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A Study on Optimal Operation Strategy for Mild Hybrid Electric Vehicle Based on Hybrid Energy Storage System

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Abstract – This paper proposed an optimal operation strategy for a hybrid energy storage system (HESS) with a lithium-ion battery and lead-acid battery for mild hybrid electric vehicles (mild HEVs). The proposed mild HEV system is targeted to mount the electric motor and the battery to a conventional internal combustion engine vehicle. Because the proposed mild HEV includes the motor and energy storage device of small capacity, the system focuses on low system cost and small size. To overcome these limitations, it is necessary to use a lead acid battery which is used for a vehicle. Thus, it is possible to use more energy using HESS with a lithium battery and a lead storage battery. The HESS, which combines the lithium-ion battery and the secondary battery in parallel, can achieve better performance by using the two types of energy storage systems with different characteristics. However, the system requires an operation strategy because accurate and selective control of the batteries for each situation is necessary. In this paper, an optimal operation strategy is proposed considering characteristics of each energy storage system, state-of-charge (SOC), bidirectional converters, the desired output power, and driving conditions in the mild HEV system. The performance of the proposed system is evaluated through several case studies with respect to energy capacity, SOC, battery characteristic, and system efficiency.

Keywords: Hybrid energy storage system, Lead-acid battery, Lithium-ion battery, Mild hybrid electric vehicle, State-of-charge

1. Introduction

Vehicle technologies based on the internal combustion engine, such as turbocharger and gasoline direct injection, have been continuously developed. As a result, there has been a lot of improvement in the fuel efficiency and performance. However, this progress reached a level of technical saturation. Recently, to resolve the fuel efficiency and environmental issues, electric vehicles (EVs) and hybrid electric vehicles (HEVs) have been proposed [1]. However, EV is still being ignored by the public because of various problems such as pricing and performance. The mild HEV is a suitable alternative for those who have a negative feel for EV [2]. The figure 1 shows proposed mild HEV system. The mild HEV system based on the internal combustion engine vehicles has been proposed. The motor that can be integrated with the starter and generator can support to improve fuel economy by assisting the output of the engine when the vehicle is running. In addition, the regenerative braking device can be charged the energy storage device. It is possible to operate the lead acid battery and the vehicle electrical system by using a DC/DC converter through the alternator operation. The operations of all the power systems controlled by Hybrid Control Unit (HCU). These basic operation is the same as the HEV or EV, but the mild HEV system can't drive the vehicle using motor only. The system assists the engine to improve fuel economy. Because the small motor and battery are used in the proposed system, lead acid battery can be supported to increase performance. However, lead-acid battery has low power density and high internal impedance.

Therefore, if it discharges a large output current, its terminal voltage and state-of-charge (SOC) are significantly reduced. In contrast, the lithium-ion battery can be charged and discharged quickly with high efficiency, fast response, and no memory effect. Moreover, if the lead-acid battery discharges a large output current, the usable energy in the battery will be reduced [3]. Previous studies about HESS had focused on removing the fluctuations using a battery that has a fast response [4-6].

This paper proposes the effective method to select the optimal operation power for each ESS in a mild HEV system. First, the characteristics of the lead-acid battery are studied. Second, an optimal operation strategy and algorithm are proposed for the mild HEV system

2. System Analysis and Modeling of HESS

2.1 System description

The overall system configuration is shown in Fig. 1. The

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HESS is composed of a lithium-ion battery and a lead-acid battery, and the charging or discharging operation in the lead-acid battery is controlled by a bidirectional DC/DC converter. The DC/AC inverter uses the power of the lithium battery to drive the motor. The parameters of the proposed system are shown in Table 1.

The first step in the operation of the system is to determine the desired output of the motor based on the driving conditions of the mild HEV. Second, the output powers of the lithium-ion battery and the lead-acid battery are determined by a higher control unit (HCU) that manages the overall system. The lead-acid battery is operated through the controller of the bidirectional DC/DC converter.

In terms of the driving conditions of the mild HEV, it is important to maintain the output power of the motor accordingly, regardless of the state and output of each ESS. The output power of each ESS is determined by the HCU based on the power reference of the motor, SOCs, the driving conditions and the battery characteristics. If the HCU assigns the output power to each battery using an optimal allocation strategy, the power consumption of the HESS can be reduced under the same driving conditions.

2.2 Characteristic of lead-acid battery

As mentioned before, the lead-acid battery has the lower price, and it is easy to manufacture with the high capacity when compared to the other types of batteries. Therefore, it is used in various applications such as automotive and UPS, etc. The chemical reaction in lead-acid battery generates the electricity. However, it is possible to represent its electrical equivalent circuit model to reflect its characteristics. It consists of open circuit voltage (OCV) and internal impedances depending on its SOC. Because of internal impedance, the terminal voltage drops or rises during the discharging or charging operations. A bidirectional DC/DC converter in Fig. 1 is used to guarantee the stable charge/discharge operations without regard to voltage variations even though it causes power converting losses in the system [7].

The internal power losses in the battery occur depending on the amount of the current. These characteristics have the effect on the charging and discharging efficiencies of battery. Also, the capacitance of battery is affected by the current. When the lead-acid battery discharges a high current, the battery does not convert all the stored energy into electricity. The battery generates a loss such as heat. In Table 2 [8], the lead-acid battery can be discharged to the current of 3 C. The discharging time and capacitance efficiency are changed with the current magnitude. For example, when a fully charged lead-acid battery discharges at a current of 0.05 C, the battery can continue to operate for 20 hours. However, when the battery discharges with at a current of 3 C, the efficiency of discharge capacitance is decreased rapidly according to the increased current magnitude. The lead-acid battery would provide the current for less than 8 minutes. The 64 % of the stored energy in the lead-acid battery is lost as heat and other losses. Based on the results of these experiments, it is expressed in 4th

Table 1. Mild HEV parameters

System	Parameter	Value
Lead- acid battery	Rated voltage	12 V
	Capacity	60 Ah
Li-ion battery	Rated voltage	48 V
	Capacity	9.1 Ah
Motor / Inverter	Maximum power	5 kW
Bidirectional DC/DC Converter	Maximum power	2 kW
	Rated DC voltage	48 V
	Type	Buck-boost
	Rated efficiency	95%

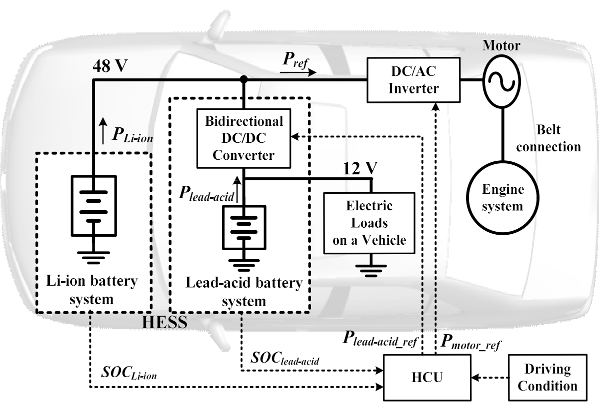

Fig. 1. The proposed mild HEV system with the HESS

Table 2. Discharge Capacitance of Lead-acid Battery

C-rate	Discharge Capacitance
0.05	1.0
0.10	0.9
0.20	0.8
0.50	0.65
1.00	0.56
2.00	0.40
3.00	0.36

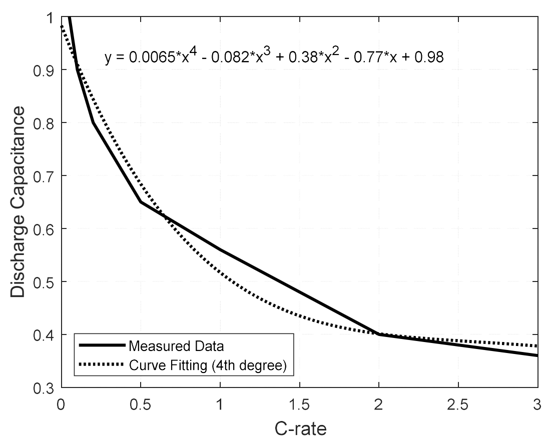

Fig. 2. Discharge capacitance of the lead-acid battery

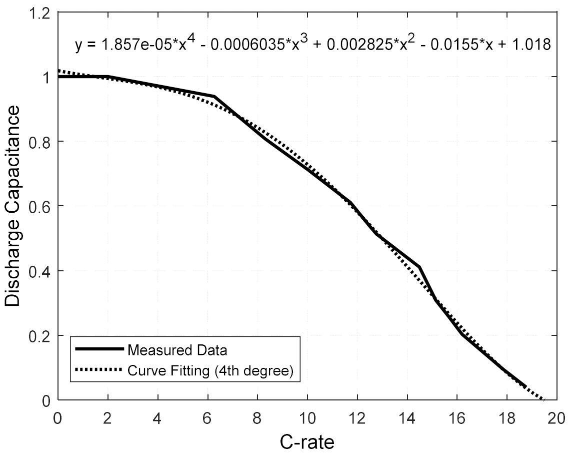

Fig. 3. Discharge capacitance of the lithium-ion battery

degree polynomial equation of the discharge current in Fig. 2.

As the magnitude of discharging current increases, not only the discharge capacitance decreases sharply, but also the terminal voltage drops more rapidly. This is the reason why the lead-acid battery is not suitable for high current applications. The lithium-ion battery, which are more expensive than lead-acid battery, also have internal impedance and discharge characteristics. However, the lithium-ion battery is suitable for high current. Fig. 3 shows discharge capacitance in the lithium-ion battery used for plug-in hybrid electric vehicle, Chevrolet volt [9]. The lithium-ion battery has a discharge capacitance of more than 70% even if it operates at a discharge current of 10 C.

By reflecting these characteristics, SOC of the battery can be estimated as

$$\Delta SOC = \frac{\int_0^t P_{battery}}{f\left(P_{battery}\right) \cdot capacity\left[\text{Ah}\right] \cdot voltage[\text{V}]} \tag{1}$$

Differently from the conventional SOC estimation method such as ampere-hour counting technique [10], proposed SOC estimation can take into account the energy loss of the battery by using the polynomial equation of the discharge current. Therefore, it is possible to estimate the practical SOC and the energy consumption of the battery.

3. Optimal Operation Strategy for HESS

3.1 Optimal operation point for HESS

The HCU determines the output power of motor depending on the driving conditions. Because it has two power sources in the proposed system, the HCU allocates the output powers from the lithium-ion battery and the lead-acid battery to supply a desired output power, P_{ref}. As shown in Fig. 1, the inverter is operated using the power of the lithium battery and an assist power of up to 2 kW from the lead-acid battery supports the motor output by the bidirectional DC/DC converter operation. P_{ref} in (3) is can be computed with the output power of the lithium-ion battery, $P_{Li\text{-}ion}$, and lead-acid battery, $P_{lead\text{-}acid}$, considering the converter efficiency.

$$P_{Li-ion} = P_{ref} - Eff_{conv} P_{lead-acid} \tag{2}$$

where Eff_{conv} is the power conversion efficiency of the bidirectional DC/DC converter.

However, the actual internal energy consumptions in the lithium-ion battery and lead-acid battery are greater than $P_{Li\text{-}ion}$ and $P_{lead\text{-}acid}$ because of the discharge capacitance of the batteries. It can be calculated using the previously proposed polynomial equations and (1). Therefore, the total amount of the consumed power in the HESS, P_{total}, is determined as

$$\begin{aligned} P_{total} = \Delta SOC_{Li-ion} & \frac{capacity_{Li-ion} \cdot vol_{Li-ion}}{time} \\ + \Delta SOC_{lead-acid} & \frac{capacity_{lead-acid} \cdot vol_{lead-acid}}{time} \end{aligned} \tag{3}$$

P_{total} can be expressed by a fractional expression with a 4th order polynomial denominator of $P_{lead\text{-}acid}$ using (1)-(3), and there should be an optimal point because (3) is a convex function in operating area. There is a specific point of $P_{lead\text{-}acid}$ where P_{total} is the minimum. The constant value of $P_{lead\text{-}acid}$ is an optimal efficiency point in accordance with P_{ref}.

Using (3), it is possible to determine the output power in the lead-acid battery to operate most efficiently in accordance with the desired output power of the motor. Therefore, the optimal efficiency point is determined to minimize the charge/discharge loss in the HESS by each characteristic of the ESS and the power conversion efficiency of the converter. Figure 4 shows the optimal efficiency point for the HESS with the lithium-ion battery and the lead-acid battery. In the low power reference, the system is operated using only the lithium-ion battery. In the high motor power reference, a large loss is generated under heavy load on the lithium-ion battery. However, if the appropriate output power is allocated to the lead-acid battery, the loss can be reduced. In addition, it is possible to select the allocation of power to the lead-acid battery in the stable operation range without any change in the loss.

For the example, as shown in Fig. 4, when the motor output is at its maximum value of 5 kW and the lithium battery is operated only, the total power consumption in the HESS is 8 kW.

However, if the lead-acid battery supports output power by 604 W using the optimal efficiency point, the total power consumption in the HESS is reduced to 7.2 kW. In addition, the total power consumption in the HESS is less than 7.4 kW when the output power of the lead-acid battery is between 400 W and 1000 W. There is no significant difference from the optimal efficiency point. Thus, it is possible to allocate flexibly because the system can be operated by placing weight on a specific ESS according to the driving state and SOC of each ESS, even when it is not the efficiency point.

3.2 Operation algorithm for mild HEV with HESS

An operation algorithm is required for the mild HEV with the HESS in order to get better performance under the same driving conditions. First, the desired output power in the HESS, P_{ref}, is determined. When the vehicle has stopped, the SOC of the lithium-ion battery, $SOC_{Li\text{-}ion}$, is checked to find whether the enough energy is stored in the battery or not. If $SOC_{Li\text{-}ion}$ is low, the lithium-ion battery is charged using the power of the lead-acid battery. The reason is that the lithium-ion battery is used as the main battery for ensuring better performance and operating efficiency of the vehicle. Next, the HCU determines whether a specific battery operates mainly in the system, depending on the driving state and the SOCs of the HESS.

During sudden power fluctuations caused by events such as rapid acceleration or uphill driving, more power is allocated to the lithium-ion battery because it can prevent sudden power fluctuation of lead-acid battery. In addition, if there is a difference between $SOC_{Li\text{-}ion}$ and $SOC_{lead\text{-}acid}$, or if the stored energy in one of the battery is insufficient, the HESS is operated by placing a weight on a specific ESS. As a result, $SOC_{Li\text{-}ion}$ and $SOC_{lead\text{-}acid}$ are maintained at similar levels. The operation process of the proposed operation algorithm is shown in Fig. 5.

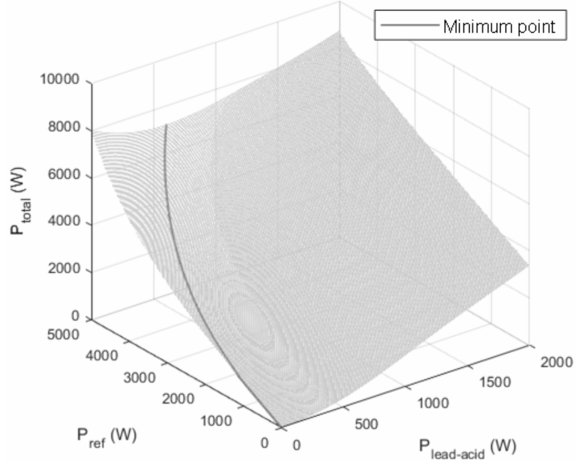

Fig. 4. Optimal efficiency points for HESS

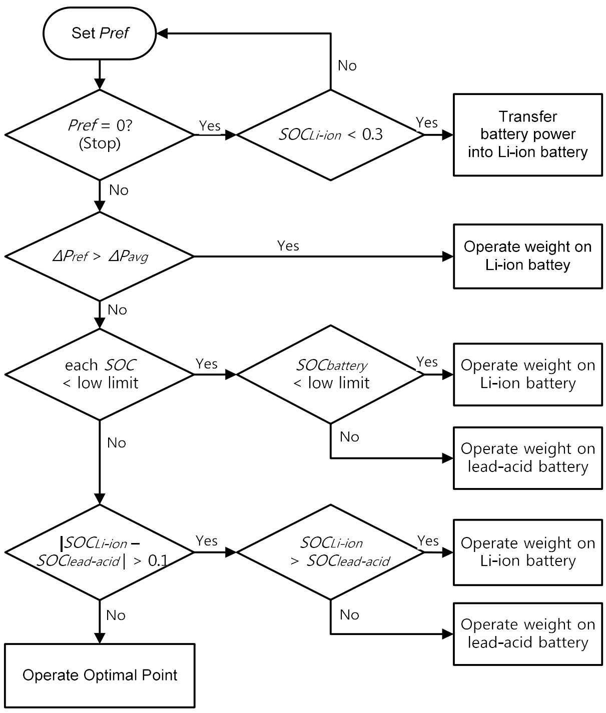

Fig. 5. Proposed operation algorithm

4. Simulation Results

The performance of proposed operation strategy by the HESS is evaluated based on a simulation using MATLAB® software. The driving pattern for the simulation is determined by the FTP75 urban drive cycle, which is a fuel consumption test mode of the vehicle for simulation [11, 12]. Fig. 6 shows the speed and power references based on the acceleration of the vehicle. A simulation was performed in three cases, and the simulation results of the operating HESS in the mild HEV are shown in Fig. 7. In all three cases, the initial SOCs of the lithium-ion battery and lead-acid battery are set to 80 % and the motor output power is the same as in Fig. 6. In a system with lithium-ion battery only, case 1, the lithium-ion battery is completely discharged in 3450 seconds as shown in Fig. 7(a). Without the proposed algorithm in the HESS, case 2, the output power of the lead-acid battery is always set to the optimal efficiency point as shown in Fig. 7(b). In the HESS with the proposed algorithm in Fig. 7(c), case 3, the operation has been completed while maintaining a

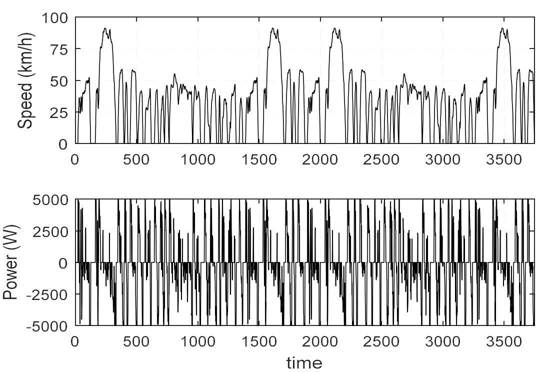

Fig. 6. Speed and reference power of motor using FTP75 urban drive cycle

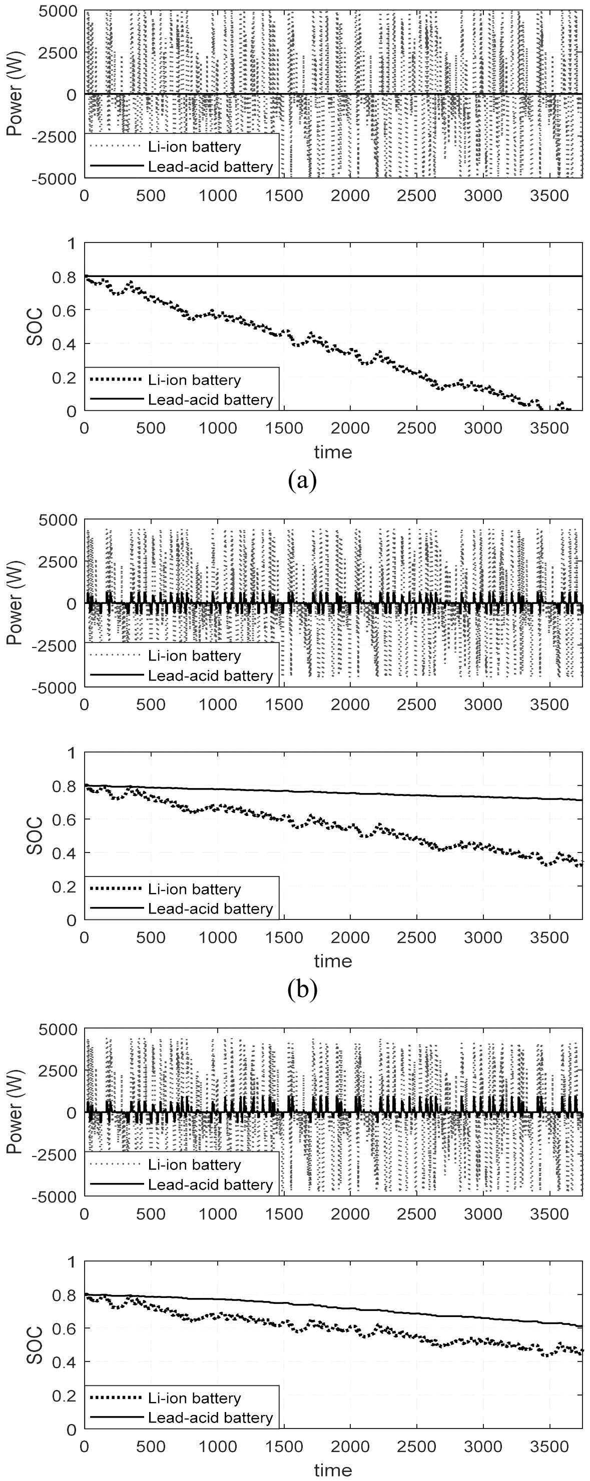

Fig. 7. Simulation results of output power and SOC variation: (a) case 1: lithium-ion battery system, (b) case 2: HESS without the proposed algorithm, and (c) case 3: HESS with the proposed algorithm

similar SOC interval. Because the HESS is operated efficiently according to the characteristics of the batteries and the driving states, the not only power loss in the system, but also the difference between the SOCs of the HESS are reduced.

Table 3. Simulation results of SOCs and remaining capacities in HESS

Case	Parameter	Result
Case 1	$SOC_{Li\text{-}ion}$	0
	$SOC_{lead\text{-}acid}$	0.8
	Remaining capacity in HESS	576 [Ah]
Case 2	$SOC_{Li\text{-}ion}$	0.352
	$SOC_{lead\text{-}acid}$	0.712
	Remaining capacity in HESS	666.18 [Ah]
Case 3	$SOC_{Li\text{-}ion}$	0.475
	$SOC_{lead\text{-}acid}$	0.611
	Remaining capacity in HESS	647.60 [Ah]

Table 3 shows the final state of each case. In the case 1 which only operates with the lithium-ion battery, the final remaining capacity in the lead-acid battery is 576 Wh. Compared with the case 2, it is possible to reduce the loss by 90.18 Wh in the same motor operation. It shows that the system is operated longer than case 1 by the optimal efficiency point using the lead-acid battery. In the case 3, it shows that the difference of SOC is reduced even though the remaining capacity in the HESS is similar to the results in case 2. When the difference between the SOCs increases as the operation continues, one of the battery finally reaches the full discharge first. Because energy is stored only in the other battery, the system no longer operates even with the remaining energy. Therefore, it can be operated the longest and most efficiently using the proposed algorithm.

5. Conclusion

This paper proposed a HESS with a lithium-ion battery and a lead-acid battery for a mild HEV system. It also proposed to optimal operate of the HESS and an operation algorithm for the mild HEV system. The simulation results were shown that the HESS can save more power by the proposed algorithm. Using the proposed method, the same driving performance could be achieved with a smaller battery for the mild HEV. Therefore, this method is expected to help improve the performance of the mild HEV.

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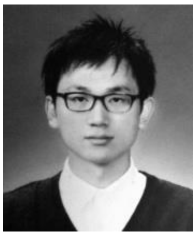

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