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Development of ultracapacitor modules for 42-V automotive electrical systems

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Abstract

Two types of ultracapacitor modules have been developed for use as energy-storage devices for 42-V systems in automobiles. The modules show high performance and good reliability in terms of discharge and recharge capability, long-term endurance, and high energy and power. During a 42-V system simulation test of 6-kW power boosting/regenerative braking, the modules demonstrate very good performance. In high-power applications such as 42-V and hybrid vehicle systems, ultracapacitors have many merits compared with batteries, especially with respect to specific power at high rate, thermal stability, charge–discharge efficiency, and cycle-life. Ultracapacitors are also very safe, reliable and environmentally friendly. The cost of ultracapacitors is still high compared with batteries because of the low production scale, but is decreasing very rapidly. It is estimated that the cost of ultracapacitors will decrease to US$ 300 per 42-V module in the near future. Also, the maintenance cost of the ultracapacitor is nearly zero because of its high cycle-life. Therefore, the combined cost of the capacitor and maintenance will be lower than that of batteries in the near future. Overall, comparing performance, price and other parameters of ultracapacitors with batteries, ultracapacitors are the most likely candidate for energy-storage in 42-V systems.

Keywords: Ultracapacitor; Supercapacitor; 42-V system; Energy-storage; Regenerative braking; Automobile

1. Introduction

The application of electrical energy-storage devices in advanced vehicle systems requires new technologies to fulfill the enhanced mission profile, namely, start–stop and regenerative braking at the 42-V level [1,2]. This is the reason why NESSCAP has designed the 42-V ultracapacitor module.

The automotive industry is moving to a higher voltage for the electrical system. This change will occur because the total electrical power required by vehicles will increase to a level where the current requirements at 14-V will be impractical. The introduction of a 42-V PowerNet enables new power-train features in future vehicles. The 42-V technology will serve power demanding drive-train hybrid functions such as boost and regenerative braking, as well as a lot of safety functions and comfort functions (electrical braking, braking by wire, active body control, windshield heating, etc.). On the other hand, the most notable change is the proposed start–stop mode of vehicle operation where the engine is stopped and restarted frequently to avoid prolonged operation at idle for reducing pollutant gases and enhancing fuel economy.

Energy-storage devices for 42-V systems must deliver high-power for a specified time, accept and hold a charge, and meet specified requirements for operating temperature range, durability and safety. Ultracapacitors, also known as supercapacitors, have approximately 10 times the power density of a same sized battery and the capability of being charged and discharged over 100 times faster than a battery. Also, ultracapacitors have a very long life span. Due to the ultracapacitors favorable characteristics, it is ideal for high-power demand applications.

The primary goal of this paper is to demonstrate the many benefits of ultracapacitors as energy-storage devices for 42-V systems. In our tests, 42-V modules consisting of 2.7 V, 1700 F and 2.7 V, 3500 F were tested. These tests included basic performance, thermal, cycle-life, and simulation tests as a 42-V energy-storage system.

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2. Basic technology of the NESSCAP ultracapacitor for 42-V systems

The ME0085P-0540A and ME0175P-0540A ultracapacitor modules developed for use as energy-storage for 42-V systems in automobiles are shown in Fig. 1. The modules are composed of 20 cells of 2.7 V, 1700 F and 2.7 V, 3500 F models. The ultracapacitors are passive, electrostatic, energy-storage devices and consist of porous carbon electrodes that are immersed in an organic solvent.

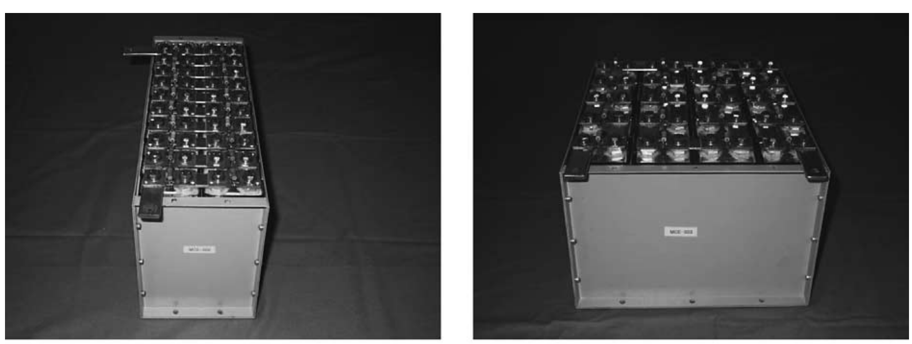
Ultracapacitors have very high-power density and the capability of being charged and discharged faster than a battery. This is why they are excellent intermediate power sources, or battery-performance enhancers. Ultracapacitors do not, however, have the characteristic battery limitations of short life, cold intolerance, and critical charge and discharge rates.

The specifications of the ME0085P-0540A and ME0175P-0540A modules are listed in Table 1. Model ME0085P-0540A has a capacitance of 85 F and a specific energy of 2.89 Wh kg^{-1}. The ME0175P-0540A has a capacitance of 175 F and a specific energy of 3.77 Wh kg^{-1}.

The specific power and energy of the ultracapacitor modules exceeds that of other ultracapacitors in production today. The extremely low internal resistance (ESR) characteristic of the ultracapacitors enables the devices to supply large amounts of instantaneous peak power, when demanded by the load. This is particularly advantageous in automotive and industrial applications. The ultracapacitors also have a very long life span. They have been subjected to more than 500,000 charge and discharge cycles at room temperature and typically exhibit only a small loss of capacitance (<20%) and an even smaller than typical increase in ESR (less than double). The long life of the ultracapacitor means that it may never need to be replaced during the lifetime of the vehicle. In addition, all materials used in the ultracapacitor are non-toxic, and all of the manufacturing processes are environmentally friendly.

2.1. Discharge characteristics of ultracapacitor modules

The discharge profiles of the ME0085P-0540A and ME0175P-0540A modules, under various discharge rates,



(a) (b)

Fig. 1. Ultracapacitor modules for 42-V systems: (a) ME0085P-0540A; (b) ME0175P-0540A.

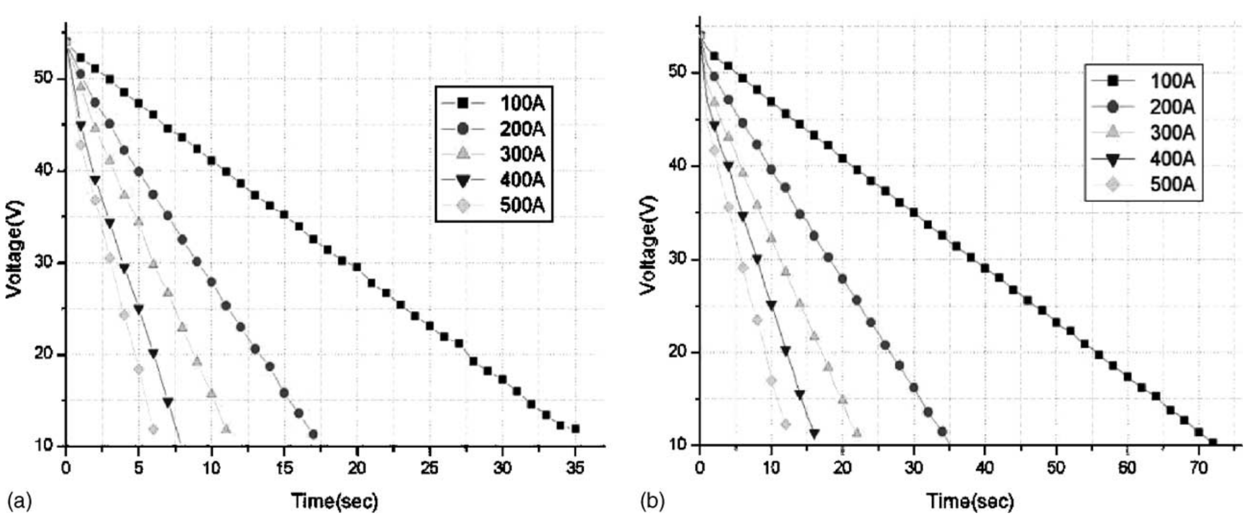


Fig. 2. Discharge characteristics of ultracapacitor modules: (a) ME0085P-0540A; (b) ME0175P-0540A.

Table 1
Module specification of ME0085P-0540A and ME0175P-0540A ultracapacitors

Item	ME0085P-0540A	ME0175P-0540A
Capacitance (F)	85	175
Rated voltage (V)	54	54
Peak voltage (V)	57	57
ESR (mΩ)	14.0	10.0
Leakage current (mA)	4	8
Specific energy (Wh kg^{-1})	2.89	3.77
Specific power (Wh kg^{-1})	4376	3878
Life (cycles)	500000	500000
Dimensions (mm)	305 × 131 × 200	254 × 347 × 200
Volume (l)	8.0	17.6
Weight (kg)	11.9	18.8

are given in Fig. 2. The tests were conducted at 25 °C. The modules have been discharged under various constant-currents in the range 100–500 A. The plots show that the ultracapacitor modules exhibit extremely stable capacitance over the wide range of discharge currents. In many applications, the most critical characteristic of a capacitor is how its energy output varies with the discharge profile. The results of these tests show that the ultracapacitor modules have adequate energy and capacitance stability.

2.2. Ragone plot of ultracapacitor

Ragone plots of the ultracapacitors are shown in Fig. 3. The data show that the specific energy of the ultracapacitor under test is extremely stable over a wide range of specific power. This indicates that ultracapacitors are very good energy-storage devices for applications where high-power is required.

2.3. Temperature characteristics of ultracapacitor

The variation in capacitance of the ultracapacitor as a function of temperature, for constant of 50 and 250 A is shown in Fig. 4. Current discharges, the plots show that the capacitance values and the ESR of the ultracapacitor vary only slightly over a wide temperature range of −40 to +60 °C.

2.4. Cycle-life characteristics of ultracapacitor

The cycle-life of the ultracapacitor is presented in Fig. 5. The test was conducted at 25 °C and used a constant-current charge and a constant-current discharge cycle. One cycle consists of a constant-current charge for 20 s, a constant-current discharge for 20 s, and two resting times each of 10 s. The capacitance of the ultracapacitor is reduced by about 6.5% and the ESR is increased about 12% after 100,000 cycles.

2.5. Charge–discharge cycling characteristics of ultracapacitor modules

Power, current and voltage profiles of the ME0085P-0540A and ME0175P-0540A modules during constant-power charge–discharge cycling are presented in Fig. 6. The tests were conducted at 25 °C and the modules were charged at 6 kW to rated voltage and discharged at 6 kW to half of the rated voltage with a rest period of 30 s between charge and discharge. The data show that discharge time and the charge time of the two modules is 15 and 30 s, respectively. This means that the ME0085P-0540A module has sufficient energy for a 42-V system in which the motor/generator output is 6 kW and acceleration and regenerative braking times are each up to 15 s. Also, the ME0175P-0540A module

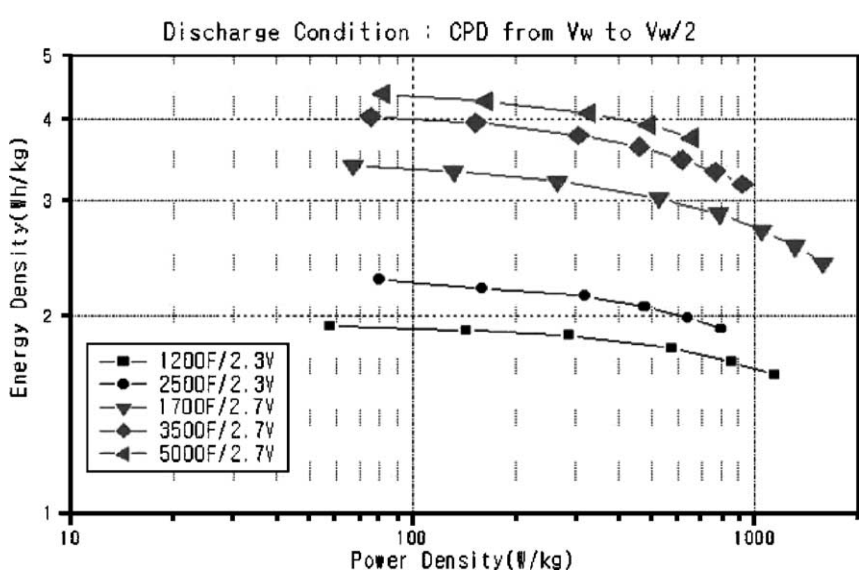


Fig. 3. Ragone plots of ultracapacitor.

has sufficient energy for a system in which the motor/generator output is 6 kW and acceleration and regenerative braking times are each up to 30 s.

Almost all automobile makers plan to develop 42-V systems which have output powers in the range 6–8 kW and acceleration/regenerating times below 10 s. The long-term targets of the system are about 6–10 kW and 20 s. Therefore, the test results demonstrate that the ME0085P-0540A and ME0175P-0540A ultracapacitor modules are suitable for use as energy-storage units for 42-V systems in the mid- to long-term.

2.6. Simulation test of ultracapacitor module for 42-V systems

A typical test cycle for the energy-storage device is shown in Fig. 7. An equivalent microcycle of 100 s represents driving at 40 km h^{-1} for a distance of 1.05 km. This micro-

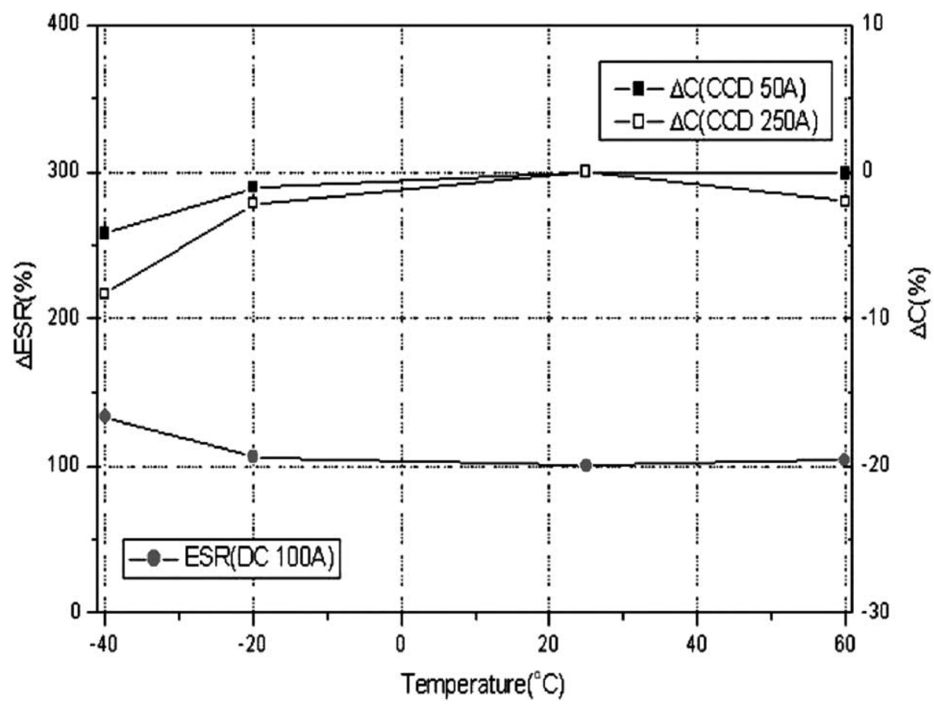


Fig. 4. Temperature characteristics of ultracapacitor.

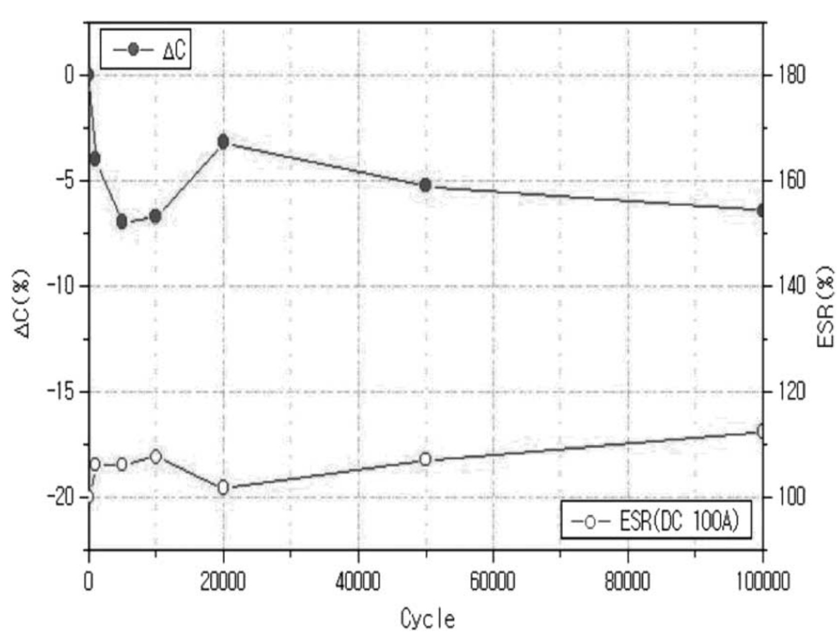


Fig. 5. Cycle-life characteristics of ultracapacitor.

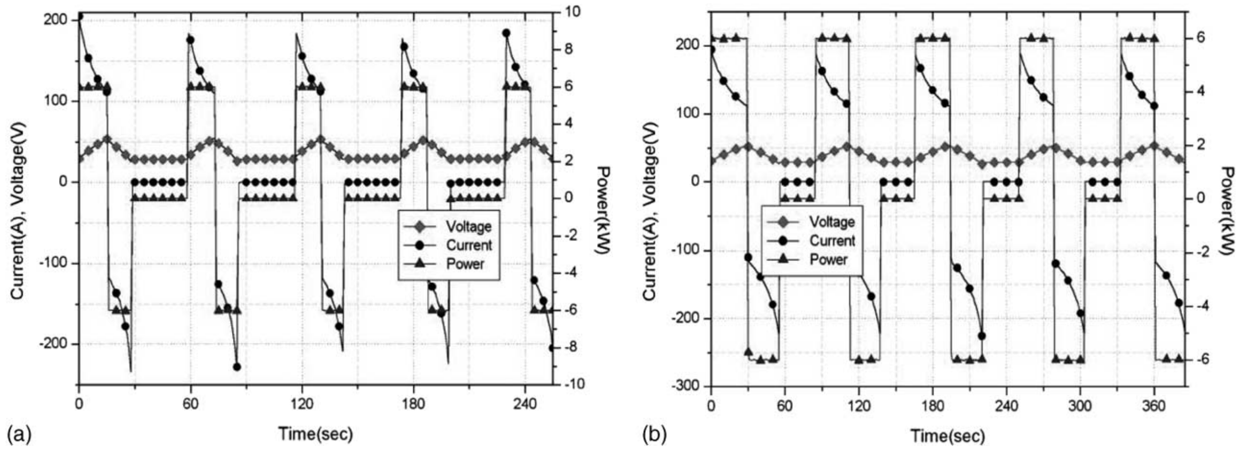


Fig. 6. Constant-power charge–discharge cycling of ultracapacitor modules: (a) ME0085P-0540A; (b) ME0175P-0540A.

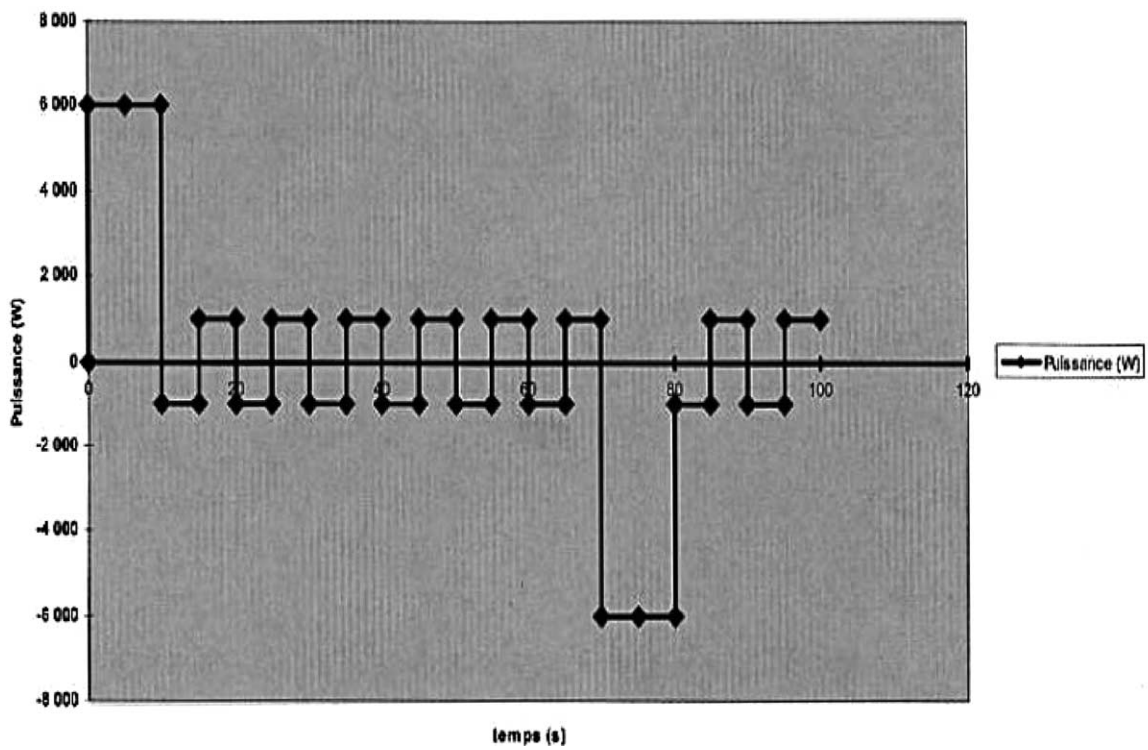


Fig. 7. Test cycle for 42-V module with break and boost at ISO.

cycle is composed of the following: (i) an acceleration phase (boost) of 6 kW for 10 s; (ii) a driving phase of 60 s with six typical cycles of 1 kW regeneration for 5 s after discharge for 5 s; (iii) a regeneration phase (brake) of 6 kW for 10 s; (iv) a stop phase of 20 s with two steps of 1 kW regeneration for 5 s and discharge for 5 s.

The 42-V module was subjected to the above test cycle to determine whether or not the ultracapacitor could be used as an energy-storage device for 42-V systems with the respect to available energy. The test results of the ME0085P-0540A ultracapacitor module are presented in Fig. 8. The red and blue lines in Fig. 8(a) gives the power and the voltage profiles of the module. The module voltage is always above 36 V, which means that the module has sufficient available energy for 42-V systems that have 6 kW of output power, and acceleration and regeneration time of 10 s. The voltages of all cells in the module were measured during cycling and the results are given in Fig. 8(b). The deviations in cell voltage are narrow enough for application as an energy-storage unit for 42 V systems.

The power and module voltage profiles of the ME0175P-0540A module are presented in Fig. 9. The module was discharged and charged for twice the cycle period in Fig. 7, for example, 6 kW charge–discharge for 20 s for the acceleration/regenerating periods. The data in Fig. 9(a) show that the module voltage is above 36 V at every point. This

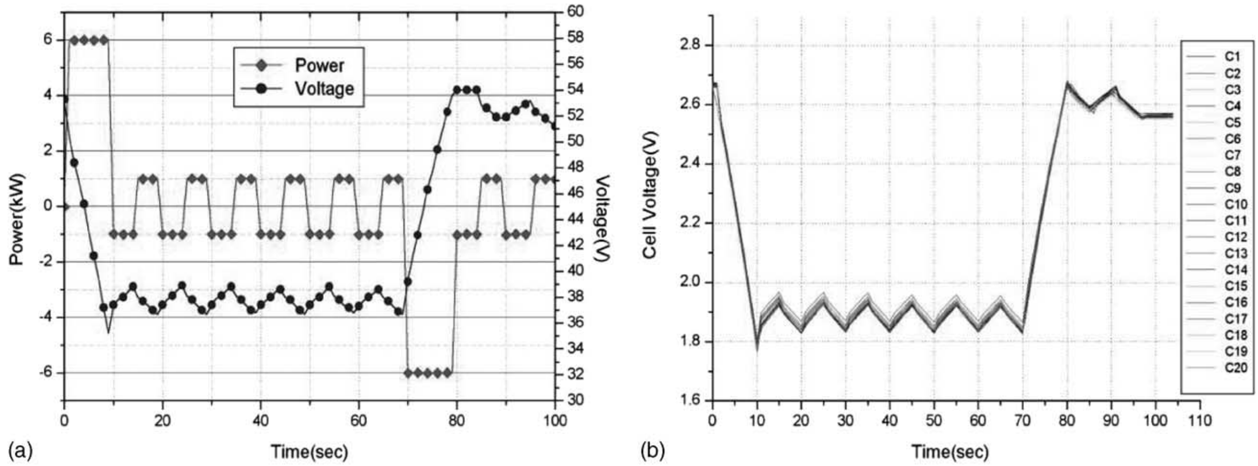


Fig. 8. ISO mode cycling profile of ME0085P-0540A module: (a) power–voltage profile; (b) cell voltage profiles.

indicates that the module can be used in 42-V systems that have 6 kW of output power, and acceleration and regenerating times of 20 s.

The temperature profiles of the terminals and cases of the individual ultracapacitors ME0175P-0540A module during the test cycle for the 42-V module (Fig. 7) are presented in Fig. 10. The test was conducted at room temperature. The data show that the maximum temperature in the module is below 45 °C after 200 cycles, i.e. approximately 4.5 h. The maximum difference between the cells in the module, measured at the terminals, is below 4 °C and the difference between cells measured on the cases is about 3 °C. Also, the average temperature difference between the terminal and the case is about 5 °C. The maximum temperature after 4.5 h from the start of the test is below than the upper limit of the operating temperature of the ultracapacitor, viz., 60 °C.

2.7. Cell voltage equalization of ultracapacitor

Since sustained overvoltage can cause an ultracapacitor to fail, it is of primary importance that the voltage across each cell in a series string does not exceed the maximum continuous working voltage rating of the individual cells. Thus, preventing the voltage impressed upon each cell in the string from exceeding the 'continuous working' voltage rating is the most important preventive measure that can be taken to ensure trouble-free operation for the expected life of the string. Therefore, it will be necessary either to reduce the 'rate of charge' being delivered to a cell, or to completely stop charging a cell whose voltage is approaching its surge voltage rating.

The simplest implementation of the active circuit method involves using a resistor 'ladder'. The active circuit has an active switching device, such as a bipolar transistor or a MOSFET, connected in series with each bypass element of the ladder. The switches are controlled by voltage detection circuits that only turn a switch 'on' when the voltage across that particular cell approaches a value just slightly below the 'continuous working' voltage rating of the cell, which is referred to as the bypass threshold voltage.

Each ultracapacitor cell in the string has a printed circuit board (PCB) mounted across its terminals. Each PCB has its

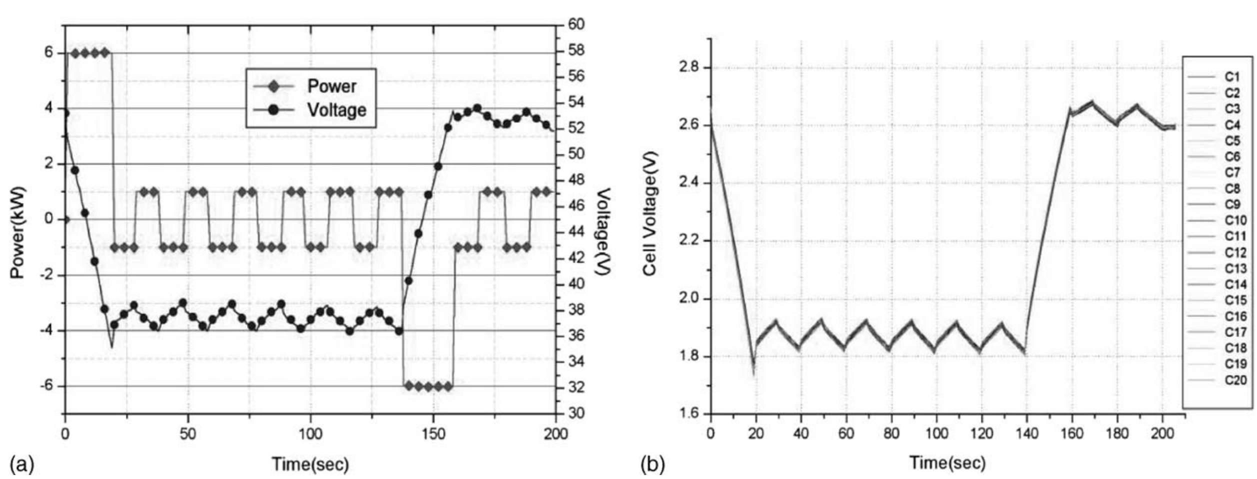


Fig. 9. ISO mode cycling profile of ME0175P-0540A module: (a) power–voltage profile; (b) cell voltage profiles.

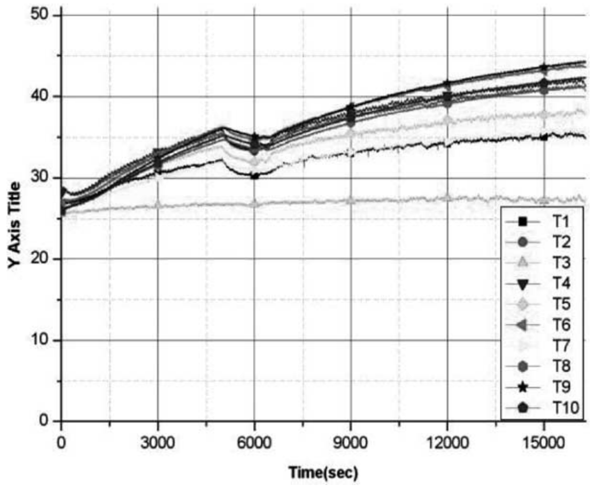


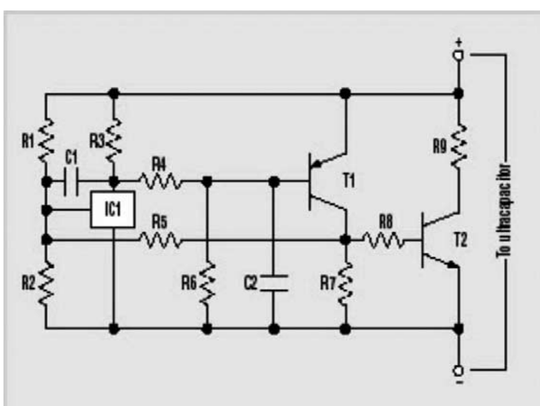
Fig. 10. Temperature variation during ISO mode cycling of ME0175P-0540A module.

own voltage detection circuitry, switch and bypass element. The circuit diagram and appearance of the PCB are given in Fig. 11.

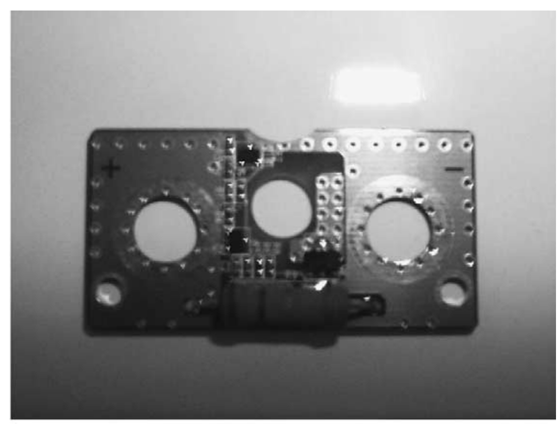
The current in the bypass circuit is shown in Fig. 12(a) as a function of cell voltage. The circuit becomes active at the bypass threshold voltage, viz., 2.68 V. The voltage profile of the ultracapacitor cells in the series string during charging is presented in Fig. 12(b). The charge consists of two steps, namely, constant-current charging and constant-voltage charging. The graph shows that cell voltage difference is reduced with time due to cell balancing and the circuit installed on both terminals of the ultracapacitor cells.

3. Fuel saving comparison between energy-storage

At present, the average fuel consumption per passenger car in the USA is 250 gallons per year and costs on average US$ 500. When vehicles are equipped with 42-V systems

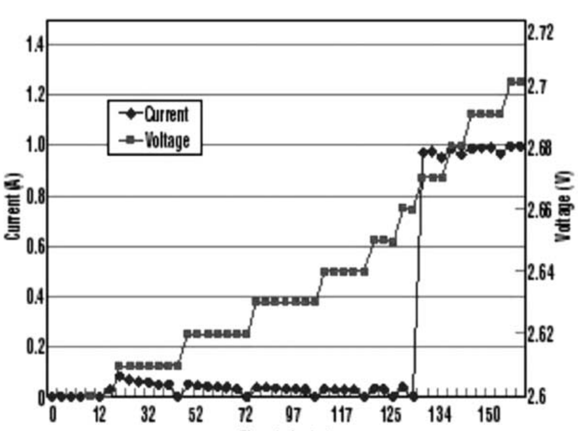


(a)

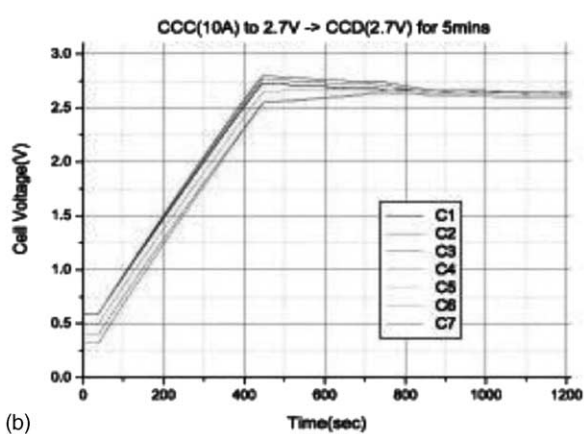


(b)

Fig. 11. Cell balancing circuit for equalization of ultracapacitor cells: (a) circuit diagram of cell-balancing circuit; (b) appearance of cell-balancing circuit.



(a)



(b)

Fig. 12. Current bypassing profiles of cell balancing circuit for ultracapacitor: (a) bypass threshold voltage of balancing circuit; (b) voltage profiles of cells during charging.

using batteries as energy-storage, fuel savings are expected to be approximately 20% due to an improvement in energy consumption. That is, the savings in fuel costs will be approximately US$ 100 per year. If it is assumed that the lifetime of the vehicle is 10 years, the total cost savings due to the 42-V system would be US$ 1000.

In city driving, fuel savings due to regeneration and power boosting will be about 60% of the total fuel savings achieved by using a 42-V system [3]. Under such duty, charge–discharge efficiency is up to 90% and the efficiency of the batteries is about 60% at high-power charge–discharge. Therefore, if ultracapacitors are used instead of batteries in the 42-V system, additional fuel savings may increase due to high efficiency, e.g. from US$ 1000 to 1300.

4. Cost estimation of ultracapacitor module for 42-V system

Currently, the specific energy of the NESSCAP ultracapacitor cells is about 5 Wh kg^{-1}. Today, the price of the 42-V module is about US$ 1200. The specific energy and the price of ultracapacitors are estimated to be 15 Wh kg^{-1} and US$ 300, respectively, in 2007 [4]. That is, even though the specific energy of the ultracapacitor is low and the price is very high at present, these factors can be competitive compared with batteries in 2007.

The cycle-life of various energy-storage systems in 42-V PowerNets is summarized in Table 2. In high-power demand applications, the cycle-life of the ultracapacitor is the longest [5]. The nickel–metal-hydride (Ni–MH) and Li-ion batteries are second in performance, and the lead-acid battery is the worst. Many experts in the field state that 300,000 cycles and 10 years is the optimum for energy-storage of 42-V systems. Therefore, lead-acid batteries must be replaced twice with the life span of the vehicle. Li-ion and Ni–MH batteries must be replaced once. By contrast, ultracapacitors provide satisfactory performance for the whole of vehicle life, ultracapacitors with stand 500,000 cycles. Thus, the maintenance costs of the ultracapacitor will be nearly zero. Moreover, lifetime costs of the ultracapacitor, including initial and maintenance costs, is the lowest among the various energy-storage devices, viz., lead-acid, Ni–MH and Li-ion batteries.

Table 2
Cycle-life of energy-storage devices for 42-V systems

System	Estimated cycle-life
Lead-acid battery	100000
Ni–MH battery	200000
Li-ion battery	200000
Ultracapacitor	500000

5. Conclusions

Ultracapacitors are excellent candidates for energy-storage in 42-V systems. Their advantages include high specific power, high charge–discharge efficiency at high rates, wide operating temperature range, long cycle-life, and very low maintenance. The fuel savings to be gained by using Ultracapacitors in 42-V systems are projected to be greater than when traditional batteries are deployed. The overall maintenance and lifetime costs will be lower than those for batteries. Even though the specific energy of ultracapacitors at present is relatively low, the ultracapacitor can be used by itself as the energy-storage device for the 42-V PowerNets. The price of ultracapacitors is expected to decrease rapidly with advancements in technology and mass production.

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