Adaptive Controller for Power Sharing in Modular Battery Energy Storage Systems

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Abstract

Modular battery energy storage systems (MBESS) allow individual battery power control, with reduced voltage ratings of the converters, and enhanced system reliability. The power is shared amongst different battery modules based on the state of charge (SoC) of each module. In this paper, an adaptive power sharing control method is proposed for an MBESS that is connected to the DC bus voltage of a distributed generation system. The adaptation process considers the efficiency and balancing speed of the system at different battery loads. Simulation results (MATLAB/Simulink) are presented to compare the proposed systems performance in terms of balancing speed and efficiency, with conventional and adaptive power sharing methods.

1 Introduction

The increasing penetration of distributed resources into power systems creates problems in terms of energy quality, and supply and demand variations, because of their stochastic nature. One of the solutions is to integrate battery energy storage systems (BESS) alongside the distributed resources [1-3]. Normally, a central, high power bidirectional dc-dc converter is used as an interface between the DC bus and the battery, to control the charge/discharge current, and to boost the battery voltage [4, 5]. Although, this is a simple and cost effective method, the reliability of central BESS is low, as the system has to stop working when one or more cells fail in the battery pack, or when there is a fault in the converter [6, 7]. Although active voltage balancing circuits have been proposed to minimise battery failures caused by under / overcharging [8, 9], the addition of more components required for active voltage balancing reduces the reliability even further. In addition, the converter voltage gain ratio has to be high to connect low voltage batteries to the high voltage DC bus [5, 10]. Recently, modularized battery energy storage systems (MBESS), have been proposed with their advantages over the conventional BESS being reduced converter ratings, improved reliability, and module level balancing features [6, 11, 12].

In an MBESS, converter modules are connected in series at the DC bus side, with each battery module independently connected to its corresponding converter, as shown in Fig.1. With such a modular design, DC bus voltage regulation, and module level balancing of MBESSs, can simultaneously be achieved using a power sharing controller. To balance the state of charge (SoC) of each battery module, higher charged battery modules release more power, while the lower charged ones release less power in discharging mode. Conversely, the

the lower charged battery modules are charged with a higher power during charging, and vice versa. The power difference amongst the modules is created by the voltage differences at the DC bus side $V_{DC,n}$, as the bus current (I_{BUS}) is the same for all of the modules.

Fig. 1. Modular Battery Energy Storage System with Half Bridge Converters

MBESS power sharing methods in the literature are based only on the SoC differences for the balancing process. With this control method, the speed of balancing, and system efficiency, vary depending on the battery load [13]. The battery power also shows variable characteristics according to the power management scheme, such as those proposed in [1, 14, 15]. However, no authors have considered the systems performance in terms of balancing speed and system efficiency when sharing the power in MBESS. Unlike conventional BESS in which battery cells are connected in series, MBESS can tolerate SoC variations between the modules and this provides a degree of freedom for load sharing. In this paper, an adaptive control strategy for power sharing is proposed to improve the energy conversion efficiency of an MBESS connected to a 400 V DC bus at different battery loads. When multiple MBESSs are connected to the same DC bus, power sharing is achieved by using the same DC bus voltage reference for all the MBESSs with a different current for each MBESS depending on the average SoC of its module. This paper will focus on power sharing amongst different battery modules of a single MBESS.

2 Control Method for Modular Battery Energy Storage System

2.1 Conventional SoC based Power Sharing Method in MBESS

The SoC balancing and voltage regulation control loops during discharging operation are shown in Figs. 2 and 3, respectively. In [11] the different modules of an MBESS are balanced using outer SoC compensators that generate individual voltage multipliers (α_{vn}) in SoC balancing loop. These determine the individual voltages, $V_{DC,n}$, of each module at the series connected side, and create power differences between each module (Fig. 2). To ensure the DC bus voltage is always equal to V_{BUS} , the reference DC bus voltage is divided by the sum of the voltage multipliers (M_v) as shown in Fig. 3. Each local controller adjusts its DC side voltage ($V_{DC,n}$) based on the reference value ($V_{DC,nref}$). Therefore, DC bus voltage regulation, and modules' SoC balancing, are achieved simultaneously.

Fig. 2. State of Charge Balancing Loop during Discharging

Fig. 3. Output Voltage Control Loop during Discharging

Although, this control method provides feasible solution for battery balancing and DC bus voltage regulation, it lacks of considering the energy efficiency and balancing speed of the system at different battery load.

2.2 Adaptive Power Sharing Method in MBESS

In this paper, an adaptive controller for the SoC balancing loop is proposed which considers the efficiency of the system. To do this, the efficiency map of the half bridge bidirectional dc-dc converter is generated based on the equations used in [6], and using datasheets of the component chosen for the simulation. These are the SIR606BDP MOSFET, WE-HCFT-3540 inductor, and V40PW10C Schottky diode. The efficiency map for 100 kHz switching frequency is shown in Fig. 4. The peak efficiency is obtained at 30% of rated power, with reduced efficiency at increased load, while at light load conditions, efficiency decreases significantly. Fig. 4 can be represented using (1), and it also shows that the duty cycle has less impact on the efficiency at all load conditions.

$$\eta_s = \sum_{x=1}^n \eta_x * w_x \quad (1)$$

where η_x is the efficiency, w_x is the weighting factor of converter x , and η_s is the system efficiency

Fig. 4. Efficiency Map of Bidirectional Half Bridge DC-DC Converter in Boost Mode

Fig. 5. Adaptive State of Charge Balancing Loop During Discharging

The power differences amongst modules are desired to be high at light load, while it is aimed to be low at heavy load with the consideration of energy efficiency and balancing speed of the system. With the proposed adaptive controller, the voltage loop multipliers, which generate voltage difference at the DC bus side, and thus the power difference between modules, are decided by both the SoC difference, and the battery load, as shown in Fig. 5. To do this, a 2D lookup table, whose inputs are SoC difference, and the battery load, is used. Whilst the voltage difference is kept as high as possible at light load, it is gradually reduced with increasing battery load and reduced SoC differences. This power sharing method does not have a negative impact on the battery efficiency, as the healthier battery modules are charged/discharged with higher powers, and it is assumed that the resistances of modules with higher state of health (SoH) are lower than that of the modules with lower SoH. This is based on information from [16, 17].

3 Simulation Results & Discussion

In the simulation, six 24 V, 30 Ah, Li-ion battery modules, and six half bridge converters are used for a 400 V DC bus. Each converter is designed to process the full battery power (1C) of 30A. Table 1. shows the initial states of each battery module. To show the effectiveness of the proposed controller, the simulation is performed with different battery discharge powers (P_{bat}), 65% (0-1000 s), 15% (1000-2000 s), and 50% (2000-4000 s) of rated power.

Table 1 Initial State of Charge of Each Battery Modules

Battery Module	Initial State of Charge (%)
Battery 1 (shown red)	80
Battery 2 (shown black)	75
Battery 3 (shown blue)	78
Battery 4 (shown green)	79
Battery 5 (shown tile red)	76
Battery 6 (shown grey)	76.5

3.1 Simulation Results with SoC based Power Sharing Method

In Fig 6. the simulation results with SoC based power sharing method are illustrated in discharging mode. For the purpose of SoC balancing, the battery with higher SoC releases more power, and its voltage at the series connected side is higher than the others, and vice versa. It can be seen from Fig.6 (a) that the battery module 1 has the highest SoC, and thus has highest voltage at the DC bus side, while the battery module 2 has the lowest SoC and hence has the lowest voltage at the cascaded connected side. The voltage differences at the series connected side are directly related to the SoC difference, and it is large when there is a high mismatch as shown in Figs 6 (c) and (d). When the battery modules' SoC converge, the voltage difference reduces irrespective of battery load, and all module voltages are equal when there is no mismatch between any battery modules. In this system, the balancing speed depends on the power difference amongst the modules, and higher power differences result in faster balancing of battery modules. The power difference is the multiplication of the voltage difference at the series connected side and DC bus current, (2).

$$\Delta P_x = I_{BUS} * \Delta V_{DC,x} \quad (2)$$

When the battery load increases the power differences amongst modules, and thus speed of balancing also increases. For this reason, most of the balancing occurs in the heavy load area, and the variations in DC bus side module voltage are higher at heavy load than at light load, for the same time. As can be seen in Figs. 6 (c) and (d), the convergence of modules' SoC and DC bus side voltages are too slow at 15% rated power (1000-2000 s), whilst they convergence relatively fast at 65% (0-1000 s), and 50 % (2000-4000 s) rated power.

With this control method, because of the high mismatch between battery modules there may be a high voltage difference in the heavy load area, which reduces the system efficiency. This may be important when the system consists of pre-used battery modules where continuous balancing is required. On the other hand, the voltage difference may be small due to low SoC differences at light battery load (1000-2000s), although a better efficiency would be obtained with higher power differences at light load.

The battery load is decided by the energy management system which is out of scope of this paper. On the other hand, this paper aims to control the voltage differences of each battery module at the series connected side, and hence to control the speed of balancing and system efficiency at all SoC differences for a given battery load.

Fig. 6. SoC Based Power Sharing Method with different battery discharge power (a) Voltages at the series connected side, (b) State of charge of each module, (c) Differences between modules' voltages and voltage at equal power sharing, (d) Differences between modules' SoC and average SoC

3.2 Simulation Results with Adaptive Power Sharing Method

With the proposed adaptive controller, the voltage difference is kept as high as possible at light load, without violating the converter voltage rating, and it is gradually reduced with increasing load and reduced SoC differences in order not to degrade the efficiency. Simulation results with the adaptive power sharing control method are shown in Fig.7. The systems conversion efficiency is also calculated using (1), and compared to the system efficiency with adaptive controller, as shown in Fig. 8.

Compared to the SoC based energy sharing method, the individual DC bus side voltage differences is lower at 65% battery load. The highest voltage difference at the series connected side with respect to equal power sharing voltage is 2.5 V with adaptive power sharing method, whilst it is 9 V with SoC based power sharing method for the same SoC differences as illustrated in Figs. 6(c) and 7(c). Thus, the efficiency reduction with respect to equal power sharing is limited with the adaptive power sharing method (Fig. 8). The narrower voltage limit will result in the higher efficiency at heavy load. However, the balancing speed is also reduced because of the lower voltage differences at the DC bus side. After 1000s, the SoC difference with respect to the average SoC is above 1.5% with the adaptive power sharing method, while it is below 1% with the SoC based power sharing method. The power differences also reduce with reduced SoC difference with adaptive power sharing method as in SoC based power sharing method (2000-4000 s), and all modules share the load evenly if there is no SoC differences amongst battery modules. When the SoC differences reach predefined values stated in the 2D lookup table, the power sharing ratio is adjusted again as seen at the time instants of 2500 s and 3000 s as seen in Fig. 7(c).

With the adaptive power sharing method, the voltage difference is kept high at light load even with lower SoC differences, hence the light load system efficiency, and balancing speed, is improved. The upper limit of the voltage at the series connected side is decided by the voltage rating of the converter. As shown in Fig. 8, the light load efficiency is improved with the adaptive power sharing method irrespective of the level of mismatch amongst the battery modules. Besides achieving higher efficiency at any SoC difference, faster balancing is also obtained at light load due to higher power differences (Fig.7(c)). Therefore, more energy is balanced at light load compared to the SoC based power sharing method.

Fig. 7. Adaptive Power Sharing Method with different battery discharge power (a) Voltages at the series connected side, (b) State of charge of each module, (c) Differences between modules' voltages and voltage at equal power sharing, (d) Differences between modules' SoC and average SoC

Fig. 8. Comparison of System Efficiency with SoC based Controller and Adaptive Controller

4 Conclusion

In this paper, the performance of a SoC based power sharing control method is investigated at different battery loads. Although, the method shows good performance in balancing speed at heavy load, the system efficiency reduces with higher power sharing. On the other hand, higher power differences amongst the modules leads to increased efficiency at light load, but the DC bus side voltage difference, and the balancing speed, may be reduced due to the low SoC difference. By considering the variable battery charge/discharge power, an adaptive power sharing controller for MBESS is proposed which considers both the status of the battery modules, and the battery charge/discharge current. Compared to the SoC based power sharing method, faster balancing is obtained at light loads with improved light load efficiency regardless of the level of the SoC difference amongst the modules. The efficiency degradation is also reduced at heavy loads but at the expense of reduced speed of balancing.

5 References

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