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].

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

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 ($I_{Batt\text{-}C}$) 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:

$$V_{bus\ ref} = \text{constant} \tag{5}$$

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

$$I_{Batt\ ref} = I_{load} + I_{UC\text{-}C} - I_{FC\ feedback} \tag{7}$$

$$I_{FC\ ref} = I_{load} + I_{Batt\text{-}C} + I_{UC\text{-}C} \tag{8}$$

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, $I_{UC\text{-}C}$ and $I_{UC\text{-}D}$ 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 $I_{Batt\text{-}C}$ 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.

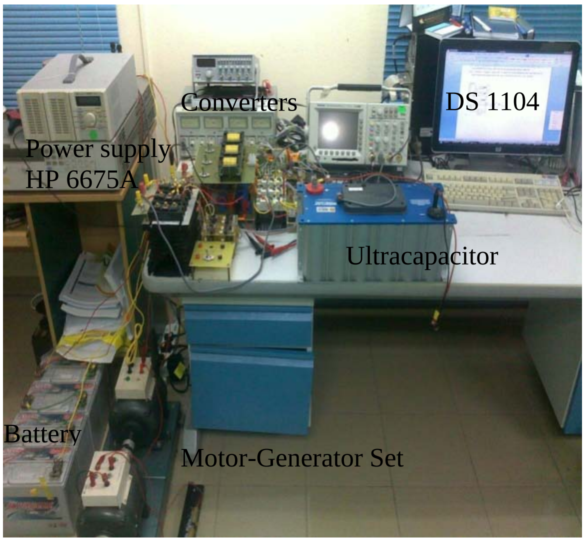

Figure 4 Picture of experimental set-up

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.

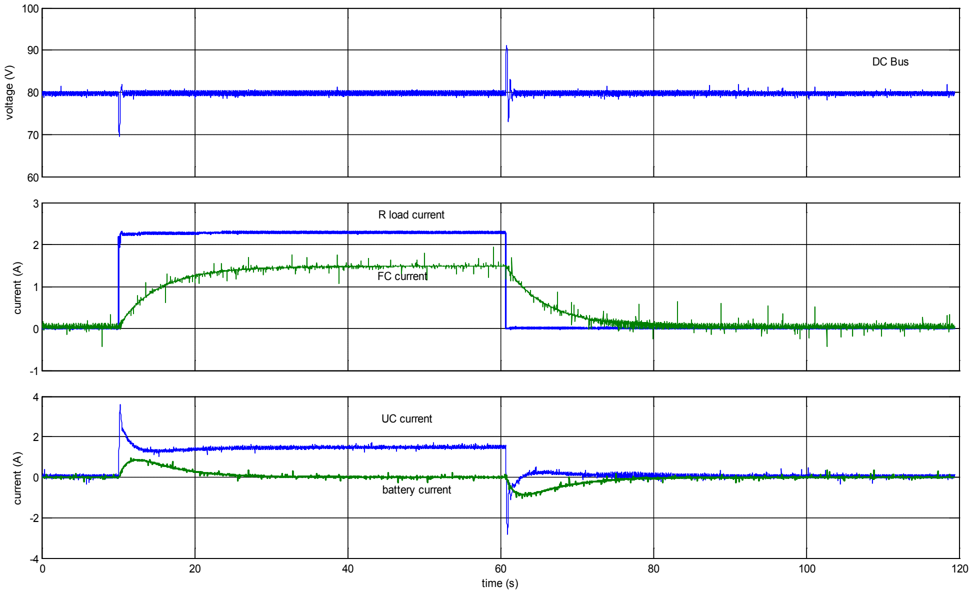

Figure 5 Pulse response using resistive load

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).

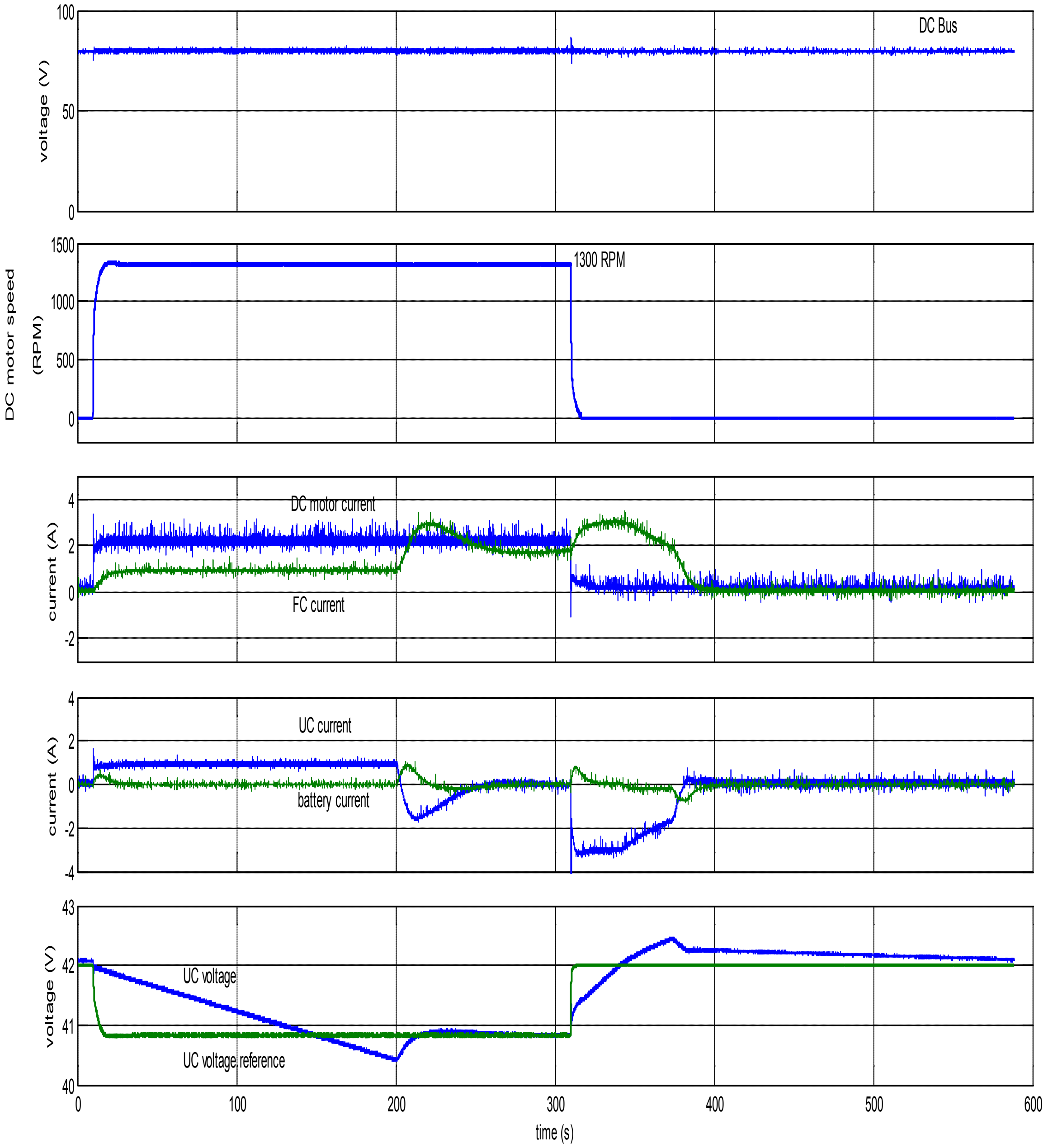

Figure 6 An ideal start-stop drive cycle response for the proposed hybrid system

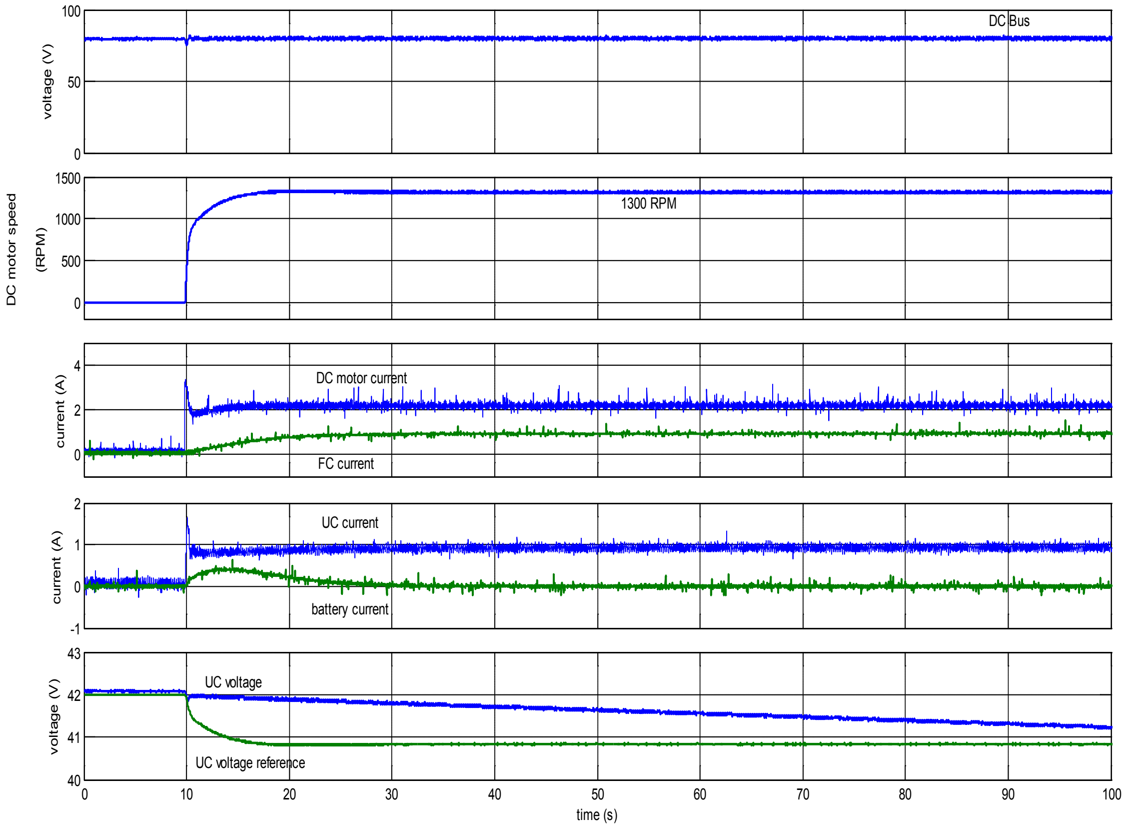

Figure 7 Response during motor acceleration (zoom in view)

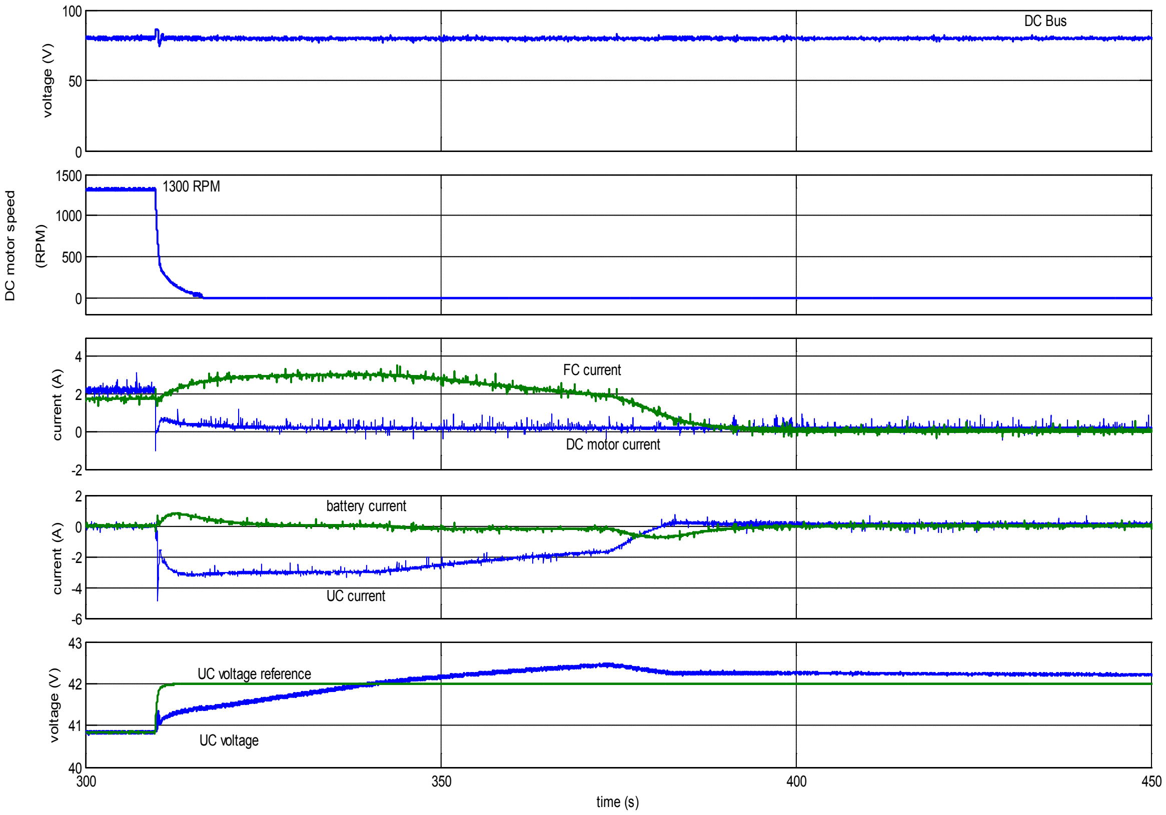

Figure 8 Response during motor deceleration (zoom in view)

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.

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