

Research and test platform for hybrid electric vehicle with the super capacitor based energy storage

Yonghua Cheng¹, Van Mierlo Joeri² and Philippe Lataire³
^{1,2,3}Vrije Universiteit Brussel, IR-ETEC, Pleinlaan 2, B-1050 Elsene, Belgium
Tel: +32 2 629 2839, +32 2 629 2803, +32 2 629 2802
Fax: +32 2 629 3620
e-mail: yonghua.cheng@vub.ac.b, jvmierlo@vub.ac.be, plataire@vub.ac.be
URL: <http://www.vub.ac.be/>

Acknowledgements

The authors would like to thank the support and founding from the EU 6th framework, and the collaboration with the project partners of Intelligent DC/DC Converter for Fuel Cell Road Vehicles (INTELLICON) and the project partners of Hybrid High Energy Electrical Storage (HYHEELS).

Keywords

Test bench, Power management, Hybrid electric vehicle, Supercapacitor and Power converter for HEV

Abstract

In this paper, the research and test platform for hybrid electric vehicle has been presented, which comprises power supply system, super capacitor based energy storage, traction system and the simulated load of vehicle. The strategies of energy sources control and management have been tested and verified in the standard speed cycle. The results show that the current of the power supply system (e.g. fuel cell) can be directly or indirectly controlled to be continuously changing. This feature can ensure good operating condition of power supply system. The test platform presented in this paper can be used for the further system test and optimization.

Introduction

Due to the effect on climate change and finite fossil energy resources, reducing air pollution and gas emission, efficiently using energy sources become more and more important. Fuel cell and battery are expected to gradually replace combustion engines as a main power supply system in hybrid electric vehicles. In order to ensure the efficiency, the dynamics and the lifetime of fuel cell or battery or both in hybrid electric vehicles, the super capacitor based energy storage is a very suitable application. But the electrical characteristics of super capacitor, in particular, low energy density and large voltage variation (in comparison with battery) increase the complexity to well configure the propulsion system in hybrid electric vehicle.

As often there are multiple energy sources in the propulsion system of hybrid electric vehicle. The strategies of energy sources control and management will strongly affect the global efficiency of the vehicle and the lifetime of power supply system (e.g. fuel cell, battery). In the development of hybrid electric vehicle, test according to some typical speed cycles (e.g. NEDC, FTP) is very important procedure to evaluate the configuration of propulsion system and to verify the strategy of energy sources control and management. For instance, the on-road tests are often applied to verify the strategies of energy sources control and management.

However, on-road tests sometime are not always possible to thoroughly test each sub system. These tests are likely done during very later phase. It is not easy to change too much configuration of the propulsion system. In order to maximally optimize the configuration and verify the strategy of energy sources control and management in early phase, bench tests must be taken place before the on-road test.

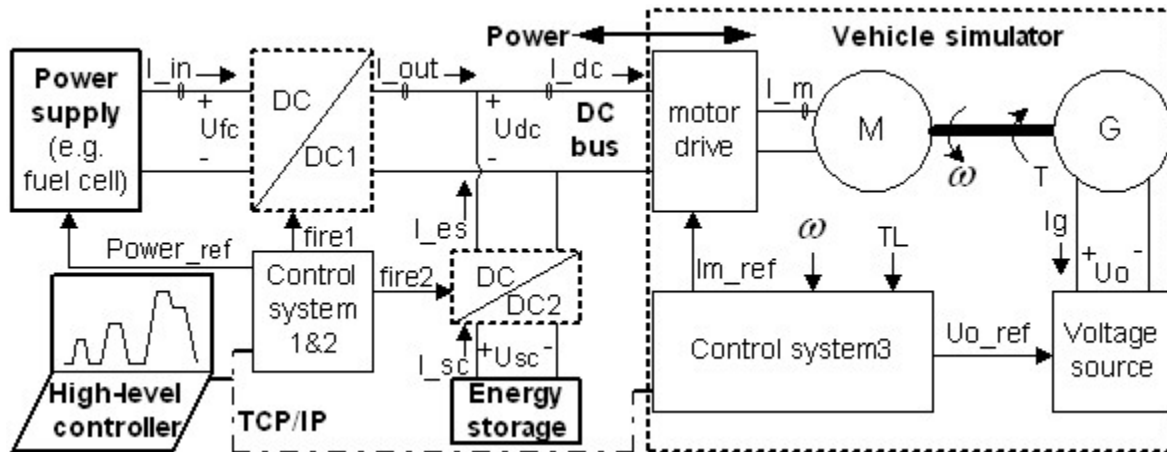


Fig. 1 Research and test platform of hybrid electric vehicle

Therefore, the research and test platform for hybrid electric vehicle has been developed in our laboratory as shown in Fig. 1, which comprises power supply system, super capacitor based energy storage, traction system and the simulated load of vehicle. In this platform, the distributed architecture is formed. The real-time control system individually forms the control loops and exchange the signals between each control loop and a high level controller via a communication network. The roles of the high level controller are to monitor the system variables (e.g. speed, voltage), and to improve the performance of each distributed controller. For example, the high level controller can tune the parameters of each controller, and it can also make the decision for each distributed controller, according to the values of system variables. In this platform, the strategies of energy source control and management can be verified. And each sub system can be optimized, according to the standard speed cycles.

Configuration of NI-PXI based real-time control and real-time simulation system

Although the real-time control system logically composes several controllers (e.g. controller2 and controller3) as shown in Fig. 1, it can physically be implemented in one system. In this platform, NI-PXI based system can be used for real-time control, real-time simulation, data acquisition and system identification. Eventually a CAN (control area network) based communication between each distributed controller and the high level controller will be established.

Real-time control system

NI-PXI based real-time control is configured as shown in Fig. 2, where PXI-8196RT is the real-time control system coupled with PXI 7833R FPGA board to establish several parallel loops for the benchmarks of input and output signals. cRIO expansion system and SCXI system are the signal conditioning systems, in which isolation is achieved.

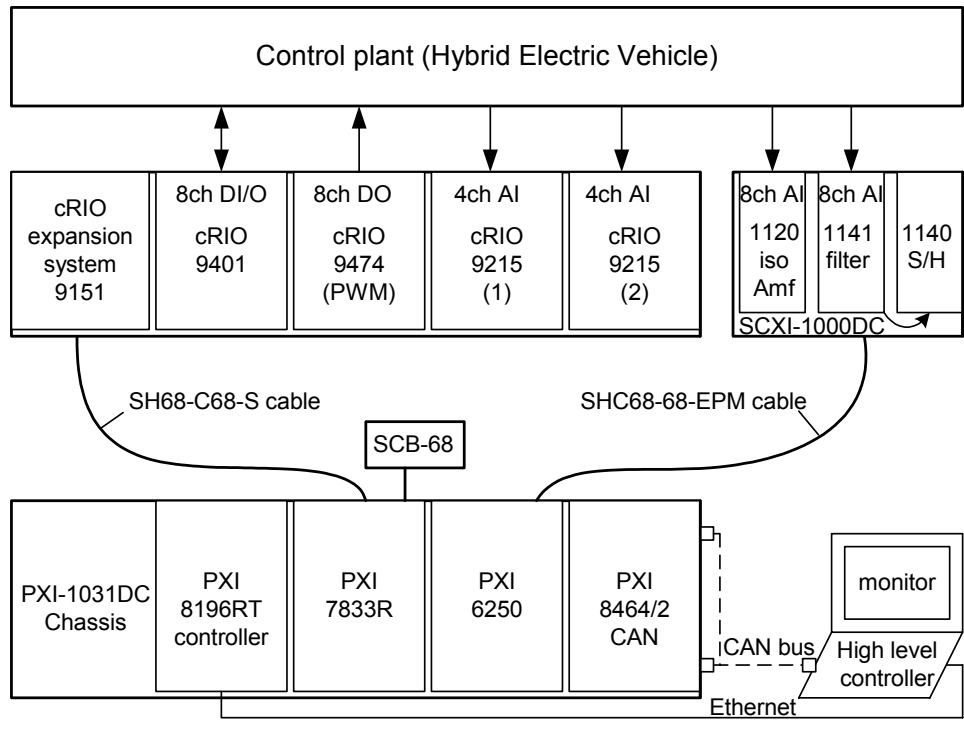


Fig. 2 NI-PXI based real-time control and simulation system

Real-time simulation system

The characteristics of hybrid electric vehicle can be simulated in hardware. Alternatively the characteristics of hybrid electric vehicle, the energy storage and the power supply can also be simulated in soft ware in the PXI system as in Fig. 3 (in real-time), which is often referred to HIL (hardware in the loop) simulation. HIL has the advantage of fast and precisely verifying the function of the real time control system before the entire sub systems (control plant) are available. Because, the real-time control system is the same in both cases of control plant simulated in hardware and in software.

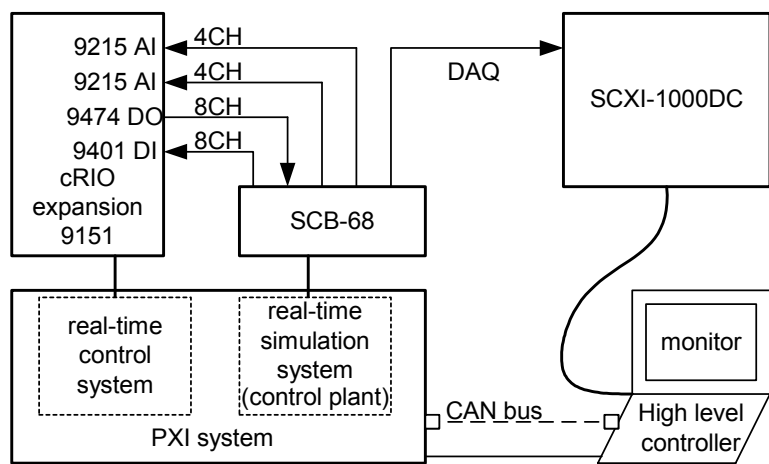


Fig. 3 Real-time simulation system

The characteristics of the vehicle

In order to generate a power flow on the DC bus in the test bench (as in Fig. 1) for the purposes of optimizing the performance of each subsystem and evaluating the strategy of energy source control and management, the characteristics of the vehicle is studied.

In principle, the traction force of the vehicle can be expressed as the friction force, the air resistance force and the inertia as in (1).

$$F = A + B \cdot V^2 + C \cdot dV/dt \quad (1)$$

Where V is the speed of vehicle in m/s; A , B and C are the coefficients (on a flat road) as given in (2).

$$A = K_r \cdot M \cdot g \quad (\text{kg} \cdot \text{m}/\text{s}^2) \quad (2)$$

$$B = C_d \cdot \frac{1}{2} \cdot \rho \cdot S \quad (\text{kg}/\text{m})$$

$$C = M + M_r \quad (\text{kg})$$

The power of the vehicle P_{vehicle} can be expressed as in (3).

$$P_{\text{vehicle}} = F \cdot V = (A + B \cdot V^2 + C \cdot dV/dt) \cdot V \quad (3)$$

The power of the traction motor P_{motor} should be at least same as the power of the vehicle (due to the power losses in gear and differential). The speed and the torque of the traction motor ω_{motor} and T_{motor} can be expressed as in (4).

$$\omega_{\text{motor}} = \frac{V}{R} \cdot K_G \cdot K_D \quad (4)$$

$$T_{\text{motor}} = \frac{1}{\eta_G \eta_D} \cdot \frac{R}{K_G K_D} \cdot F$$

Here K_G and K_D are the ratios of the gear and the differential. R is the radius of the wheels. $\eta_G \eta_D$ is the efficiency of the gear and the differential. According to the rotating speed of motor ω_{motor} and the torque T_{motor} , the power demand of the traction motor on the DC bus can be expressed as in (5).

$$P_{\text{motor}} = T_{\text{motor}} \cdot \omega_{\text{motor}} \quad (5)$$

This power profile will be used for the energy source control and management.

Method of energy sources control and management

In this platform, the super capacitor based energy storage is applied for the purposes of keeping good dynamics of hybrid electric vehicle and fast recuperating the regenerative braking energy. In this case, the global efficiency of the vehicle will be increased significantly. The strategy of energy source control and management are that the main power supply system (e.g. fuel cell) only provides the moving average current and the super capacitor based energy storage provides the peak current.

The moving average of the power demand P_{average} is defined as in (6).

$$P_{average} = \frac{1}{\tau * s + 1} * P_{motor} \quad (6)$$

The peak power of the power demand P_{peak} can be defined as in (7).

$$P_{peak} = P_{motor} - P_{average} \quad (7)$$

In case that the power flow of the main power supply system can not be reversed, the regenerative braking energy will be stored in the energy storage (e.g. super capacitors). The principle of energy source control and management is presented as in Fig. 4. The required input and output power of the super capacitors P_{sc_ref} is corresponding to the peak power P_{peak} plus the negative moving average of the traction system plus a slow power flow $\Delta Power$ (for the regulation of super capacitor voltage). In order to efficiently use the super capacitor based energy storage, the voltage of the energy storage will be controlled within 100%~50% of its rated voltage. The high level controller will set the voltage reference of the super capacitors, according to the real situation (e.g. speed of the vehicle, slope of the road). In this case, much regenerative braking energy can be recuperated. And the output power of the main power supply is equal to the positive part of the moving average power in (6).

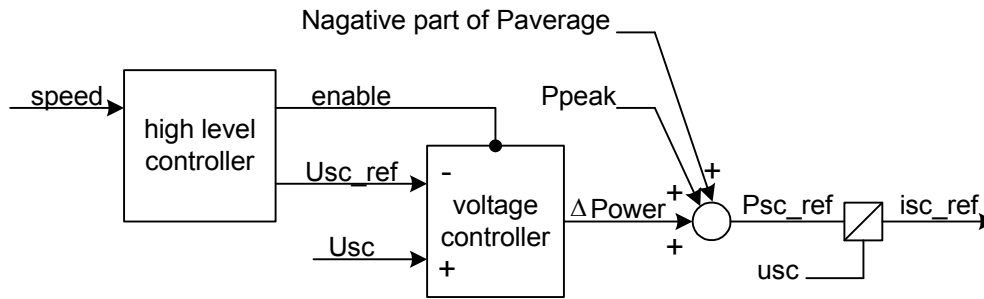


Fig. 4 Principle of energy source control and management

According to the current reference of the super capacitors isc_ref , the DC/DC converter of the super capacitor based energy storage can well be controlled [4]. In order to verify the control principle, the battery pack is used as the power supply. The super capacitor based energy storage (20 cells in series connection, with rated capacitance 2700F and 2.5V per cell) is connected to the DC bus via a DC/DC converter. A stepwise load current is generated on the DC bus in the test bench. The waveforms of the voltage and the current are shown in Fig. 5. Here, usc is the voltage of super capacitors; isc is the current of super capacitors; udc is the DC bus voltage; idc is the load current on the DC bus; and iba is the current of batteries. According to the measurements, the energy consumed by the load is 87.95 kJ within 40 seconds (after the stepwise load), the energy supplied by batteries is only 27.33kJ, and the energy released from the DC/DC converter of super capacitors is 60.62kJ. Obviously, high amount of energy is supplied by super capacitors. In Fig. 5, the current of the batteries is controlled to be continuous. In addition, the high level controller can decide when to charge the super capacitors, according to the road situation, the vehicle speed besides the super capacitor voltage. (It is not always necessary to fully charge the super capacitors immediately when the voltage of the super capacitors is low.) The waveforms of voltage and current during charging the super capacitors are shown in Fig. 6. The current of the batteries are also kept continuous, and the output power of the batteries is limited.

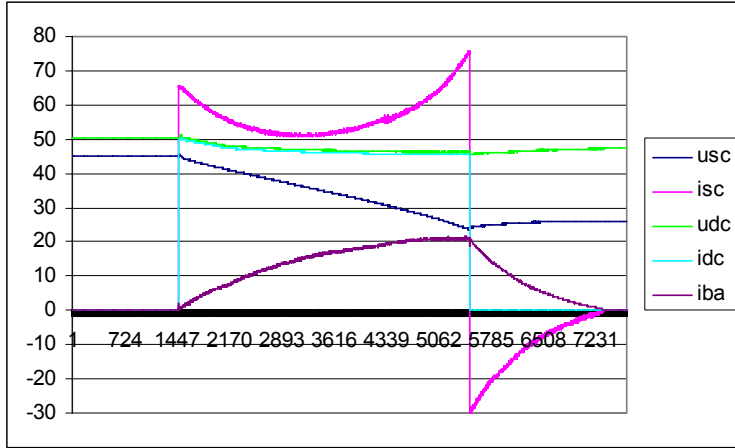


Fig. 5 test results of super capacitor based energy storage supplying peak power (10ms/dot)

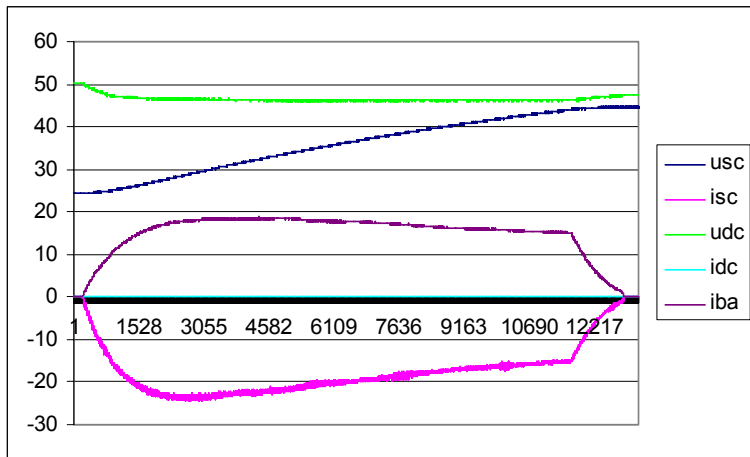


Fig. 6 test results of slowly charging super capacitors (10ms/dot)

Vehicle load simulator

The purposes of the vehicle load simulator are to evaluate the performance of each subsystem in a more close to the real operating condition, and to optimize system configuration and control strategy. In this test bench, the vehicle load simulator is implemented as in Fig. 7. Here M is a series DC motor (with rated power 19kW). G is a DC generator, which simulates the load of the vehicle.

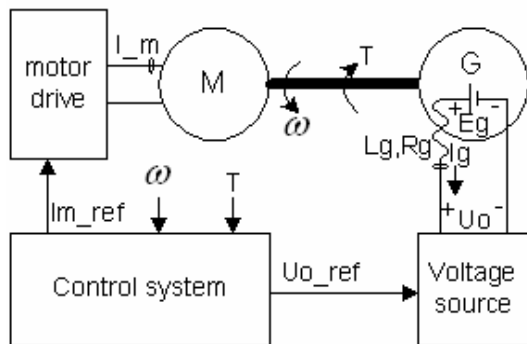


Fig. 7 Vehicle load simulator

In this test bench, the motor with its drive is in speed control mode to follow a test cycle (e.g. a simplified NEDC cycle); and the generator with a voltage controllable source is in torque control mode to follow a torque reference. Both systems are power flow reversible. In principle, the open circuit voltage of generator E_g and its output current I_g can be estimated according to the speed reference ω_{ref} and the torque reference T_{ref} as in (8), if both speed and torque control loops work properly.

$$\begin{aligned} E_g &= K_e * \Phi * \omega_{ref} \\ I_g &= T_{ref} / (K_t * \Phi) \end{aligned} \tag{8}$$

Here Φ is the flux. K_e and K_t are the coefficients. In order to control the generator to follow the required torque reference, the output voltage of the controllable voltage source can be estimated as in (9).

$$U_{0_ff} = E_g - L_g \frac{dI_g}{dt} - R_g * I_g \tag{9}$$

The control principle is presented as in Fig. 8. Here U_{0_ff} is a feed forward signal, which can achieve fast response in this control system. The steady error is corrected by using a feedback controller.

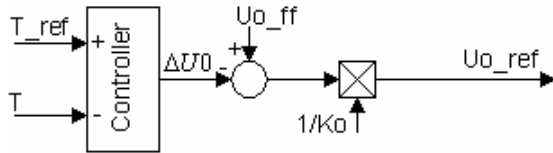


Fig. 8 Control loop of torque

In Fig. 8, T is the torque measurement, which can also be observed by using the output current measurement of the generator I_g as in (10).

$$T = K_t * \Phi * I_g \tag{10}$$

In Fig. 8, K_o is the gain between the input reference and the output voltage of the voltage source as in Fig. 7. Its nonlinearity (not constant) is also corrected by the above controller.

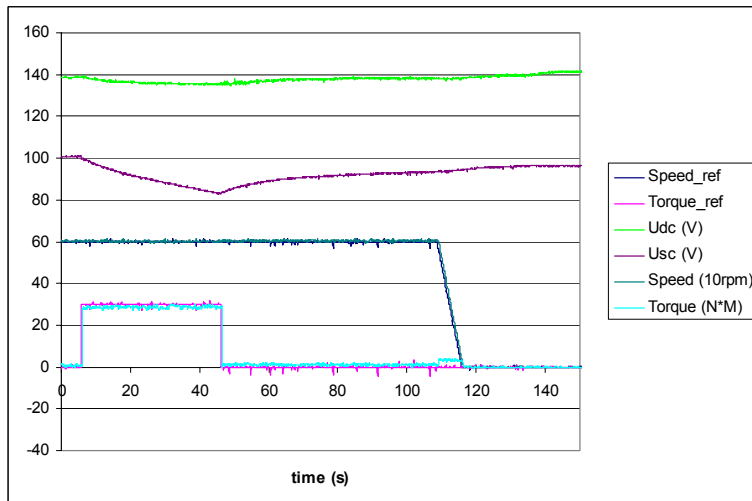


Fig. 9 Control results of vehicle load

In order to verify the control principle of the vehicle load simulator, the motor is kept in constant speed (600rpm), a stepwise torque reference (30N*M) is generated within 40 seconds. The real torque follows its reference as shown in Fig. 9. One can see that the vehicle load simulator works properly.

Test results in ECE15 speed cycle

In this section, the standard speed cycles will be applied, to fully evaluate the performance of each subsystem, and to do further optimization and validation. The traction system (motor plus drive as in Fig. 1) will generate a power demand on DC bus, which is corresponding to the parameters of a vehicle and a typical test cycle (e.g. NEDC, FTP). The power supply system is directly or indirectly controlled to provide the moving average power, and the super capacitor based energy storage is controlled to provide the peak power. According to the speed cycle, the voltage of super capacitors is slowly controlled. This ensures the safety and the possibility to store much regenerative braking energy. In this case, high efficiency can be achieved. In this paper, the dedicated vehicle is assumed to have the following parameters:

The weight M is 495 kg.

The equivalent weight due to the rotational part (wheel, gear, differential and motor)

M_r is 2.2 kg.

The front surface S is 2.74 m².

The rolling resistance coefficient K_r is 0.0267.

The drag coefficient C_d is 0.31.

In this case, the coefficients of A, B and C can be calculated as in (11).

$$A = K_r * M * g = 0.026667 * 495 * 9.80665 = 129.5 \text{ (kg*m/s}^2\text{)} \quad (11)$$

$$B = C_d * \frac{1}{2} * \rho * S = 0.31 * 0.5 * 1.23 * 2.736 = 0.5216 \text{ (kg/m)}$$

$$C = M + M_r = 495 + 2.2 = 497.2 \text{ (kg)}$$

The force of the vehicle can be expressed as in (12).

$$F = A + B * V^2 + C * dV/dt = 129.5 + 0.5216 * V^2 + 497.2 * dV/dt \quad (12)$$

If the speed of the motor $Speed_{motor}$ in the simulated traction system is specified from 0~1400rpm to represent 0~70km/h of the vehicle speed, then $K_G K_D / R$ can be calculated as in (13).

$$\frac{K_G K_D}{R} = \omega_{motor} / V = (1400 * \frac{2\pi}{60}) / (70 * \frac{1000}{3600}) = 7.54 \quad (13)$$

Substituting (13) into (4), the rotating speed of motor ω_{motor} and the torque reference T_{motor} can be calculated as in (14), according to the force of the vehicle F and the speed reference V .

$$\omega_{motor} = 7.54 * V \text{ or } speed_{motor} = 20 * (3.6 * V) \quad (14)$$

$$T_{motor} = \frac{1}{\eta_G \eta_D} * F / 7.54$$

Here ω_{motor} is in rad/s; V is in m/s; $Speed_{motor}$ is in rpm. As explained in previous section, the motor M is controlled to follow the speed test cycle (e.g. NEDC), and the generator G is controlled to follow the torque reference by controlling the voltage at the terminal of the generator as in Fig. 7. In this case, the

power demand on the DC bus (as in Fig. 1) corresponds to the required power of vehicle plus the power losses during the power conversion. Once the power demand on the DC bus is known, the behaviors of power supply and energy storage can be evaluated.

In this test, the fuel cell and DC/DC1 converter (as in Fig. 1) are replaced by using the AC power supply with a diode rectifier. The super capacitor based energy storage (1500F each and 40 cells in series connection, rated capacitance 37.5F and rated voltage 108V) via the dedicated DC/DC2 converter (as in Fig. 1) is connected on the DC bus. The test results of both vehicle load simulator and the energy storage are presented as in Fig. 10 and Fig. 11. Obviously, the speed and the torque are controlled to be the same as their references. The current from the power supply system (I_{source}) is controlled to be slowly varying. This will improve the operating condition of the power supply system (e.g. fuel cell). Hence, long life time of power supply system and high global efficiency can be achieved.

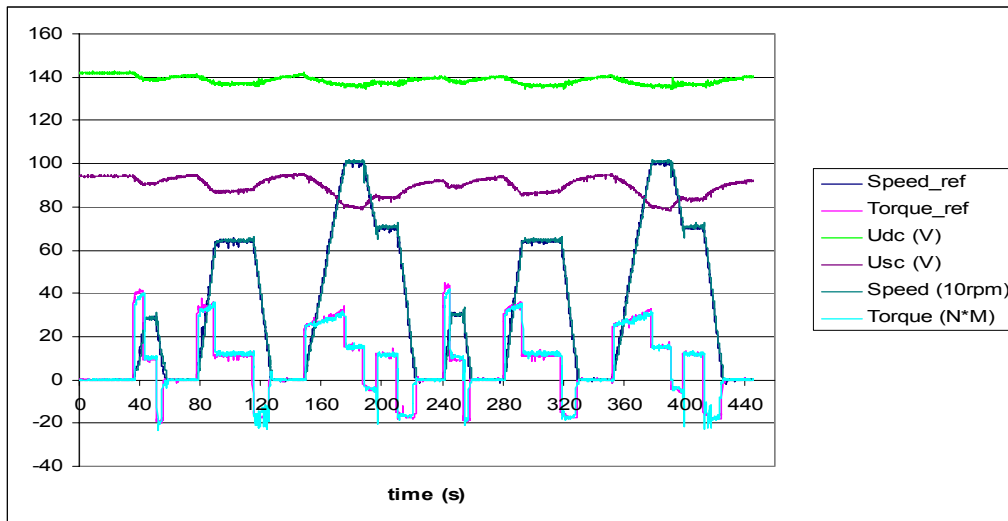


Fig. 10 test results of speed and torque in ECE15 speed cycle

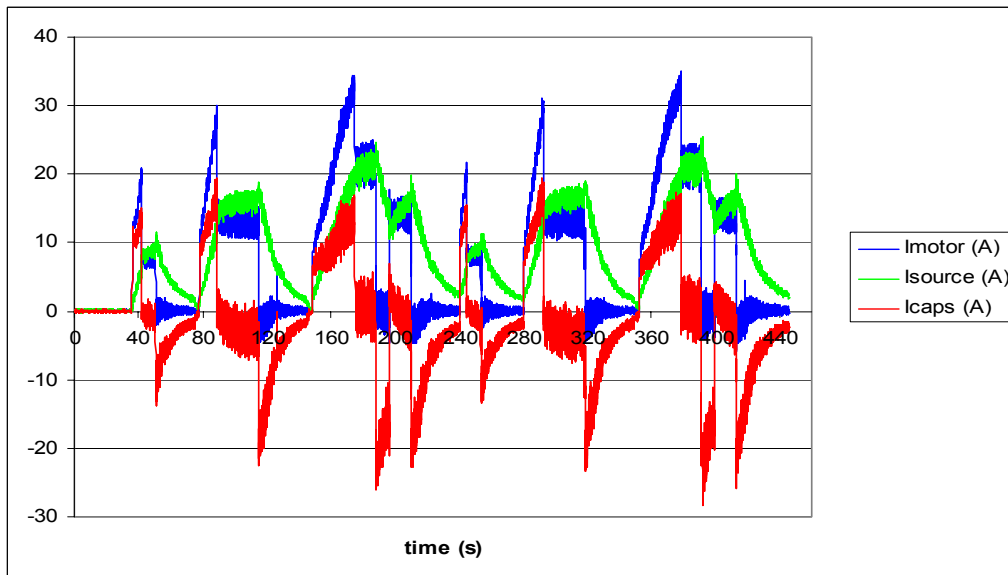


Fig. 11 Test results of load current, source current and super capacitor current in ECE15 cycle

Conclusions

The research and test platform of hybrid electric vehicle has been presented, and the configuration of NI_PXI based real-time control and simulation system has also been introduced. The super capacitor based energy storage as peak power unit was tested under conditions of stepwise load current and in standard speed cycle. The results show that the current of the main power supply system (battery) can indirectly be controlled to be continuous, which can ensure good operating condition and hence high efficiency and long life time of the power supply system (e.g. battery, fuel cell). This research and test platform can further be applied to define and verify new strategy of energy sources control and management in modern propulsion system of hybrid electric vehicles. It can be used for the purposes of scientific research as well as education.

References

- [1] G. Maggetto and J. Van Mierlo, 2001, "Electric vehicles, hybrid vehicles and fuel cell electric vehicles: state of the art and perspectives", *Annales de Chimie - Science des matériaux*; Thematic issue on "Material for Fuel Cell Systems"; issn 0151-9107, Volume 26; N4/2001; pg 9-26.
- [2] A. Rufer and Ph. Barrade, "A Super Capacitor-based Energy Storage System for Elevators with Soft Commutated Interface", *IEEE transactions on industry applications*, Vol. 38, No.5, September/October 2002.
- [3] M.Y. Ayad, S. Rael and B. Davat, "Hybrid Power Source Using Supercapacitors and Batteries", *EPE2003*, in Toulouse, France.
- [4] Yonghua Cheng, Joeri Van Mierlo, Peter Van den Bossche and Philippe Lataire, "Super Capacitor based Energy Storage as Peak Power Unit in the Applications of Hybrid Electric Vehicles", *PEMD 2006*, in Ireland
- [5] J. Lachaize, M. Fadel, S. Caux, P. Shott and L. Nicod, 2003, "Modelling and Control of a Fuel Cell System for Electrical Rail Transport", *EPE 2003*, in Toulouse, France.
- [6] J. Van Mierlo, G. Maggetto and Ph. Lataire, "Which energy source for road transport in the future? A comparison of battery, hybrid and fuel cell vehicles", *Energy Conversion and Management*, 2006 Elsevier Ltd.
- [7] Phatiphat Thounthong, Stéphane Rael and Bernard Davat, "Supercapacitors as Energy Storage for Fuel Cell Automotive Hybrid Electrical System", *ESSCAP 2004*, in France.
- [8] Alfred Rufer, "Power-Electronic Interface for a Supercapacitor-Based Energy-Storage Substation in DC-Transportation Networks", *EPE2003*, in Toulouse, France.
- [9] B.Destraz, P. Barrade and A. Rufer, "A Solution for Increasing the Efficiency of Diesel-Electric Locomotives with Supercapacitive Energy Storage", *ESSCAP 2004*, in France.
- [10] Yonghua Cheng, Joeri Van Mierlo, Peter Van den Bossche and Philippe Lataire, "Energy sources control and management in hybrid electric vehicles", *EPE-PEMC2006*, in Slovenia.
- [11] J. Van Mierlo, G. Maggetto, L. Vereecken, V. Favrel, S. Meyer, W. Hecq, 2003, "How to Define Clean Vehicles? Environmental Impact Rating of Vehicles", *International Journal of Automotive Technology (IJAT), KSAE, SAE*, issn 1229-9138, Vol 4, Nr 2, Pg 77-86.
- [12] G. Maggetto and J. Van Mierlo, 2001, "Electric vehicles, hybrid vehicles and fuel cell electric vehicles: state of the art and perspectives", *Annales de Chimie - Science des matériaux*; Thematic issue on "Material for Fuel Cell Systems"; issn 0151-9107, Volume 26; N4/2001; pg 9-26.
- [13] J. Van Mierlo and G. Maggetto G., 2004, "Innovative Iteration Algorithm for a Vehicle Simulation programme", *IEEE Transaction on Vehicular Technology*, issn 0018-9545, Vol 53, No 2.
- [14] J. Van Mierlo, G. Maggetto, P. Van den Bossche, 2003, "Models of Energy Sources for EV and HEV: Fuel cells, Batteries, Ultra-Capacitors, Flywheels and Engine-generators", *Journal of Power Sources*, issn 0378-7753, Vol. 128, Nr. 1, pp. 76-89.