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Development of an Advanced Hybrid Energy Storage System for Hybrid Electric Vehicles

Baek-Haeng Lee*, Dong-Hyun Shin**, Hyun-Sik Song***, Hoon Heo*** and Hee-Jun Kim†

*Dept. of Electronic, Electrical, Control and Instrumentation Engineering, Hanyang University, Korea
**Dept. of Mechatronics Engineering, Hanyang University, Korea
***Dept. of Control and Instrumentation Engineering, Korea University, Korea
†School of Electrical Engineering and Computer Science, Hanyang University, Korea

ABSTRACT

Hybrid Electric Vehicles (HEVs) utilize electric power as well as a mechanical engine for propulsion; therefore the performance of HEVs can be directly influenced by the characteristics of the Energy Storage System (ESS). The ESS for HEVs generally requires high power performance, long cycle life and reliability, as well as cost effectiveness. So the Hybrid Energy Storage System (HESS), which combines different kinds of storage devices, has been considered to fulfill both performance and cost requirements. To improve operating efficiency, cycle life, and cold cranking of the HESS, an advanced dynamic control regime with which pertinent storage devices in the HESS can be selectively operated based on their status was presented. Verification tests were performed to confirm the degree of improvement in energy efficiency. In this paper, an advanced HESS with improved an Battery Management System (BMS), which has optimal switching control function based on the estimated State of Charge (SOC), has been developed and verified.

Keywords: Storage System, Hybrid Energy Storage System, Hybrid Electric Vehicle, Mild-HEV

1. Introduction

Owing to recent pressures toward greenhouse gas reduction, as well as rising oil prices, the interest in environment friendly and highly efficient vehicles, such as HEVs, Plug-in HEVs, and EVs has increased. Since the

world first saw the HEV Toyota Prius in 1997, various types of HEVs, such as mild, soft, hard, and plug-in types, have been developed and sold while meeting the regulations and/or the needs of customers.

In the case of the mild type HEV with the features of idle stop & start, power boosting, and regenerative braking, Toyota presented the first CROWN 3.0 model to the Japanese market in 2002, and then GM showed the SATURN VUE model to the US in 2006, followed by the SIERRA and the SILVERADO pick-up model in 2004. Almost all market forecasts present drastic and steady growth of the HEV market in the next decade.

Effective HEV driving normally implies a proper

combination of mechanical engine power and electric motor power to propel the vehicle, so HEV driving efficiency, indicated as fuel economy, must be affected by the electric system performance, which strongly depends on the characteristics of the Energy Storage System (ESS). To improve the total system efficiency of the HEV, it is necessary to build up the pertinent ESS so that it is capable of sufficiently supplying and receiving electric energy. In other words, the ESS should cope with high power discharging and charging operations due to various driving conditions such as starting, passing, and regenerative braking. [1-2]

Although most of the HEVs currently available on the market are equipped with Ni-MH batteries, the lead-acid batteries are still attractive and used in the mild HEVs, which have relatively restricted functions and require consideration of cost effectiveness. Lead-acid batteries represent both reasonable cost and high reliability in automotive applications, but they generally show some drawbacks in cycle life, power characteristics, and weight, etc. Studies to improve their performance are being continuously performed, [3-5] and different viewpoints have arisen providing resolutions other than strictly improving the battery itself. One of those is combining different types of energy storage devices to improve the cycle life, power characteristics, and operating efficiency of an ESS; utilizing a high power storage device such as an ultracapacitor and a high energy device like a lead-acid battery, i.e., a hybrid energy storage system (HESS) as in Fig. 1.[6-13] Moreover, further improvement could be achieved when a proper storage device is selectively used corresponding to respective charging status and vehicle driving conditions, which can be called an advanced Hybrid Energy Storage System (advanced HESS).

In this paper, an advanced HESS with storage device selecting function via BMS is presented, and experimental tests are performed to verify the degree of improvement in energy efficiency for mild HEV applications.

2. Advanced HESS

2.1. System configuration

The typical mild HEV calls for an improved energy storage system due to a rather high current operation at a low operating voltage range. In particular, the idle stop &

start function significantly increases the number of engine startings, which involves frequent high current discharge. Sometimes the starting current reaches the 10C to 15C rate and it causes a decrease in performance and cycle life. The regenerative braking function is another major factor compromising performance, because a rather high charging current is applied to the energy storage device in a short time span when kinetic energy is transformed into electrical energy while braking. [5]

But the battery widely used as the energy storage device for automotive applications comes with chemical reactions during energy input and output processes, restricting its ability for high current charge or discharge in a short time span. As a means of counteracting these drawbacks and meeting the requirements for the ESS of a mild HEV, pairing a high power storage device (ultracapacitor), with a high energy storage device (battery), in parallel as in Fig. 1 was considered and called a hybrid energy storage system. [6-13]

Obviously, the cycle life and charge/discharge characteristics of the HESS have improved compared to the battery alone, but there is still room for further improvement, if the HESS could be controlled appropriately in accordance with the charging status of each storage device and predicted vehicle operating conditions, i.e. advanced HESS.
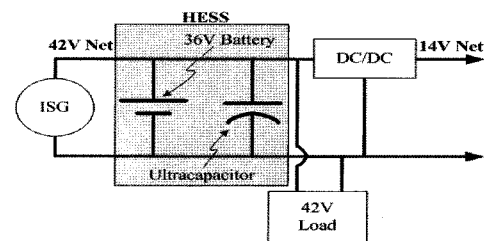

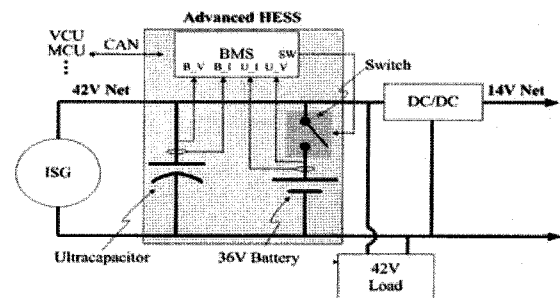Fig. 1   HESS using an ultracapacitor and a battery in parallel

Fig. 2   An advanced HESS with dynamic control

The basic control strategy of the advanced HESS is selectively connecting the proper storage device(s) to the power-net on the basis of State of Charge (SOC) information to achieve high efficiency and good cycle life. This is achieved by using the ultracapacitor alone under peak power needed operations, such as idle stop & start and regenerative braking, and combining the ultracapacitor with the battery under energy concerned conditions where more electric energy should be supplied to the loads, especially for the engine off period.

The advantage of the advanced HESS is the minimal cost increase due to adding just a switch. Moreover, the SOC of each storage device could be manipulated by considering the vehicle driving conditions such as vehicle speed, throttle position, and engine speed, etc., Lowering the SOC of the ultracapacitor in advance, so as to receive much more recuperative energy when regenerative braking is expected, and raising the SOC of the ultracapacitor when engine restarting or power boosting is predicted are suggested. In order to achieve these manipulating functions, an energy conversion device such as a DC to DC converter between the ultracapacitor and the battery could be implemented, but this causes a relatively high additional cost. The dynamic control of the advanced HESS is performed by the Battery Management System (BMS), which estimates the SOC of the relative storage devices and controls the connecting/disconnecting switch, as well as exchanges the information with vehicle controllers via the CAN (Controller Area Network).

2.2. The advanced HESS

The advanced ultracapacitor-battery hybrid energy storage system consisting of an ultracapacitor module, a 36V Valve Regulated Lead-Acid (VRLA) battery, a selective switch, and a BMS is described in Fig. 2.

The chosen battery was the same as the one that was used for the Toyota CROWN, representative of a mild hybrid vehicle with 42V power-net. The battery was a valve regulated type, and made by GS-Yuasa. Its electrical specifications are shown in Table 1. The ultracapacitor module consisted of 18 serial connected 1700F cells, supplied by NESSCAP, and the electrical characteristics are described in Table 2. The switch used to connect or disconnect the battery to the power-net was a NAIS EB

100 relay, which was developed for a 42V system by Matsushita. The rated current carrying capacity of the relay was 100A at DC 42V with a contact resistance of 1.5mΩ.

In this advanced HESS configuration, shown in Fig. 3, the ultracapacitor was always connected to the power-net as its primary source, due to its superior power characteristics and efficiency. While the VRLA battery was selectively connected via the switch under high energy needed conditions because it shows relatively lower power density than the ultracapacitor. Thanks to its very low Equivalent Series Resistance (ESR), the ultracapacitor is suitable for high current operation under very high power conditions. Accordingly, efficiency at high power charge/discharge operation can be improved. The hybrid configuration is expected to improve the performance and life-time by maximizing the usage of the ultracapacitor.

Table 1   36V VRLA battery specification

Nominal Voltage	Rated Capacity	Energy Density	Power Density (10Sec)
36 [V]	20 [Ah]	27.5 [Wh/kg]	376.3 [W/kg]

Table 2   Electrical characteristics of the ultracapacitor module

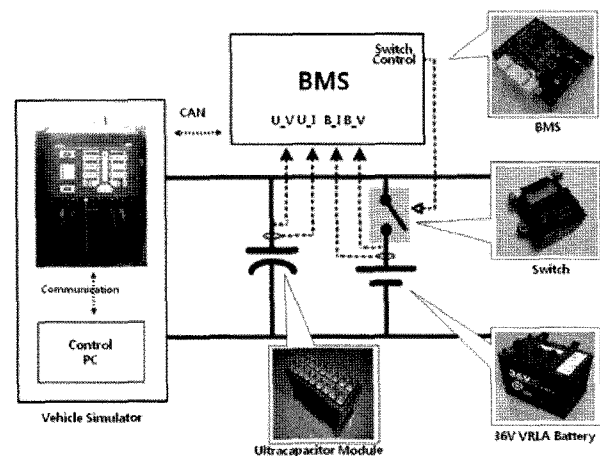| Rated Voltage	Rated Capacity	DC ESR	Available Energy
42 [V]	94.5 [F]	7.5 [mΩ]	0.41 [Ah]

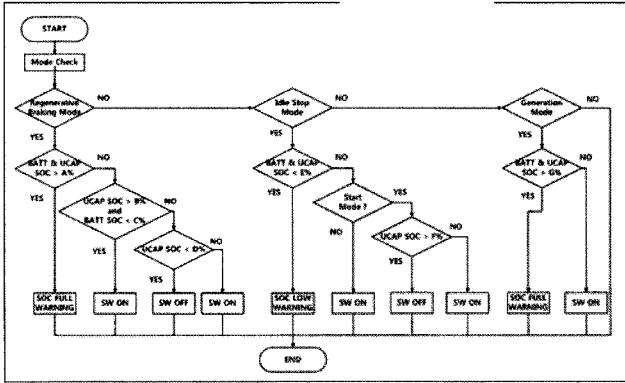Fig. 3   System configuration of the advanced HESS for test

Fig. 4 Control algorithm of the advanced HESS

In the proposed advanced HESS, the BMS should play a decisive role; properly controlling the switch, with which the parallel connection would be configured, based on the estimated SOC of each storage device to improve the HESS efficiency and life-time. The BMS with the optimal switching control algorithm, based on the estimated SOC has been developed and applied in verification tests.

Fig. 4 shows the algorithm to control the switch with the status of energy storage devices estimated in the BMS of the advanced HESS. First, the BMS executes the mode (i.e., regenerative braking mode, idle stop & start mode, or generative mode) in accordance with the SOC of the storage devices, composed of an ultracapacitor and a battery, or a control command received from the VCU.

Second, the SOC is compared to the control value determined previously. And finally, the switch is controlled, or the SOC warning messages (such as full, empty, etc.) of each storage device is outputted, through previous logic of the BMS.

3. Test Results

3.1. Profile for cycle tests

The degree of improvement, in terms of operating efficiency, of the advanced HESS containing the switch control function based on the estimated SOC was verified with a series of tests. First of all, an appropriate test profile had to be defined to serve the purpose of comparing and contrasting the operating efficiency. At first, 'Freedom CAR 42V Battery Test Manual' presented by INEEL and DOE was applied in the comparison tests.[14]
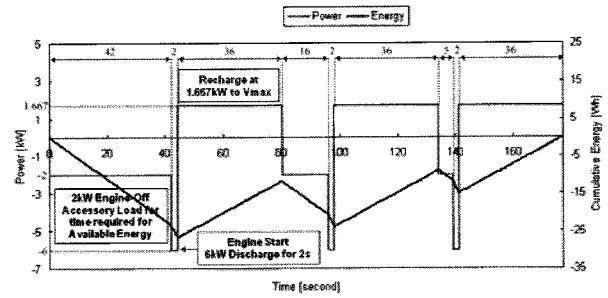

Fig. 5 Efficiency test profile of ZPA

The Zero-Power Assist (ZPA) efficiency and life test profile was chosen for the tests of the battery alone and the ultracapacitor-battery parallel configuration. Fig. 5 shows the ZPA cycle test profile simulating the driving pattern of a 42V mild hybrid vehicle without regenerative function.

But some mild HEVs, such as the Toyota CROWN adopting a 3.5KW belt-driven Integrated Starter-Generator (ISG), apply the regenerative braking function with ZPA to increase vehicle efficiency (fuel economy).

Therefore, it is more reasonable to consider the regenerative braking condition in the ZPA test profile. Fig. 6 shows the modified test profile which implies both the idle stop & start and regenerative braking conditions; and simulates charging and discharging patterns representing mild HEV driving conditions.

The modified test profile reflects regenerative charging of 3.334kW for 2 seconds, which simulates the braking condition of a mild HEV adopting a 3.5kW belt-driven ISG. This was discussed with and consented to by a representative Korean motor company developing a 42V mild HEV using the HESS to assure its objectivity.

In the test profile of Fig. 5 and Fig. 6, the amount of charge/discharge energy was decided on the assumption that the charge/discharge efficiency of the energy storage system is 90%.
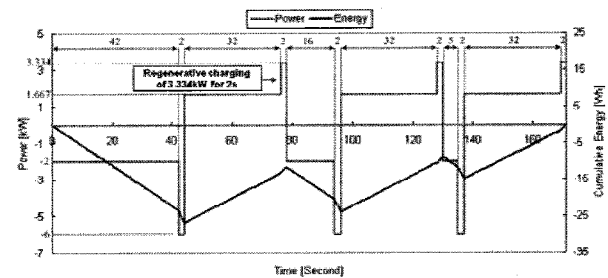

Fig. 6 Modified test profile with regenerative braking

3.2. Results of cycle tests

In order to verify the degree of improvement of the advanced HESS for a 42V mild hybrid vehicle with regenerative braking implementation, cycle tests were conducted using the modified cycle profile shown in Fig. 6.

The efficiency tests for the 3 types of storage configurations, which are the battery alone, the ultra capacitor-battery parallel connection, and the advanced HESS with BMS, were performed. Before the energy efficiency cycle tests, the SOC for each storage system was set to 60% of its full capacity to consider the room for absorbing recuperative energy while braking, and all the tests were performed under a constant temperature condition of 25°C.

At first, the VRLA battery alone was tested as indicated in Fig. 7. As shown in Fig. 7, instantaneous peak power due to engine restarting and regenerative braking causes high current discharging and charging, which leads to low energy efficiency, and results in battery degradation. It can be easily analogized from the results that the battery performance seriously declines as the modified cycle is repeated, implying acceleration of drop in efficiency.
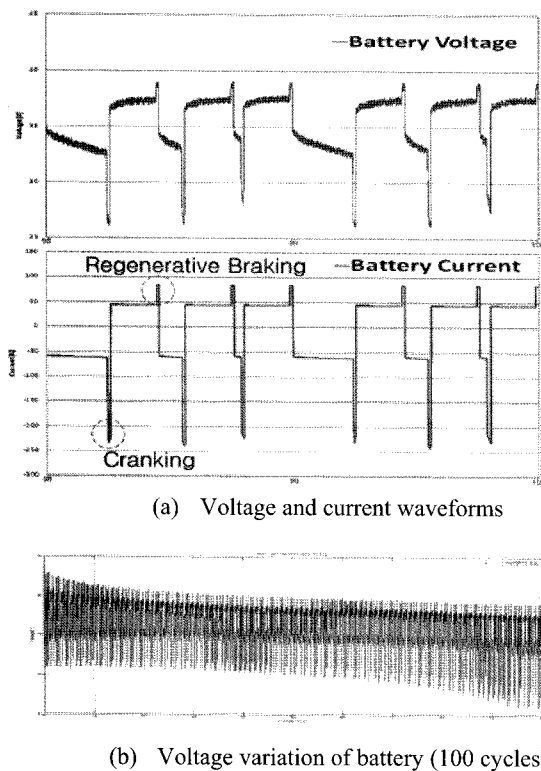

(a) Voltage and current waveforms

(b) Voltage variation of battery (100 cycles)

Fig. 7 Cycle test results of the battery alone

(a) Voltage & Current waveforms of battery

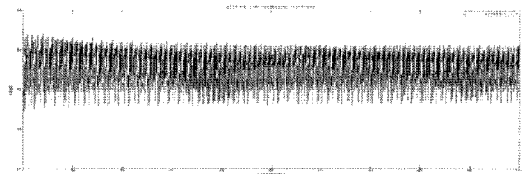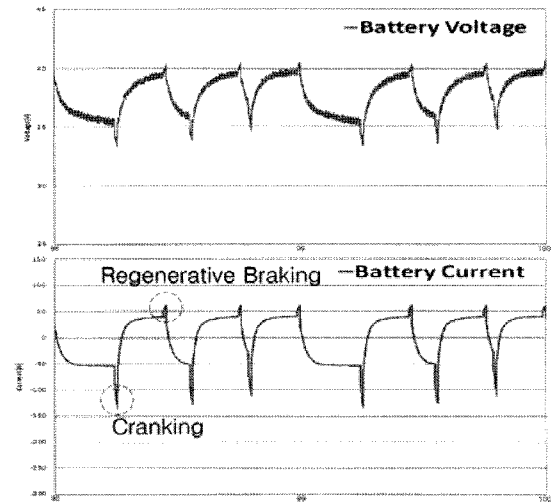(b) Voltage variation of the HESS (100 cycles)

Fig. 8 Cycle test results of the HESS

Second, the HESS, having the ultracapacitor-battery parallel connection without a switch was tested as indicated in Fig. 8. The voltage decline has been obviously alleviated, compared to the battery alone, and it implies the efficiency of the parallel configuration is higher than that of the battery alone. The charging and discharging current from the battery is reduced because the ultracapacitor has a lower internal resistance than that of the battery and is able to cope with the most instantaneous high power burden.

According to the test results, peak discharge current decreased by approximately 47% (239[A] → 127[A]). Consequently, pairing the ultracapacitor with the battery makes an obvious improvement in efficiency as well as battery cycle life.

However, in the HESS, even though the magnitude of the charging and discharging current of the battery was reduced, there is still relatively high current that could undermine energy efficiency and cycle life. Especially, the high recuperative charging current by regenerative braking could precede degradation of the battery, which obviously affects the efficiency and cycle life.

(a) Voltage and current waveforms of battery

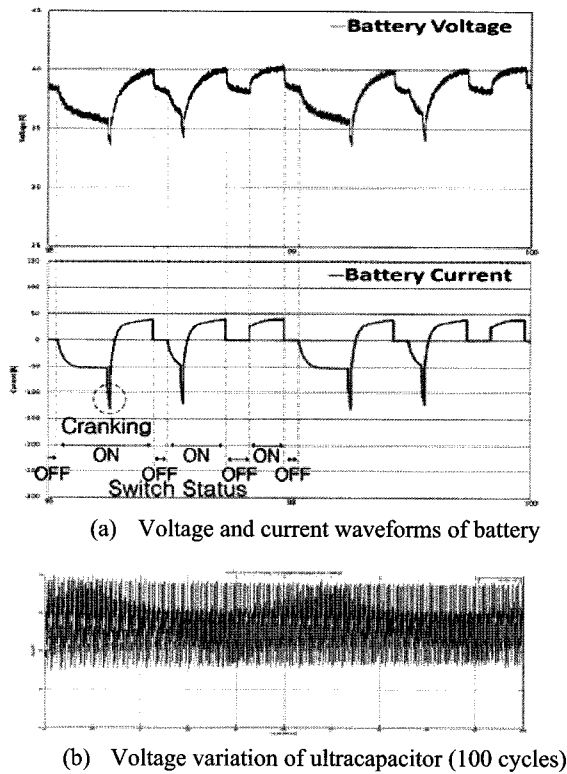(b) Voltage variation of ultracapacitor (100 cycles)

Fig. 9   Cycle test results of the advanced HESS

It can be inferred that a simple parallel connected HESS itself is not sufficient to cope with the high current charging caused by regenerative braking, although it provides certain improvement in efficiency and cycle life compared to the battery alone.

Finally, the advanced HESS adopting switching control illustrated in Fig. 2 was tested, and Fig. 9 shows the test results. The switch kept normal open status as long as the SOC of the ultracapacitor maintained a predefined range, and the battery could be disconnected from the power-net. It made the ultracapacitor absorb the entire instantaneous peak charging current during braking and supply peak discharging current during engine restarting, thereby increasing efficiency owing to the low ESR of the ultracapacitor.

As shown in Fig. 9(a), the peak charging current due to regenerative braking was eliminated, and the discharge current was also reduced. Due to these decreased peak currents, the HESS performance should be improved.

Moreover, a wider range of operating voltage variation in Fig. 9(b) implies effective utilization of the ultracapacitor, leading to efficiency improvement. In other

words, as the frequency of usage of the high efficiency storage device, i.e. the ultracapacitor, is expanded, the energy efficiency of the advanced HESS is expected to be more improved than the ultracapacitor-battery parallel configuration.

The SOC changing ratio can be calculated through the following process:

Step 1: Measure the full capacity of each storage system, and repeat it 2 more times. Calculate the mean value. (= Fully charged capacity → C_{Full})

Step 2: Set the SOC to the predefined value, 60%, by constant current discharging of $1/5C_5$ rate for 2 hours. (= Capacity before cycle test → C_{SOC60})

Step 3: Do the tests with modified profile for 100 cycles.

Step 4: Measure the remaining capacity of the storage by discharging it to the cut-off voltage.(= Remain Capacity → C_{Remain})

Step 5: Calculate the capacity change ratio of 100 cycles using equation (1) below.

$$Capacity\ Change\,[\%] = \frac{C_{Remain} - C_{SoC60}}{C_{Full}} \times 100 \qquad (1)$$

Table 3 shows the summarized amount of capacity change during the cycle tests for three different types of energy storage systems: battery alone, ultracapacitor-battery parallel (HESS), and advanced HESS for mild HEVs.

Table 3   Comparison of energy efficiency

	Battery alone	HESS	Advanced HESS
Fully charged capacity [Wh] (C_{Full}, estimated SOC 100%)	802.78	832.43	830.18
Capacity before cycle test [Wh] (C_{SOC60}, estimated SOC 60%)	501.83	535.41	542.11
Remain capacity [Wh] (C_{Remain}, after cycle test)	234.37	494.11	587.81
Changed capacity [Wh] ($C_{Remain} - C_{SoC60}$)	- 267.46	- 41.3	+ 45.7
Capacity change ratio [%]	- 33.32	- 4.96	+ 5.50

According to the test results, the battery alone shows a capacity decrease of approximately 33%, while the HESS decreases less than 5%. Moreover, the advanced HESS with selective connecting function shows a capacity increase of 5.5%, because the appropriate switching scheme encourages the usage of the highly efficient ultracapacitor. Therefore, by just utilizing a switch, the advanced HESS can improve the energy efficiency by approximately 10.5% compared to the ultracapacitor-battery parallel connection, and this aspect will be clear by increasing the number of cycles as in a life-time test.

3.3. Cold cranking test

An experiment was performed on the cold cranking test with 'FeedomCar 42V Battery Test Manual' for estimating the power capability of the battery. The cold cranking test profile is a direct implementation of the cold cranking power goal, which requires the ability to provide 8kW of discharge power for three 2-second pulses without exceeding (i.e. dropping below) the minimum cold cranking voltage (21V). The 2-s pulses are performed at 12-s intervals (i.e., 10-s between pulses). The test profile is defined in Table 4.

Table 4   Cold cranking test profile

Time increment(s)	Cumulative time(s)	System power(kW)
2	2	8
10	12	0
2	14	8
10	24	0
2	26	8

The cold cranking test is performed by the following process.

Step 1: At 25°C, establish each storage system at the Full SOC, 100%.

Step 2: Set the SOC to the predefined value, 60%, by constant current discharging of 1/5C5 rate for 2 hours.

Step 3: Set the ambient temperature to -30°C, and soak each storage system for a period of time. (More than 12 hours.)

Step 4: Perform the cold cranking test with the cold

cranking test profile. Set the limited-voltage (21V) that is defined by the minimum cold cranking voltage of 'FreedomCAR 42V Battery Test Manual'.
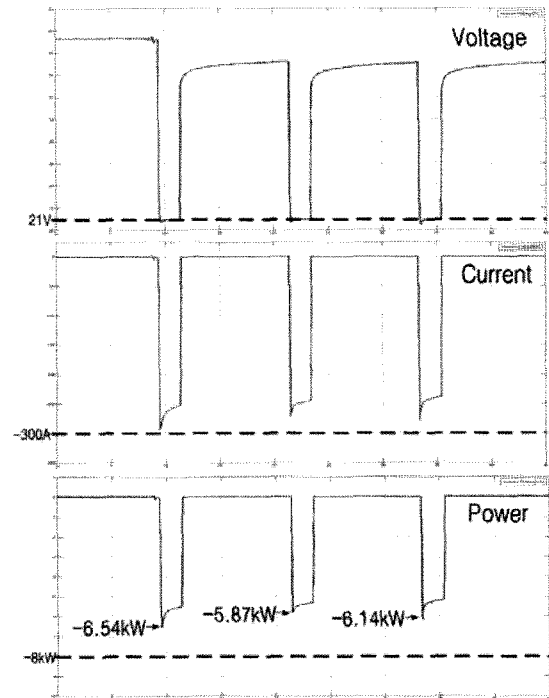

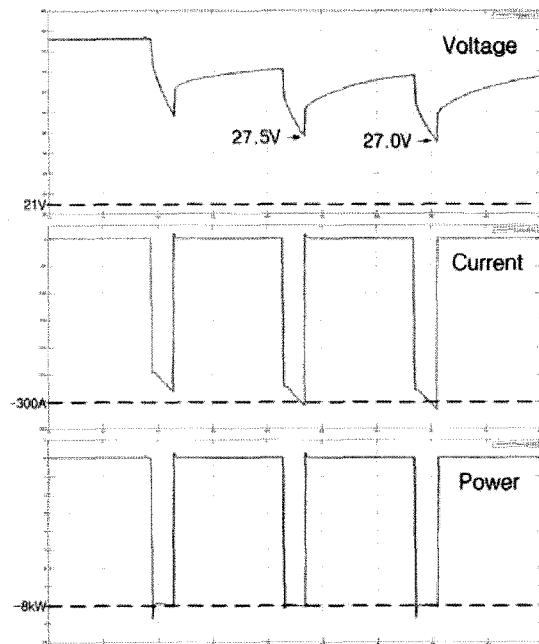Fig. 10   Cold cranking test results of the battery alone

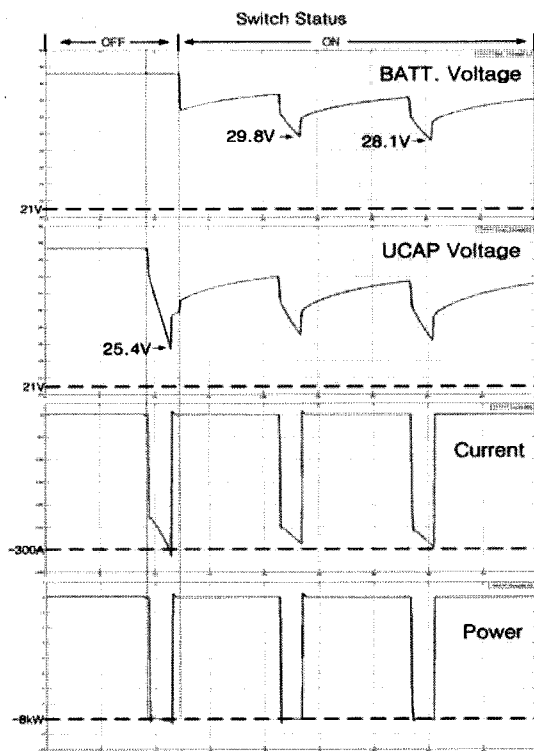Fig. 11   Cold cranking test results of the HESS

Fig. 12   Cold cranking test results of the advanced HESS

According to the results of the cold cranking test, the battery alone type shows that power capability seriously declines due to a drop in the minimum cold cranking voltage. As shown in Fig. 10, the voltage waveform of the battery alone type dropped the limited voltage. The HESS type having the ultracapacitor-battery parallel connection without the switch approached 8kW-power providing for three 2-second pulses as shown in Fig. 11. Therefore, the HESS was satisfied with the power capability of the cold cranking test profile. But the discharging current of the battery was a very high current that could undermine the life-time. On the other hand, the results for the advanced HESS type under cold cranking power, as shown in Fig. 12, is different from the HESS. The BMS of an advanced HESS controls the switch in order to have an OFF-status according to the ultracapacitor's SOC, as in Fig. 12. Because the ultracapacitor supplies all energy at the first cranking pulse of the test profile, the current of the battery is zero at the first cranking. Therefore, it can be assumed that cold cranking has no bad effects on the battery's life-time, supposing that it performs successfully at the first cranking in an actual situation. In other words, if the battery alone and HESS perform the cold cranking (2-s

pulse three times) according to the test profile, the battery of the advanced HESS is only used at second and third cranking.

4. Conclusions

An advanced hybrid energy storage system consisting of an ultracapacitor, a battery, a switch, and a BMS was developed to improve energy efficiency, cycle life, and cold cranking, and then tested to verify the degree of improvement in energy efficiency. To perform reliable verification tests, a modified cycle profile was developed based on the ZPA efficiency and life test profile presented by INEEL and DOE, and was discussed with and consented to by a representative Korean motor company developing a 42V mild HEV, using the HESS to assure its objectivity. Afterward, energy efficiency tests were performed with the three different types of ESS: battery alone, ultracapacitor-battery parallel connection, and the advanced HESS.

The energy efficiencies of the battery-alone, the HESS, and the advanced HESS in the test results were -33.32%, -4.96% and 5.50%, respectively. It has been shown that the advanced HESS achieves improvement of energy efficiency by adopting a storage selecting function, governed by the BMS, based on the SOC estimation. This implies that appropriate storage combinations improve the efficiency of energy storage systems, and that proper switch control algorithms that consider the SOC of respective storage devices and driving information should be the foundation.

Appendix

HEV   : Hybrid Electric Vehicle
ESS   : Energy Storage System (Battery alone)
HESS : Hybrid Energy Storage System (linking a battery and an ultracapacitor module)
SOC   : State Of Charge
BMS   : Battery Management System
VRLA : Valve Regulated Lead-Acid battery
ZPA   : Zero-Power Assist
ISG   : Integrated Starter-Generator
ESR   : Equivalent Series Resistance

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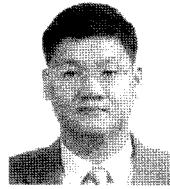
Baek-Haeng Lee received his B.S and M.S. degree in Electrical Engineering from Chung-Ang University, Seoul, Korea, in 1992 and 1994, respectively. He is presently a Ph. D. candidate in the Department of Electronic, Electrical, Control and Instrumentation Engineering in Hanyang University, Korea. His research interests are power converters, energy storage devices and electronic ballasts. He is currently the Head of the Electronics R&D Center in the Korea Automotive Technology Institute.

Dong-Hyun Shin received his B.S degree in Mechanical Engineering from Sungkyunkwan University, Korea, in 1999 and M.S degree in Mechatronics Engineering from Gwangju Institute of Science and Technology, Korea, in 2001. He is presently a Ph. D. candidate in the Department of Mechatronics Engineering in Hanyang University, Korea. His major fields of interest are design of Hybrid (Electric) vehicles and optimal control & modeling of energy storage systems. He is currently the Senior Researcher of Electronics R&D Center in the Korea Automotive Technology Institute.

Hyun-Sik Song received his B.S degree in Control & Instrumentation Engineering from Korea Maritime University, Busan, Korea, in 2001 and M.S degree in Mechatronics Engineering from Gwangju Institute of Science and Technology, Korea, in 2003. He is presently a Ph. D. candidate in the Department of Control and Instrumentation Engineering in Korea University, Seoul, Korea. His research interests are in embedded controllers, energy management, and Human machine Interfaces. He is currently the Senior Researcher of Electronics R&D Center in the Korea Automotive Technology Institute.
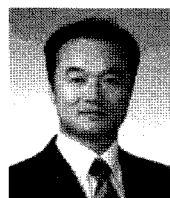
Hoon Heo received his B.S degree in Mechanical Engineering from Korea University, Korea, in 1975 and M.S degree in Aerospace Engineering from the University of Texas at Austin, USA, in 1981. He received his Ph. D. in Mechanical Engineering from Texas Tech University, USA, in 1985. Since 1989, he has been with the School of Control and Instrumentation Engineering, Korea University, Seoul, Korea, where he is currently a Professor. His fields of interest include random vibration control, stochastic control and dynamic control of vehicles.

Hee-Jun Kim received his B.S and M.S. degree in Electronics Engineering from Hanyang University, Seoul, Korea, in 1976 and 1978, respectively, and his Ph. D. in Electronics Engineering from Kyushu University, Kyushu, Japan, in 1986. Since 1987, he has been with the School of Electrical Engineering and Computer Science, Hanyang University, Ansan, Korea, where he is currently a Professor. His fields of interest include switching power converters, electronic ballast, soft switching techniques, and analog signal processing. Dr. Kim is a Fellow of the Korean Institute of Electrical Engineers, the Institute of Electronics Engineer of Korea, and the Korean Institute of Power Electronics.