_{UC\text{-}C}$ and $I_{UC\text{-}D}$ are the UC charge and discharge signal that are 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 $I_{Batt\text{-}C}$ is the battery charging command.

4. Simulation Results and Discussion

Simulation study using MATLAB/Simulink was carried out to verify on the proposed energy management algorithm. An FCs stack with 18kW 112v, battery bank with 144v 156Ah and UC modules of 48F 126v are applied in the simulation. The test load consists of a DC motor rated at 30hp 240V 1750 r.p.m. is connected to the DC bus via H-bridge converter. The DC motor emulates as a propulsion system would draw the power from the hybrid source once the speed command is given. Table 1 shows the assumed vehicle parameters and the minimum and maximum controlled parameters that are applied in the simulation.

Table 1. Assumed vehicle parameters and min-max controlled parameters

Parameters	value
Vehicle Mass	2200 kg
Radius of Tyre	0.14 m
FC Warm-up Power	600 watt
$I_{UC\text{-}min}$, $I_{UC\text{-}max}$	-750A, 750A
$V_{UC\text{-}min}$, $V_{UC\text{-}max}$	31.5V(25%), 100V(80%)
$I_{batt\text{-}min}$, $I_{batt\text{-}max}$	-62A, 78A
$V_{batt\text{-}min}$, $V_{batt\text{-}max}$	60V(40%), 115V(80%)
$I_{FC\text{-}min}$, $I_{FC\text{-}max}$	0A, 150A

The complete simulation model for the proposed scheme, constructed using the MATLAB/Simulink environment is depicted in Figure 4. It consists of energy sources, DC-DC converters, feedback signals, proposed parallel energy control system and test loads. For the energy sources, it include of FC stack, battery and UC module.

To verify on the proposed energy control, three conditions were simulated: vehicle start-up, vehicle acceleration and vehicle deceleration. Figure 5 shows the UC voltage, UC current and the battery current during the start-up process. Assuming an initial SOC of the UC is at 25% (V_{UC} =31.5 V) and the initial SOC of the battery is at 85% (approximate 122.4 V).During the vehicle start-up, power is drawn by the UC to pre-charge on it and at the same time an estimated FC warm-up power of 600 watt is supplied from the battery. From the results shown in Figure 5, the UC took around 35s to charge up from SOC of 25% to 80%.

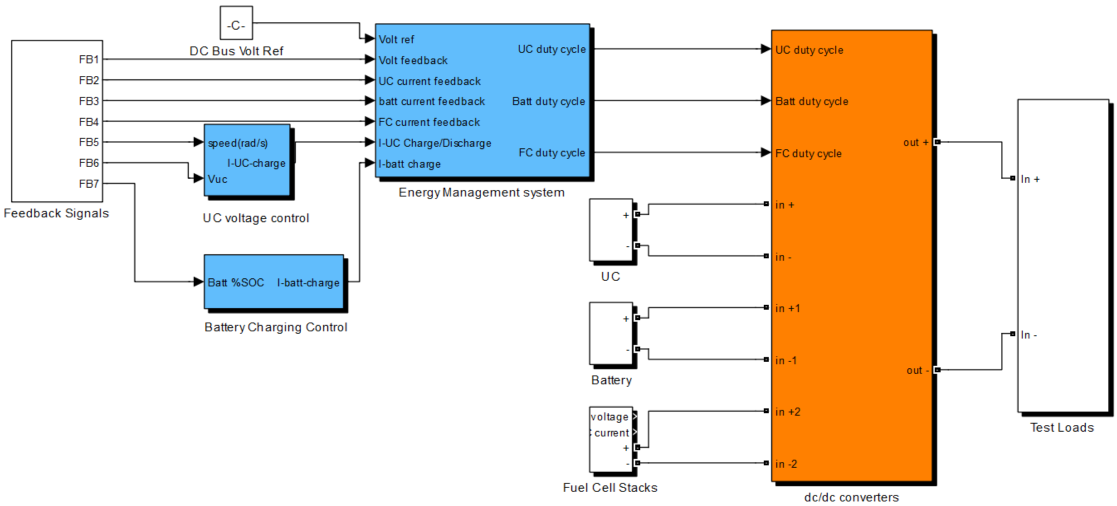

Figure 4. Complete simulation model of the proposed parallel energy-sharing control system

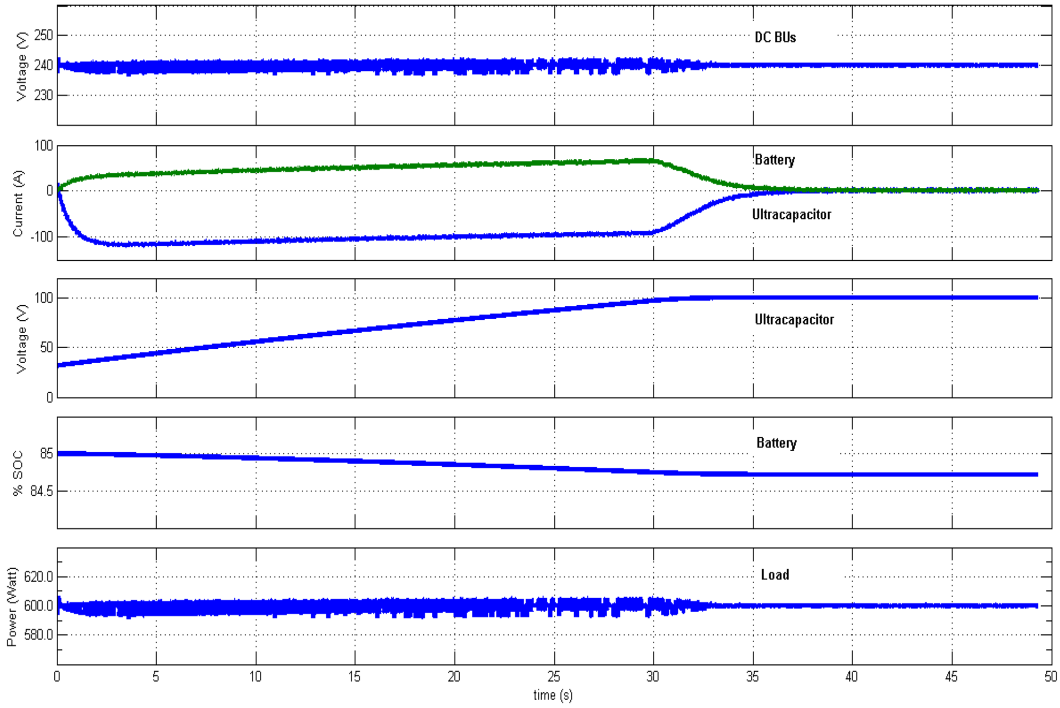

Figure 5. Result during vehicle start-up.

Figure 6 shows the simulation results during the DC motor accelerates from a stand still condition to 955rpm. As the DC motor starts to accelerate, the peak current is supplied by the UC followed by the battery and FC.

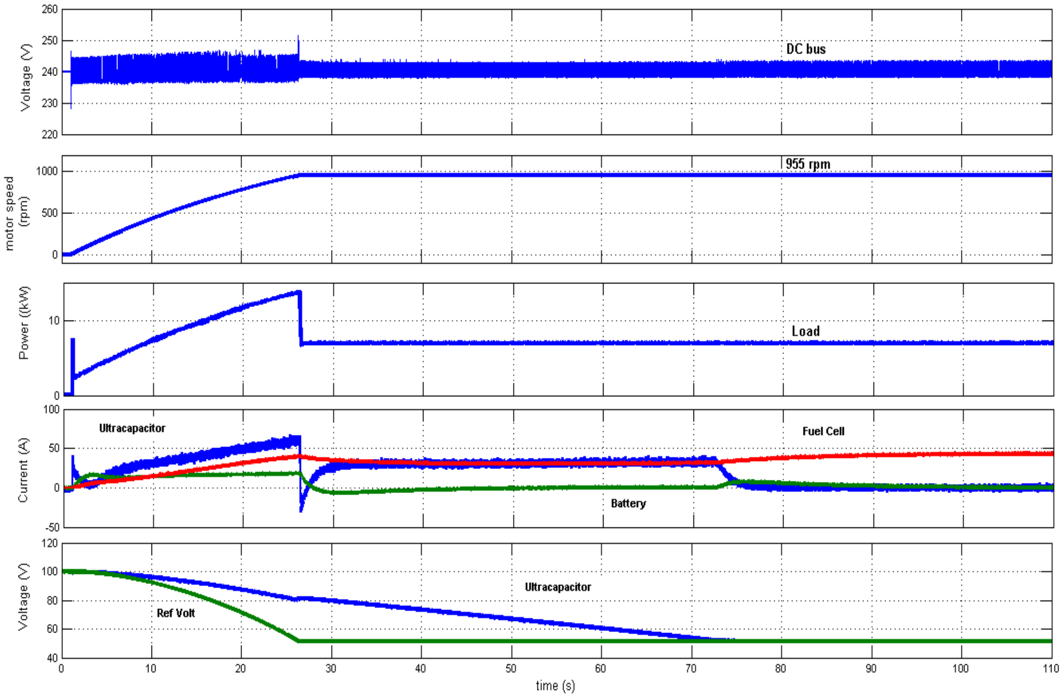

Figure 6. Results when electric motor accelerates from stand still to a final speed of 1520 rpm.

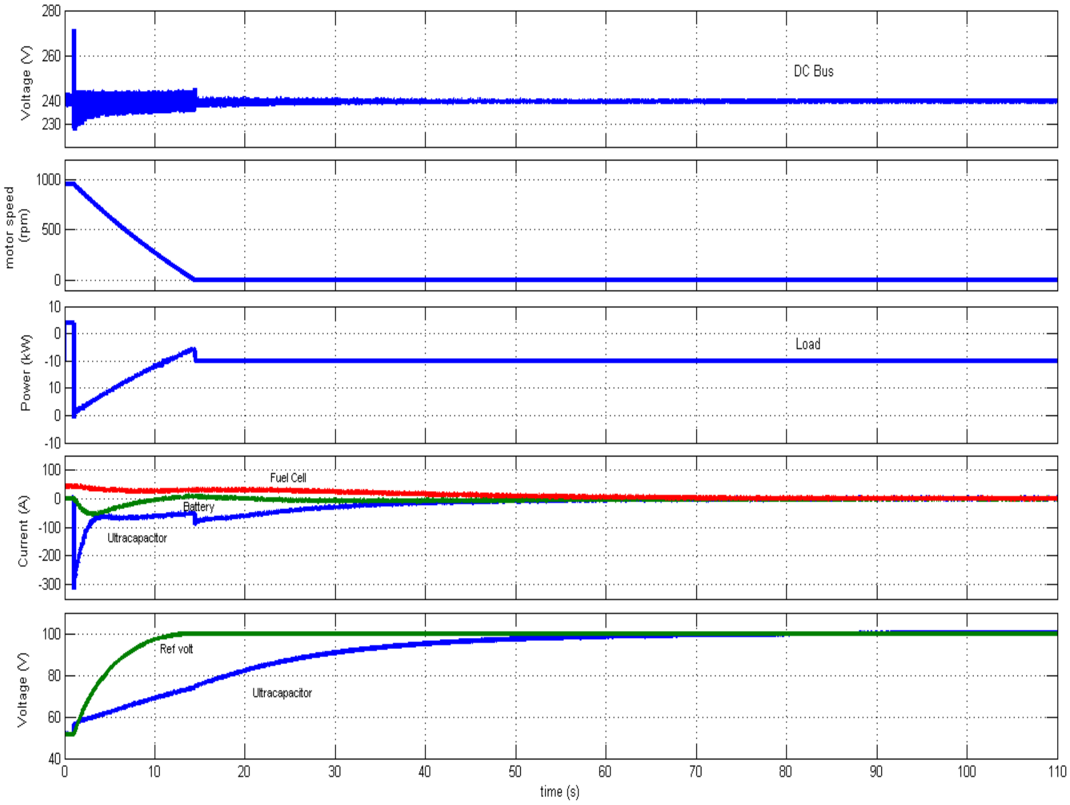

Figure 7. Results when electric motor decelerates from 1520 rpm to 0 rpm.

During the transient period, current drawn from the battery and FC are limited in a safety slope to avoid of peak power stress. Once the DC motor achieves to steady state speed, the UC quickly responses to the load change and balances the DC bus voltage. During the steady state speed, UC keep discharges to make room for the braking power as governed by equation (3). Once the UC has attained to its reference voltage referring to the motor speed, FC would supply all of the constant load power. The battery and UC would in idle condition provided that the based load power is available from the FC.

Figure 7 shows the response during the DC motor decelerates from 955 rpm to 0 rpm. It could be observed that the sharp braking power is mostly recuperated by the UC followed by the battery (within a limited current slope). Besides, the residual power from the FC due to its slow power response is also recuperated by the UC and battery. Subsequently, the battery and FC are charge the UC up to its reference voltage to ensure a high vehicle dynamic response afterward.

5. Conclusion

This work mainly discusses on the design and control structures for the proposed parallel energy-sharing control system. The proposed hybrid system is designed for vehicular application which employed of FC generator, battery bank and UC modules. It was designed based on the characteristics of energy sources and also the vehicle load components. By the proposed energy control algorithm, it avoids the fuel cell and battery being overstressed during peak power demand and efficiently utilizes the UC based on vehicle kinetic energy. In addition, the battery is designed to provide the initial charging power to UC and also provide the required power for vehicle start-up. Thus, it is expected that a more practical FCHV could obtained via the proposed energy management system. Even though the proposed method may not guarantee perfect results in all situations, but it provides a satisfactory energy management method in control the overall FCHV system. The validity of the proposed energy control scheme is supported by the simulation results as discussed above.

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