

A Self-Reconfiguration Control Regarding Recovery Effect to Improve the Discharge Efficiency in the Distributed Battery Energy Storage System*

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Abstract—The battery energy storage system in the MicroGrid tends to be distributed in the future, to solve the voltage sharing and overcharge/overdischarge problem, achieve high compatibility and reliability, etc. Based on the distributed architecture, this paper proposes a self-reconfiguration discharge strategy regarding the battery recovery effect to further enhance the battery performance and discharge efficiency of the battery energy storage system. The specific control strategy and principle analysis is presented in details, and the experimental result has verified the proposed concept.

Index Terms: battery management system (BMS), energy storage, battery recovery effect, self-reconfiguration.

I. INTRODUCTION

The MicroGrid has two main forms, AC MicroGrid (ACMG) and DC MicroGrid (DCMG) [1]-[2]. Fig.1 shows a MicroGrid in a future home based on a DC bus. The DC bus is connected to the source as well as the load. The energy storage system is of great importance in the MicroGrid. It not only guarantees the stability, but also increases the power efficiency of the system [3]-[4]. The energy storage devices mainly include the battery, the super capacitor, the high-speed flywheel and the superconducting magnetic energy storage (SMES) etc [5]. The storage battery attains a promising application due to high power density, flexibility and so on.

In order to solve the disadvantages existed in the centralized battery energy storage system (BESS), nowadays the BESS tends to be miniaturized and distributed [6]. A Micro-Bank Module (MBM), which consists of a micro-bidirectional DC/DC converter, a micro-BMS and a cell bank, is showed in Fig.2 (a). Several MBMs can be connected in parallel to increase the power level. Fig.2 (b) shows the distributed parallel architecture of the BESS. The benefits of the distributed architecture include 1) no voltage sharing problem and no overcharge/overdischarge problem; 2) high compatibility and reliability 3) high energy storage utilization; 4) better space utilization; 5) reduced volume and weight of the BMS.

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In order to improve the energy storage utilization, this paper proposes a self-reconfiguration control strategy to improve the battery performance significantly taking advantage of the battery recovery effect. With the proposed control strategy, the capacity of each battery in the BESS can be fully utilized. Hence, high energy storage utilization can be achieved.

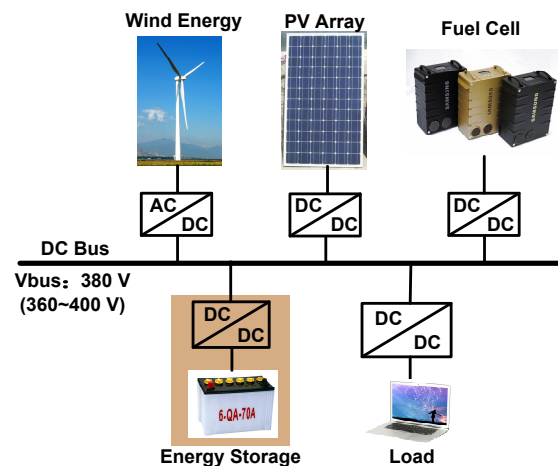


Fig.1 The Microgrid based on the DC bus

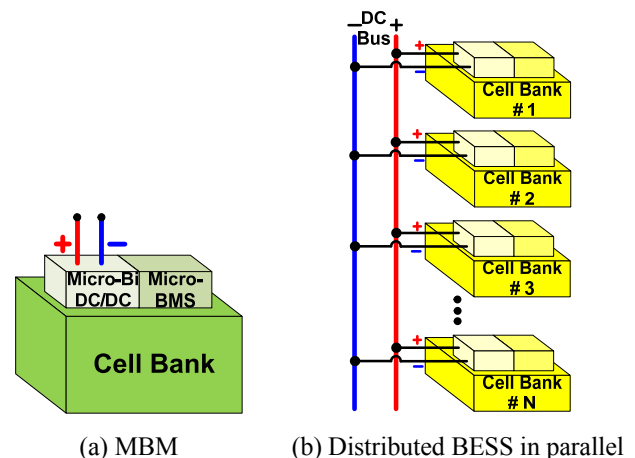


Fig.2 Distributed BESS in parallel

II. PROPOSED SELF-RECONFIGURATION CONTROL BASED ON BATTERY RECOVERY EFFECT

A. Battery Recovery Effect

The Most commercial batteries are governed by the complex non-linear internal chemical reactions to provide energy [7]-[8]. It is interesting to note that when the battery idles during some period without discharging, the diffusion process compensates for the depletion of the active materials during discharge and battery output voltage increases [9]-[10]. That is the non-linear discharge characteristic obtained by most batteries—the recovery effect, that is, the deliverable energy in a battery can be self-replenished, if left idling for sufficient time.

B. Proposed Self-Reconfiguration Control Strategy

The battery recovery effect opens up the possibility of the battery scheduling in the multiple-battery systems. The main idea here is to use multiple batteries in an interleaved fashion to prolong the combined battery life. In the proposed architecture, the battery banks are controlled by the local Micro DC/DC converters independently. So the self-reconfiguration strategy, which is to reconfigure the composite structure of multiple cell banks automatically according to the dynamic load/storage demand [11]-[12], is proposed to increase the energy utilization of the storage system.

Fig.3 shows the block diagram of the proposed control. Based on the information of the battery bank, etc. the voltage, current, the Micro-BMS can estimate the SOC of each battery bank from (1):

$$SOC_t = SOC_0 - \frac{1}{C_N} \int_0^t i(\tau) d\tau \quad (1)$$

where SOC0 is the initial SOC and is determined by the open circuit voltage of the battery bank, $i(\tau)$ is the discharge current and C_N is the rated capacity.

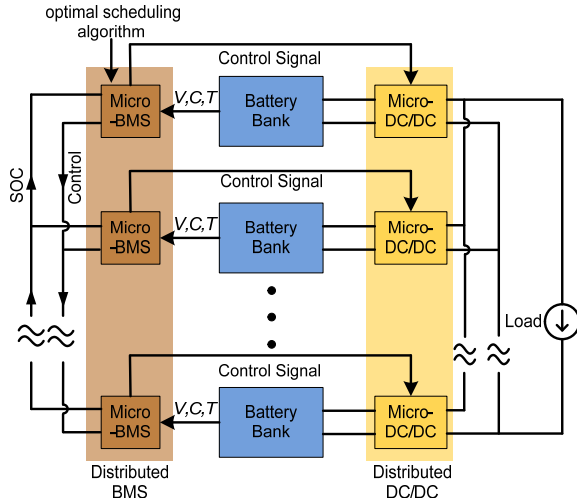


Fig.3 Block diagram of proposed self-reconfiguration control

Seen from Fig.4, with the optimal scheduling algorithm of the self-reconfiguration discharge strategy, the SOC of each battery bank is calculated real time. Then, the SOC

information of each bank is shared by the Micro-BMS. The obtained PWM control signals communicate between the local Micro-BMS and DC/DC converter. The optimal scheduling algorithm is shown in Fig.6. Initially, the range of the operation SOC is set. Firstly, the banks that meet the range of the operation SOC are determined and sorted in a descending order in terms of their average SOC. Then, the first ranking N banks are selected to discharge based on the load demand. This reconfiguration can be performed with a constant time interval T , for example, $T=10$ minutes. If the discharge current increases, the value of T reduces. With the proposed scheduling algorithm, the energy efficiency and the lifespan of the battery banks can be improved significantly.

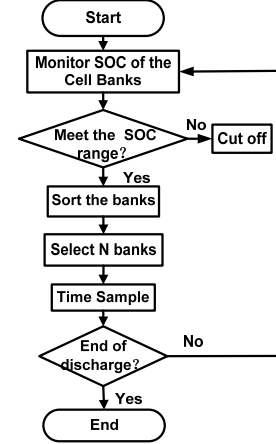


Fig.4 Flow chat of proposed Algorithm

C. The stability analysis of the proposed system

Basically, there are two types of converters in the distributed power system (DPS), one controls the bus voltage and the other controls the bus current. Though each converter in the system is well designed based on the stand-alone operation with sufficient stability, the stability is still a big potential issue in the system level due to the complex interaction among the converters [13]. The popular stability analysis method in DC DPS is based on the impedance criteria from (2) [14]-[15]:

$$T_{m_system} = \frac{Z_{v_bus}(s)}{Z_{i_bus}(s)} = \left(\sum_{j=1}^m Z_{v_busj}(s) \right) / \left[\sum_{k=1}^n Z_{i_busj}(s) \right]^{-1} \quad (2)$$

$Z_{v_bus}(s)$ is the sum of bus port impedance of the converter which controls the bus voltage, and $Z_{i_bus}(s)$ is the sum of bus port impedance of the converter which controls the bus current. T_{m_system} is the equivalent loop gain of the system, if T_{m_system} meets the Nyquist criteria, the system is stable. In order to simplify this question, the electronic load is implemented in the proposed system in this paper and set to the constant voltage mode to model a voltage source which can control the bus voltage, and the DC/DC converters are controlled with single current loop to control the bus current. The output impedance of the ideal constant voltage source is zero. So the $Z_{v_bus}(s)$ in this system is approximately zero, and the T_{m_system} can always meet the Nyquist criteria. So the testing system in this paper ensures the stability.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

In order to verify the proposed self-reconfiguration control, the hardware platform has been built. Fig.5 shows the photo of the hardware platform. The system consists of four MBMs, which can provide a maximum power of 500 W respectively. With the proposed control, three MBMs are always active while one is idling. The system can provide a maximum power of 1500 W. The lithium battery module of 12 V/ 100 Ah from Pylon Technologies is chosen as the battery bank, and four battery banks are utilized.

The photo of prototype of 500 W MBM is illustrated in Fig.6. The ZVS Dual Active Bridge (DAB) converter is used as the Micro-Bi DC-DC converter. The Freescale DSP MC56F8257 is used as the Micro-BMS to implement the proposed control strategy. The specifications are as follows: battery voltage: $V_{bat}=10.8\sim 13.8$ V; bus voltage: $V_{bus}=360\sim 400$ V; output power: $P_o=500$ W; switching frequency: $f_s=250\sim 500$ kHz. The component of the power train are as follows: the transformer turns ratio: $n=1:16$; total inductance $L_r=30$ μ H; LV side MOSFETs $Q_1\sim Q_4$: BSC014N03LS (30 V/100 A/1.4 m Ω from Infineon); HV side MOSFETs $Q_5\sim Q_8$: IPP65R380E6 (650 V/ 10.6 A/ 0.38 Ω from Infineon). A hall-effect sensor BJHCS-PS25 is used to sample the LV side current and a hall-effect-based linear current sensor IC ACS712ELCTR-05B-T is used to sense the HV side current. Two isolation amplifiers HCPL-7840 are used to sample the LV and HV side voltage respectively.

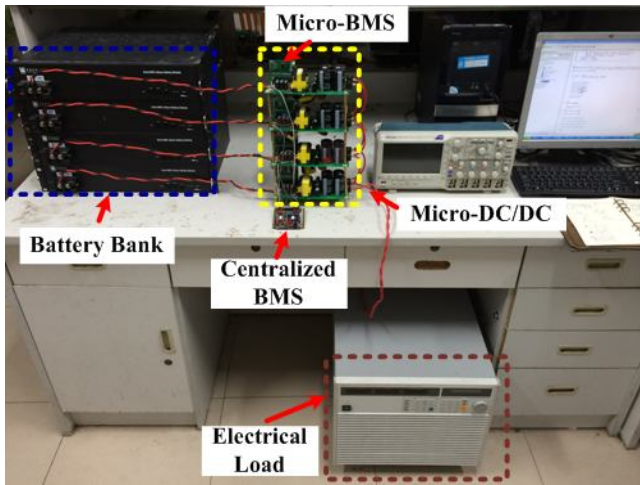


Fig.5 Photo of experimental testing platform

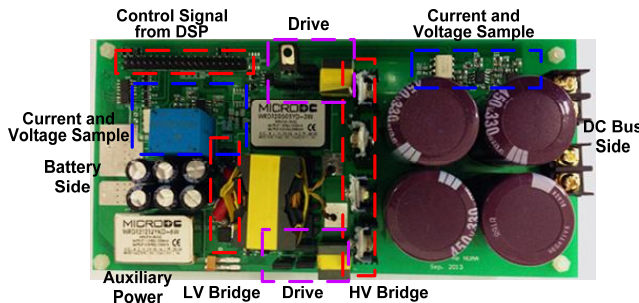
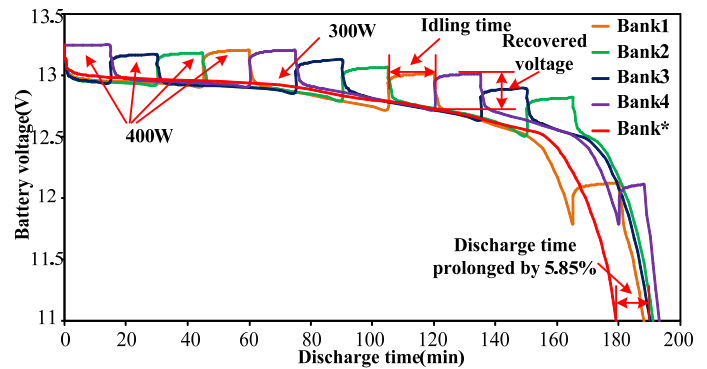


Fig.6 Photo of prototype: DAB

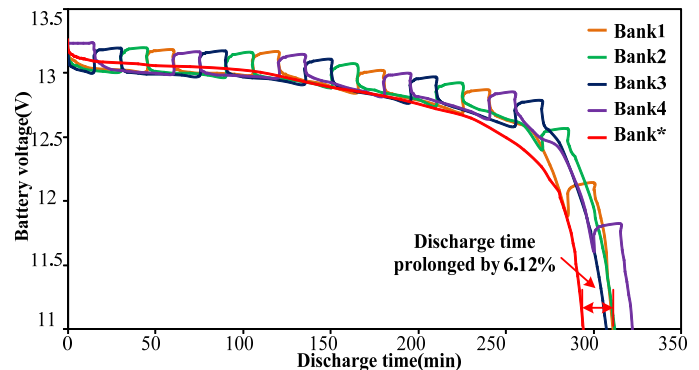
A. The same idling time with the different power level

In the test, the distributed BESS consists of four MBMs. With the proposed self-reconfiguration control strategy, three MBMs are active to provide the output power while one stands by. In order to verify the proposed control strategy in a wide load range, the power level of the BESS is set to be 750W, 900W, 1200W and 1500W, corresponding to half load, 60% load, 80% load and full load of each active MBM in the system with the proposed control. The idling time is 15min.

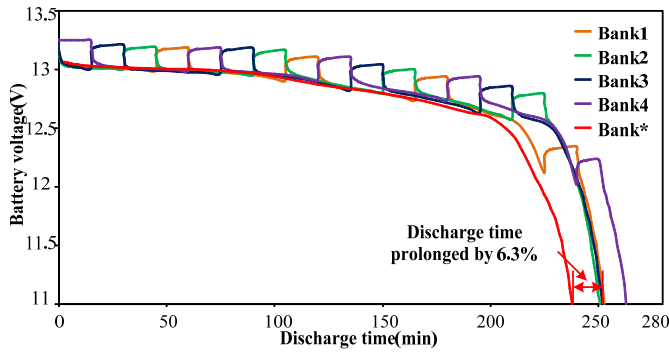
Fig.7 (a) shows the discharge curves of the MBM with and without the proposed self-reconfiguration control in the distributed BESS with a power level of 1200W. In the distributed BESS with the conventional control, all of the four MBMs are active, and provide the power of 300W. So the discharge time of the system is determined by the MBM which reaches the voltage threshold first, as the red curve shown in Fig.7 (a). The left four curves represent the discharge curve of the four MBMs in the distributed BESS with the proposed self-reconfiguration control. While with the proposed control, three MBMs need to be active all the time, so the discharge time of the system is determined when two MBMs reach the threshold voltage. Then, the improved discharge time can be calculated. The idling time is for the battery to take the recovery process. It is observed that the voltage of the battery increases during the idling time, which demonstrates that the capacity of the battery can be increased owing to the battery recovery effect. As a result, the discharge time of the BESS is extended. Fig.7 (b) - Fig.7 (d) shows the similar situation with different power level of 750W, 900W and 1500W respectively.



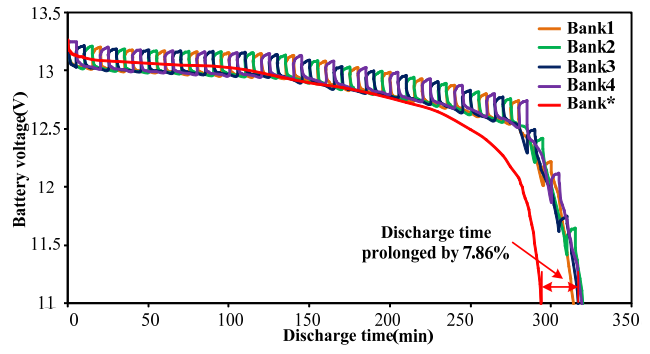
(a) 1200 W



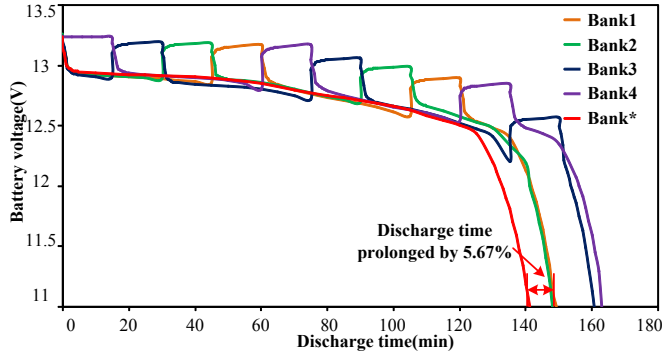
(b) 750 W



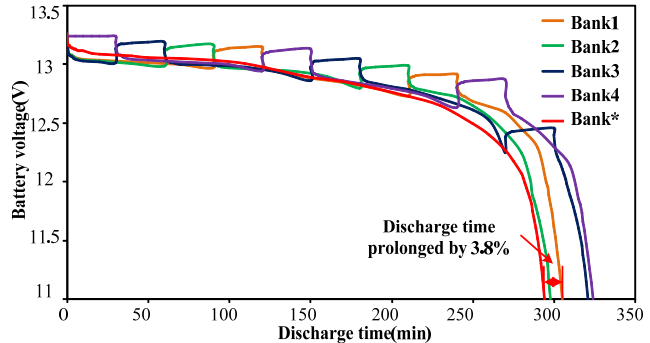
(c) 900 W



(a) 5 min



(d) 1500 W



(b) 30 min

Fig.7 Discharge curves of the MBM with different power level

Fig.8 Discharge curves with different idling time under the power level of 750 W

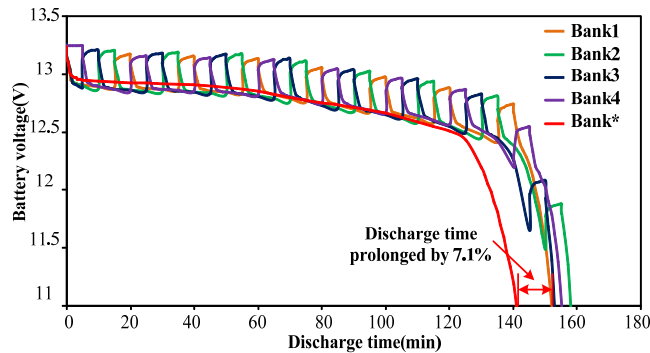
Table I summarizes the measured discharge time of the BESS with and without the proposed self-reconfiguration control. The discharge time of the BESS is increased by 6.12%, 6.3%, 5.85% and 5.67%, corresponding to the power level of 750 W, 900 W, 1200 W and 1500 W. It is observed that the increased energy decreases slightly as the discharge current increases. So, it is concluded that the discharge current has limited influence on the effectiveness of the proposed control.

Table I Measured discharge time of the distributed BESS with the idling time of 15 min

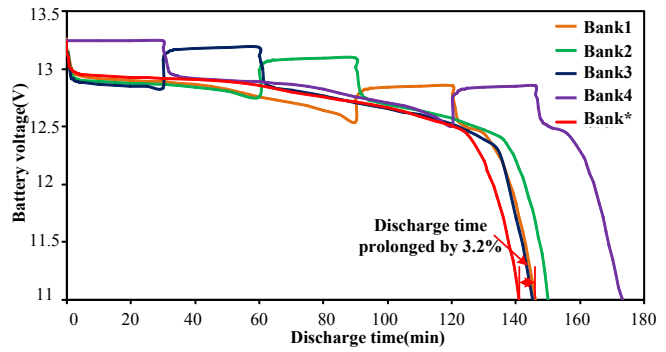
Power level (W)	Conventional (min)	Proposed (min)	Improved efficiency
750	294	312	6.12%
900	238	253	6.3%
1200	179.5	190	5.85%
1500	141	149	5.67%

B. Different idling time with the same power level

In order to investigate the impact of different idling time on the effectiveness of the proposed self-reconfiguration control under the same power level, the idling time is set to be 5 min, 15 min and 30 min respectively. The power level of 750 W and 1500 W are chosen to make a sharp comparison. Fig.8-Fig.9 shows the discharge curve of the MBM under different discharge condition.



(a) 5 min



(b) 30 min

Fig.9 Discharge curves with different idling time under the power level of 1500 W

Table II summarizes the measured energy improvement efficiency of the BESS under different discharge situation. It can be seen that the shorter idling time, higher efficiency can be achieved for both 750 W and 1500 W.

Table II Increased energy with different idling time

Power level	30 min	15 min	5 min
750 W	3.80%	6.12%	7.86%
1500 W	3.20%	5.67%	7.1%

It is shown that the energy improvement efficiency decreases significantly as the idling time increases. Therefore, a shorter idling time is preferred to realize the proposed control and improve the recovery energy efficiency. However, if the idling time is too small, it reduces the power conversion efficiency of the DC-DC converters during the re-configuration progress. Therefore, there exists an optimal idling time for the proposed self-reconfiguration control.

As a conclusion, the effectiveness of the proposed control mainly depends on the idling time, and is nearly influenced by the discharge current. A shorter idling time is more favorable to realize the proposed control and there exists optimal idling time in the design.

IV. CONCLUSION

To overcome drawbacks of the centralized BESS, a new distributed architecture of BESS based on the MBMs is proposed. The MBM consists of a micro-bidirectional DC/DC converter, a micro-BMS and a cell bank. Moreover, a self-reconfiguration control strategy based on the battery recovery effect is proposed in this paper to further improve the discharge efficiency in the distributed BESS. An experimental testing platform of 1.5 kW consisting of four MBMs and four 12 V/ 100 Ah lithium battery modules was built to verify the proposed architecture and control. The experimental results verified the effectiveness of the proposed control strategy. With the idling time of 15min, the discharge efficiency is improved by 5.67% under the power level of 1500 W. Similarly, the discharge efficiency is improved by 7.1% and 3.2% under different idling time of 5 min and 30 min with the power level of 1500 W respectively. The effectiveness of the proposed self-reconfiguration control mainly depends on the idling time, and is nearly influenced by the discharge current. A shorter idling time is more favorable to realize the proposed self-reconfiguration control and there exists optimal idling time in the design.

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