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Effectiveness analysis of energy reclamation from partially depleted batteries

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Abstract

This paper presents the study of energy reclamation from partially depleted primary batteries using secondary battery cells as temporary energy repositories. A DC/DC power converter is interposed between the two types of batteries to control the discharging of the primary battery as well as the charging of the secondary battery. The energy reclamation process is simulated and verified in the virtual test bed (VTB) computational environment using pre-validated battery models. Energy transferring and power losses among components are quantificationally studied. For an example system including a lithium sulfur dioxide primary battery with an initial state-of-charge of 0.3 at 296 K, an aggregated total of 216 kJ of energy is reclaimed and 82.87% of the energy (179 kJ) is stored in a 10-cell lithium-ion battery pack. A simple application scenario is used to show the potentially significant benefit of performing this energy reclamation technology. The study results demonstrate that 8.3% of weight and 10% of cost are saved. The main factors affecting the system performance are varied and the effects are analyzed. The results show that battery energy reclamation can be improved by: (1) appropriately increasing the battery operating temperature, (2) using relatively low discharging current, and (3) improving the power converter efficiency at the user-specified discharging current level.

Keywords: DC/DC converter; Energy reclamation; Lithium-ion battery; Lithium sulfur dioxide battery; Partially depleted

1. Introduction

Primary batteries have been widely used in off-grid high-mobility applications. In such applications, carrying the smallest number of batteries (as well as the lightest weight) and maximizing the value of every watt-hour of energy carried are two important factors for optimization of the power option. Consider an outdoor team that conducts daily missions from a remote camp. At the end of each day, several partially depleted battery cells are probably set aside. For example, wanting to carry minimum weight on each mission, every member may start with two full batteries each day and return with one depleted and one at 30% state-of-charge (SOC). On the next day, not wanting to carry the battery that will soon be empty, each person again starts with two new batteries and again returns with one cell at 30% SOC. The residual energy in the partially depleted batteries might be used in any of three ways: (1) by using each battery until it is depleted and thus having to carry all these partially depleted batteries and change them frequently during the task; (2) by installing the partially depleted cells into equipment that has a lower power demand with a hope of powering the low-demand equipment for the whole day, but the applicability of this approach is commonly limited by equipment requirement; (3) by transferring and consolidating the residual energy from several partially depleted batteries into a secondary battery. Although using secondary battery cells consumes some energy during the energy transfer, and secondary cells do not yield such high mass-specific energy as primary cells, still this approach might produce a much better energy-to-weight ratio for daily missions. Compared with the first two approaches, the third is more practical and effective in real-world applications. Currently, there are few studies

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directly addressing this problem; most research focuses on recycling of metal materials from used batteries, such as zinc, copper, nickel, and cadmium, as well as protecting the natural environment [1–3].

This paper presents the analysis and simulation of energy reclamation from partially depleted primary batteries into secondary cells. Specifically, a lithium sulfur dioxide ($LiSO_2$) battery is chosen as the partially depleted battery and a lithium-ion (Li-ion) battery pack is adopted as the temporary energy repository. The models of both batteries have been developed and pre-validated in the virtual test bed (VTB) computational environment [4]. A DC/DC power converter is interposed between the primary and the secondary batteries to control the energy reclamation process by discharging the primary battery and charging the secondary battery simultaneously. A simple scenario is presented as an example to illustrate the benefit of using this energy reclamation technology. The energy transferring and the component power losses during the energy reclamation are studied. The main factors that affect the energy reclamation of the battery system, including the battery discharging current, the battery operating temperature, and the power converter efficiency, and the reclamation improvement corresponding to each factor are explored and discussed.

In the following section, the system setup and the component modeling are detailed. Section 3 then describes the simulation results and benefit analysis. Section 4 discusses the main factors that affect the energy reclamation process. Finally, the conclusions are given in Section 5.

2. System setup and component modeling

2.1. System simulation schematic

Fig. 1 schematically illustrates the battery energy-reclamation system in the VTB, in which a $LiSO_2$ primary battery is chosen as the partially depleted battery and a Li-ion battery pack is used as the temporary energy repository. A DC/DC step-down power converter is interposed between these two batteries and it is commanded by a PI controller to discharge the partially depleted primary battery and simultaneously charge the secondary batteries. During the simulation, the power converter efficiency follows a pre-specified efficiency curve located in the converter efficiency-map model. The converter input/output current and voltage are monitored by two sensors, and the measured signals are used to calculate the energy distribution among different components as well as used by the converter controller model. A constant current followed by a constant voltage charging algorithm is adopted in this system, which charges the secondary battery until the primary battery is exhausted or the secondary battery is fully charged.

Clearly, adopting accurate battery models is the precondition to carry out quantificational analysis of the energy reclamation in this battery powered system. That is to say, the models should precisely capture the battery properties that are involved in this study, such as nonlinear equilibrium potentials, rate and temperature-dependencies, and thermal effects. In addition, since the simulation tests focus on system-level

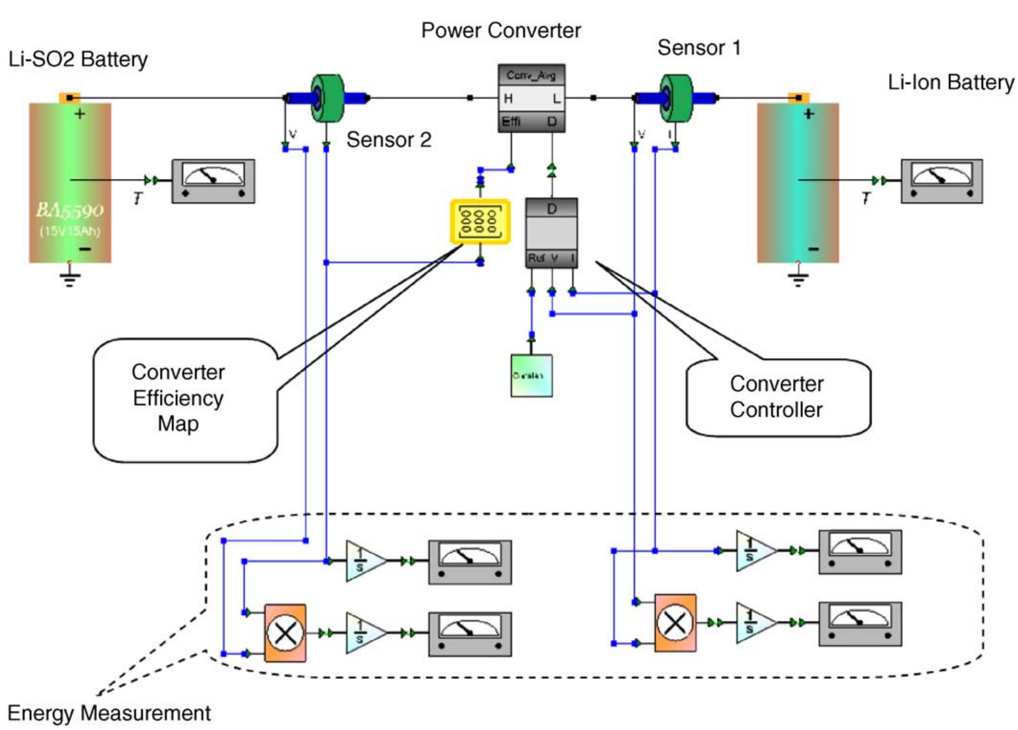

Fig. 1. System simulation schematic in VTB.

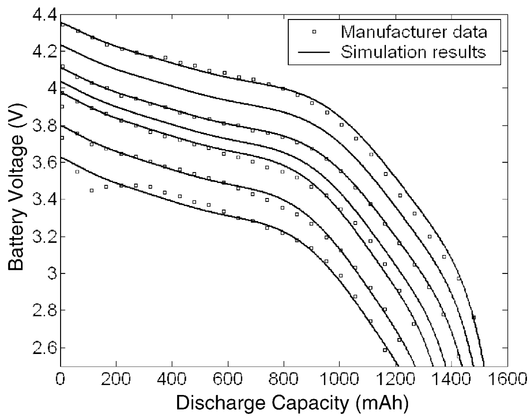

Fig. 2. Battery voltage vs. discharge capacity, at temperatures of (top to bottom): 318, 307, 296, 283, 273, 263 and 253 K.

study rather than the battery component alone, the battery models should avoid detailed calculations of internal physical processes to save computational cost. In this study, both of the battery models have been pre-validated based on experimental test results and publicly available data such as the manufacturers' data sheets, and the modeling process is detailed in [5]. The following two sections summarize the main characteristics of the two battery models concerned in this study.

2.2. *Li-ion battery model*

The Li-ion battery model (Sony US18650) used in this simulation study has a nominal 1.4 Ah capacity per cell with a cutoff voltage of 2.5 V. Since the Li-ion battery is only charged during the energy reclamation process, battery features of the temperature-dependent capacity and the charging characteristic are described here. Fig. 2 illustrates the temperature-dependent characteristic of the battery. As can be seen, good agreement is obtained in a wide operating range of temperature from 253 to 318 K.

Fig. 3 shows the charging characteristic of the battery. A constant current (1 A) followed by a constant voltage (4.2 V)

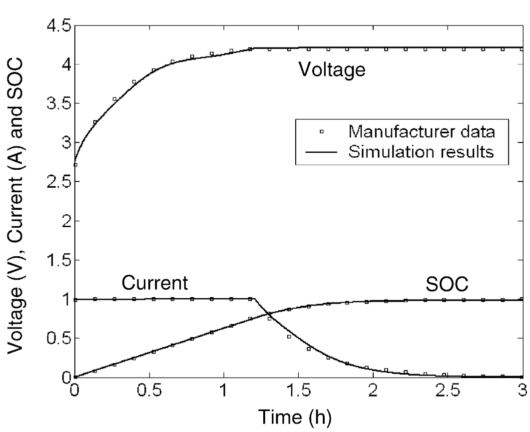

Fig. 3. Battery charge characteristics at 296 K and 1.0 A.

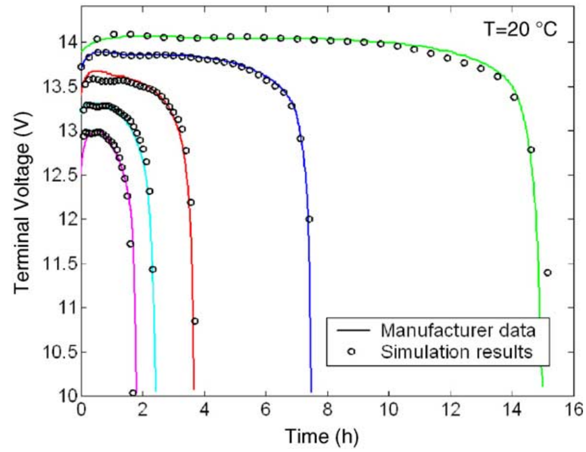

Fig. 4. Terminal voltages vs. discharge time, at discharging currents (top to bottom): 1, 2, 4, 6 and 8A.

charging profile is applied. In the case of charging at 1 A or lower, a constant charging efficiency of 92.27% is found to be sufficiently accurate. The simulation results match the manufacturer's data well.

2.3. *$LiSO_2$ battery model*

For the $LiSO_2$ battery (Saft BA-5590, 15 V, 15 Ah) model used in this study, battery features of the rate-dependent and the temperature-dependent characteristics are illustrated in Figs. 4 and 5, respectively. Fig. 4 shows the battery terminal voltage as the function of the depth of discharge at 293 K at different discharging currents from 1.0 to 8.0 A.

Fig. 5 illustrates the battery discharging capacity as the function of the discharging current at different temperatures from 233 to 328 K.

From Figs. 4 and 5, it can be seen that the battery performances are strongly affected by the discharging current and the operating temperature. For example, the discharge capacity at 253 K in Fig. 5 drops from 14.5 to 10.0 Ah as the

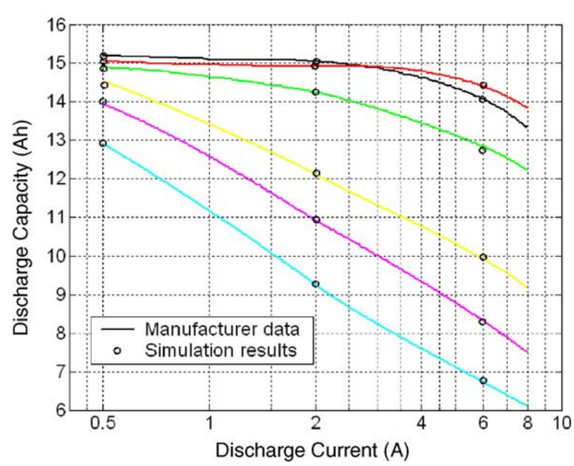

Fig. 5. Discharge capacity vs. discharge current, at temperatures of (top to bottom) 328, 293, 273, 253, 243 and 233 K.

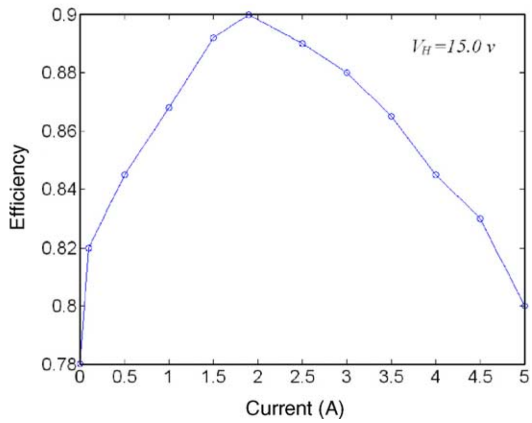

Fig. 6. Converter efficiency vs. converter high-voltage side current.

discharge current increases from 0.5 to 6.0 A, corresponding to 31% (4.5 Ah) capacity loss. Therefore, these two factors, the discharge current and the operating temperature, must be considered in the study of energy reclamation.

2.4. Power converter model

An average step-down power converter model is used in this study, which allows users to pre-specify the efficiency curve corresponding to their individual converters. Since all the energy extracted from the primary battery goes through the power converter, the power converter loss is an important factor that affects the system performance and efficiency. In this study, a general purpose step-down power converter is adopted, whose efficiency curve is shown in Fig. 6.

3. Simulation results and benefit analysis

The simulation study was carried out in the VTB and the component parameters are specified in Table 1. During the energy reclamation process, the $LiSO_2$ battery was connected to the high-voltage side of the power converter and the Li-ion battery pack was connected to the low-voltage side. The Li-ion battery array size is determined by the initial SOC of the partially depleted battery. In this study, 10 cells of Li-ion battery was found to be enough to store all the reclaimed energy from one $LiSO_2$ battery with the initial SOC 0.3. Furthermore, in order to satisfy the voltage requirement of the step-down power converter, the 10 cells of the Li-ion battery were connected as two cells in series and then five strings in parallel, yielding a terminal voltage around 7.6 V. During the Li-ion battery utilizations, the battery pack will be reconfigured according to the user's requirement.

Table 1
Specifications of simulation

	Specifications
Primary battery (Saft BA 5590)	One battery pack, 15 V, 15 Ah, cutoff voltage 10 V, initial SOC 0.3
Secondary battery (Sony US18650)	Ten cells, 3.8 V cell^{-1}, 1.4 Ah cell^{-1}, cutoff voltage 2.5 V, initial SOC 0.1
DC/DC converter	Efficiency curve shown in Fig. 6
Control algorithm	Constant charging current 3.0 A
Thermal condition	296 K, heat transfer coefficient 13.43 W m^{-2} K

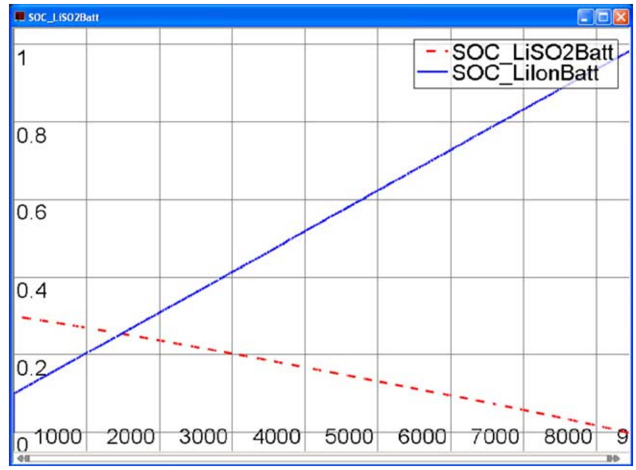

Fig. 7. Battery SOC vs. simulation time in seconds.

3.1. Simulation results

Fig. 7 illustrates the battery SOC variations during the energy reclamation process. The SOC of the $LiSO_2$ battery decreased from 0.3 to 0.0, while the SOC of the Li-ion battery increased from initial 0.1 to final 0.98.

Fig. 8 illustrates the battery terminal voltages during the simulation. The terminal voltage of the $LiSO_2$ battery decreased from the beginning 14 V to the cutoff voltage 10 V, while the terminal voltage of the Li-ion battery pack increased from 6.2 to 8.36 V.

Fig. 9 represents the discharging current of the $LiSO_2$ battery during the simulation. The charging current of the Li-ion

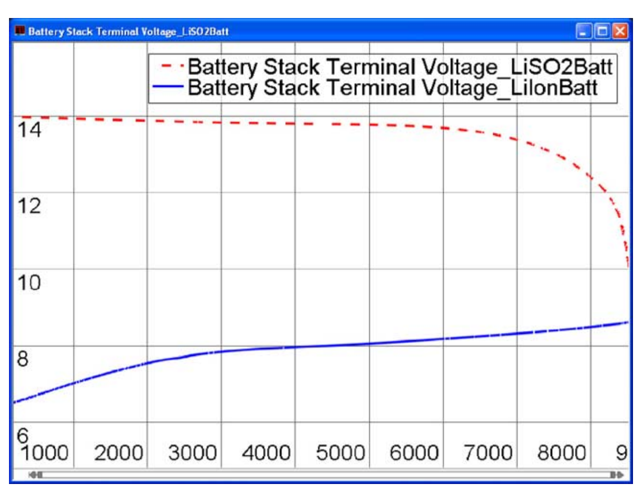

Fig. 8. Terminal voltages (V) vs. simulation time in seconds.

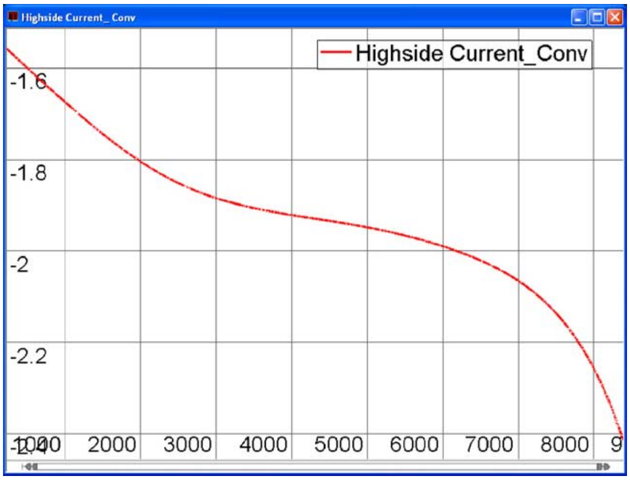

Fig. 9. $LiSO_2$ battery discharging current (A) vs. simulation time in seconds.

battery was controlled to be a constant 3.0 A. As the terminal voltage of the $LiSO_2$ battery gradually decreased and the terminal voltage of the Li-ion battery increased, the discharging current of the $LiSO_2$ battery increased from 1.56 to 2.36 A.

Fig. 10 illustrates the power converter efficiency during the simulation. It can be seen that the converter efficiency was not a constant value but varied according to the high-voltage side current. At about 3300 s, the converter efficiency reached its maximum value of 90%.

Fig. 11 shows the converter input power from the high-voltage side and the converter output power from the low-voltage side during the simulation. The difference between these two curves represents the power converter loss and it can be seen that the converter loss gradually increased during the simulation.

Fig. 12 shows the converter input/output energy during the simulation. There was a total of 216 kJ of energy extracted from the $LiSO_2$ battery, of which 194 kJ flowed out from the power converter. Given the battery charging efficiency of 92.27% (specified in the Li-ion battery model), the net energy stored in the secondary battery was 179 kJ. Therefore, the overall system efficiency was 82.87% (179/216 kJ).

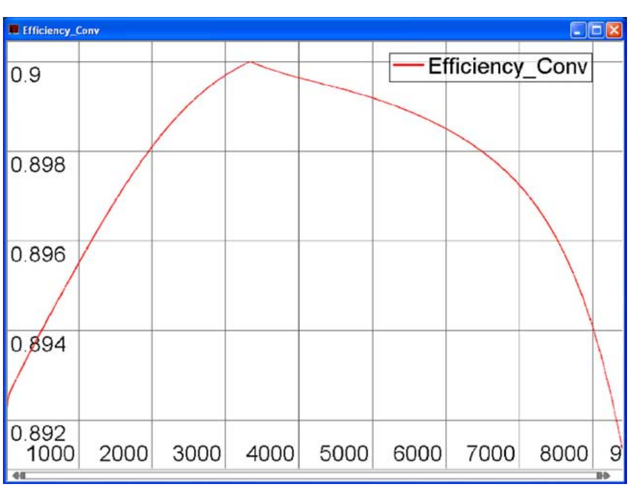

Fig. 10. Power converter efficiency vs. simulation time in seconds.

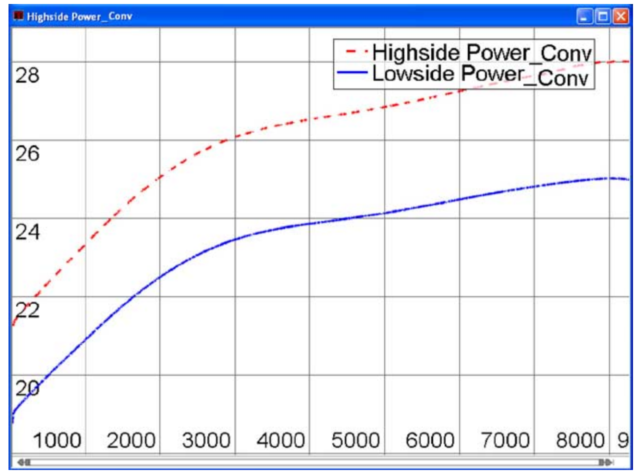

Fig. 11. Converter input/output power (W) vs. simulation time in seconds.

Fig. 13 shows the battery surface temperatures during the simulation. As can be seen, the Li-ion battery temperature stayed at 297.1 K after entering steady state at about 2000 s. This is because the battery charging current was held at a constant value during the simulation. The temperature of the $LiSO_2$ battery increased from 296 to 299 K since the discharging current kept increasing.

The above simulation results show that for one partially spent BA5590 $LiSO_2$ battery with an initial SOC of 0.3 at 296 K, 216 kJ of electricity were drawn out until the battery was depleted at 8342 s (2.3 h). 82.87% of the 216 kJ of energy (179 kJ) was stored in a 10-cell US18650 Li-ion battery pack. Of the 17.13% energy loss, 10.2% (22 kJ) was consumed by the power converter, and 6.9% (15 kJ) was lost during the battery charging process. The overall system efficiency was 82.87%.

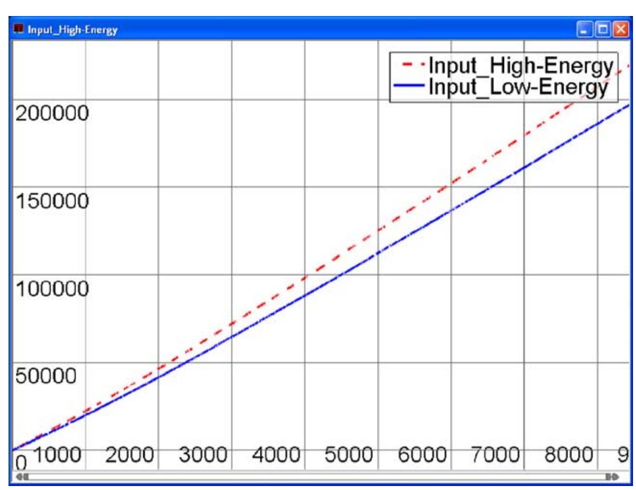

Fig. 12. Converter input/output energy (J) vs. simulation time in seconds.

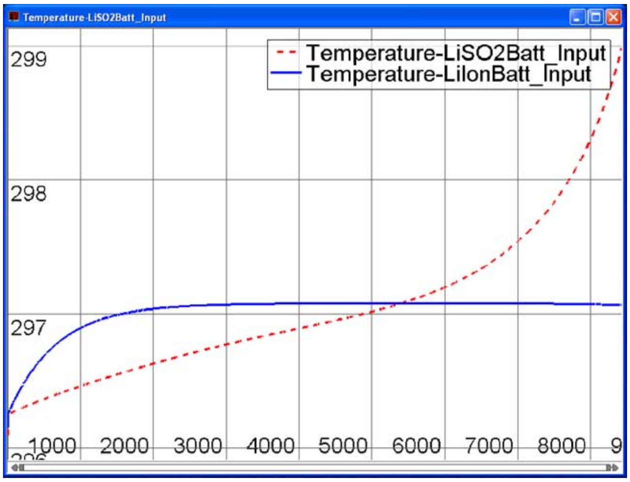

Fig. 13. Battery surface temperature (K) variation during simulation.

Table 2
Benefit analysis

	Without energy reclamation	With energy reclamation
BA5590 primary battery (cell)	100	90
US18650 secondary battery (cell)	0	40
Total battery weight (kg)	102	93.5
Battery cost per mission ($)	10000	9002[a]
Retrenchment per mission	8.5 kg payload, $ 998	
Retrenchment per year	102 kg payload, $ 11976	

[a] $90 \times 100 + 40 \times 20/500 = \$\,9002$.

3.2. Benefit analysis

Based on the above simulation results, the benefit of applying such energy reclamation technology was then analyzed. Consider a simple scenario: a five-member team takes a regular 10-day mission every month; every morning each person starts with two new BA5590 batteries and returns with one depleted and one at 30% SOC at night. Without using the energy reclamation technology, each month the team will consume 100 $LiSO_2$ batteries. Each battery weighs 1020 g and costs about $ 100.

If we adopt the above energy reclamation technology and use a Li-ion battery as the energy repository, one primary battery can be saved each mission day. Every morning, four members take eight new $LiSO_2$ batteries and the fifth member carries one new $LiSO_2$ battery and the Li-ion battery pack; at night, five spent and four partially depleted $LiSO_2$ batteries are returned, and the Li-ion battery pack is then used to reclaim the energy left in the four partially depleted batteries. In order to reclaim all the energy left in the partially spent batteries every day, a total of 40 cells of US18650 is required. Each cell of US18650 weighs 42 g, costs about $ 20, and can be cycled 500 times. The charging configuration of the 40-cell Li-ion battery pack is connected as 2 cells in series and then 20 strings in parallel in order to meet the power converter voltage requirement, while the utilization configuration is connected as 4 cells in series and then 10 strings in parallel to match the voltage requirement of the equipment.

Table 2 shows the comparison between these two situations. It can be seen that 8.3% of weight and 10% of cost are saved by applying the energy reclamation technology.

4. Discussion

This section discusses the main factors that affect the energy reclamation of the battery system: the operating temperature, the discharging current, and the converter efficiency.

4.1. Battery operating temperature

Three simulations were done to study the temperature effects using the specifications in Table 1 at varied temperatures of 256, 276 and 296 K, respectively. Table 3 compares these three simulations.

From Table 3, it can be seen that the system performance is strongly affected by the operating temperature. For example, the net energy stored in the Li-ion battery pack in simulation I (256 K) was 144 kJ, while in simulation III (296 K) it increased to 179 kJ. An additional 36 kJ of energy was saved, which equaled 25% (36/144 kJ) of the energy that was reclaimed at 256 K. Therefore, appropriately raising the battery operating temperature can increase the amount of energy that can be reclaimed. However, overheating the battery will cause battery safety issues.

It also can be seen that the system efficiency is almost independent from the operating temperature; this is because the converter loss (around 10%) and the battery charging loss

Table 3
Simulation comparison at different temperatures (constant Li-ion charging current 3.0 A)

	Simulation I	Simulation II	Simulation III
Ambient temperature	256 K	276 K	296 K
Run time	6731 s (1.87 h)	8137 s (2.26 h)	8342 s (2.32 h)
Energy extract from $LiSO_2$ battery	172 kJ (100%)	205 kJ (100%)	216 kJ (100%)
Energy loss in power converter	17 kJ (9.88%)	21 kJ (10.3%)	22 kJ (10.2%)
Energy output from power converter	155 kJ (90.12%)	184 kJ (89.7%)	194 kJ (89.8%)
Energy loss in Li-ion charging process	11 kJ (6.4%)	14 kJ (6.8%)	15 kJ (6.9%)
Energy final store in Li-ion battery	144 kJ (83.72%)	170 kJ (82.93%)	179 kJ (82.87%)
System efficiency	83.72%	82.93%	82.87%

Table 4
Simulation comparison at different battery currents (constant ambient temperature: 296 K)

	Simulation IV	Simulation III	Simulation V
Constant Li-ion charging current	1.0 A	3.0 A	7.0 A
Run time	24820 s (6.89 h)	8342 s (2.32 h)	2946 s (0.82h)
Energy extract from $LiSO_2$ battery	223 kJ (100%)	216 kJ (100%)	203 kJ (100%)
Energy loss in power converter	33 kJ (14.8%)	22 kJ (10.2%)	40 kJ (19.7%)
Energy output from power converter	190 kJ (85.2%)	194 kJ (89.8%)	163 kJ (80.3%)
Energy loss in Li-ion charging process	15 kJ (6.7%)	15 kJ (6.9%)	12.6 kJ (6.21%)
Energy final store in Li-ion battery	175.3 kJ (78.62%)	179 kJ (82.87%)	150.4 kJ (74.09%)
Overall system efficiency	78.62%	82.87%	74.09%

(around 6.5%) are increased proportionally to the energy extracted from the primary battery.

4.2. Battery discharging current

Based on simulation III, two more simulations were done using the same parameters except that the Li-ion battery charging current was set as 1.0 and 7.0 A, respectively. Table 4 illustrates the comparison results of the three simulations.

From Table 4, it can be seen that the gross energy extracted from the primary battery increased from 203 (simulation V) to 223 kJ (simulation IV) as the secondary battery charging current decreased from 7.0 to 1.0 A. An additional 20 kJ of energy was saved, which equaled 9.9% (20/203 kJ) of the energy that was reclaimed in simulation V. Therefore, using a relatively low discharging rate of the primary battery can increase the amount of energy that can be reclaimed. However, too low a discharging current will dramatically increase the time required for the energy reclamation.

It is also found that, when the Li-ion battery charging current was increased from 1.0 to 3.0 A then finally to 7.0 A, the power converter loss first decreased from 33 to 22 kJ and then increased to 40 kJ. Therefore, increasing the power converter efficiency at the user-specified discharging current level can improve the energy reclamation.

From the above simulation studies, it can be seen that the following three approaches can improve battery energy reclamation: (1) appropriately increase the battery operating temperature, (2) use relatively low discharging current, and (3) improve the power converter efficiency at the user-specified discharging current level.

5. Conclusions

Energy reclamation from partially depleted primary batteries has been studied in the VTB environment using prevalidated battery models. For an example system consisting of one partially spent BA5590 $LiSO_2$ battery with an initial SOC of 0.3 at 296 K, 216 kJ of energy were drawn out until the battery was depleted, and 179 kJ were stored in a 10-cell US18650 Li-ion battery pack. Of the energy loss, 22 kJ were consumed by the power converter and 15 kJ were lost during the battery internal charging process. The system efficiency was 82.87%. In the scenario used to illustrate the benefit of performing the energy reclamation technology, the study results demonstrated that up to 8.3% of weight and 10% of cost were saved. Finally, two sets of simulations were done to study the influence of the battery operating temperature and the battery discharging current. Appropriate increase of the ambient temperature, using relatively low discharging current, and improving the power converter efficiency at the user-specified current rate can increase battery energy reclamation.

Acknowledgement

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