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Battery Fault Tolerance of Modular Multilevel Converter-Based Battery Energy Storage Systems with Redundant Submodules

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Abstract—In a modular multilevel converter (MMC) based battery energy storage system (BESS), a fault tolerant design ensures uninterrupted operation of the MMC when a given number of submodules (SMs) have faulty batteries or no batteries. This paper quantitatively investigates the fault tolerance improvement in MMC-based BESSs with different numbers of redundant SMs, which is commonly practiced to improve the fault tolerance in modular converter topologies. Simulation results are obtained to verify the proposed analysis. The presented analysis provides guidelines for designers to choose an appropriate number of redundant SMs to achieve a desired fault tolerance.

Index Terms—Battery energy storage system (BESS), fault tolerance, modular multilevel converter (MMC), redundancy.

I. INTRODUCTION

Due to the increase of renewable energy generation, grid-connected battery energy storage systems (BESSs) are important components to the power system infrastructure. The integration of batteries to the grid requires power electronic converters as the interface, among which the modular multilevel converter (MMC) is considered as a popular candidate, especially for medium-/high-voltage applications that require a dc-terminal [1]. Compared to the conventional two-level converters, the MMC provides evident advantages, such as modularity, better harmonic performance, and lower switching frequency [2].

Fig. 1(a) depicts the circuit diagram of one phase of the MMC-based BESS, which consists of two arms and each arm has multiple cascaded submodules (SMs). The SMs can be either half-bridge SMs, as in Fig. 1(b), or full-bridge SMs, as in Fig. 1(c). The output voltage of a half-bridge SM (v_{SMun} in Fig. 1(b)) is either zero or $+V_C$, where V_C represents the capacitor voltage of one SM. The output voltage of a full-bridge SM can be $+V_C$, zero or $-V_C$. Since the half-bridge SM has fewer components and lower power losses, it is more commonly used [3].

When the MMC is used to connect batteries to the grid, it is preferred to integrate the battery units into the SMs instead of the dc-link of the MMC. Integrating the batteries

Fig. 1. Circuit diagram of the MMC: (a) A single phase system, (b) a half-bridge SM, and (c) a full-bridge SM.

Fig. 2. Connecting the batteries to a SM: (a) directly, and (b) through a dc-dc converter.

into the dc-link of the MMC involves a long string of series-connected batteries, whose charging and discharging will be limited by the weakest unit [4]. Moreover, integrating the battery units into the SMs provides higher flexibility for the battery management, e.g., state of charge (SoC) balance [5]. Battery units can be directly connected to the dc-link of the SM or through a dc-dc converter, as depicted in Figs. 2(a) and (b), respectively. Faulty batteries can be disconnected from the SM through the switch.

For the MMC-based BESS, it is important to have certain battery fault tolerance, which means the system should be able to provide the required power even when the batteries of

some SMs are faulty and disconnected. When the batteries are faulty/disconnected, the corresponding SMs can still operate, providing reactive power that supports the operation of the converter. However, the active power of the SMs with faulty batteries must be zero in the steady state to prevent their capacitor voltages from diverging. In other words, the total active power must be shared among the SMs with healthy batteries.

Since there are limits on the active power that can be processed by a certain number of SMs in each arm [6], [7], the remaining SMs may fail to meet the active power requirement if the batteries of too many SMs become faulty. There have been some investigations on the battery fault tolerance of the MMC-based BESSs. In [8], [9], the authors investigated the minimum percentage of SMs per arm that need to have healthy batteries to provide a required active power demand. In [10], [11], the authors tested whether the MMC-based BESS can provide a required active power with batteries of different percentages of SMs disconnected.

However, the investigations in [8]–[11] did not consider the use of redundant SMs, which are commonly employed in MMCs to aid operation during SM failures [12]. In an MMC-based BESS, the redundant SMs can also improve the battery fault tolerance, which has never been investigated. Indeed, if the redundant SMs are integrated with batteries, the improvement of battery fault tolerance is evident as those SMs with faulty batteries can be replaced with redundant SMs. However, even if the redundant SMs are not integrated with batteries, they can still improve the battery fault tolerance. Similar to the SMs with faulty batteries, the redundant SMs can contribute to the output voltage and reactive power, which provides more flexibility to operate the SMs with healthy batteries.

This paper investigates the improvement of battery fault tolerance of the MMC-based BESS when redundant SMs are implemented. The redundant SMs are not integrated with batteries, to reduce the implementation cost and volume. For the sake of simplicity, the analysis is presented for the MMC with half-bridge SMs only. Nevertheless, without losing the generality, a similar analysis can be applied to the MMC with full-bridge SMs.

The remainder of this paper is organized as follows. Section II introduces the operating principle and modeling of the MMC. Section III investigates the battery fault tolerance of MMC-based BESSs with different numbers of redundant SMs. To verify the analysis, simulation results are provided in Section IV. Finally, Section V summarises the main conclusions of the paper.

II. OPERATION OF THE MMC

This section briefly reviews the operating principle and modeling of the MMC [13].

Denoting the dc-link voltage of the MMC as V_{dc} , the output voltage and current of the MMC correspond to

$$v_o(t) = \frac{V_{dc}}{2} m_a \cos(\omega t), \quad i_o(t) = \hat{I} \cos(\omega t + \varphi), \quad (1)$$

where m_a denotes the modulation index ($m_a \in [0, 1]$), ω refers to the angular frequency, and φ defines the phase shift between the output voltage and current. Accordingly, the voltages and currents of the upper and lower arms are:

$$v_u = \frac{V_{dc}}{2} - v_o, \quad i_u = I_{dc} + \frac{i_o}{2}, \quad (2)$$

$$v_l = -\frac{V_{dc}}{2} + v_o, \quad i_l = I_{dc} - \frac{i_o}{2}, \quad (3)$$

where I_{dc} denotes the dc-link current of the MMC. The subscripts u and l denote the upper and lower arms, respectively.

From (1)–(3), it can be concluded that the maximum voltage reference of one arm of the MMC is V_{dc} . Hence, representing the reference capacitor voltage per SM as V_C , the necessary number of SMs per arm is

$$N = \frac{V_{dc}}{V_C}. \quad (4)$$

Since some SMs may become faulty, each arm is normally equipped with more than N SMs to provide certain degree of SM fault tolerance, where the extra SMs are the so-called redundant SMs [12]. If one arm has r redundant SMs, the ratio of redundancy can be represented as

$$R = \frac{r}{N} \times 100\%. \quad (5)$$

III. BATTERY FAULT TOLERANCE WITH REDUNDANT SUBMODULES

When the batteries of SMs fail, those SMs can still process reactive power, while the active power has to be shared by the SMs with healthy batteries. Therefore, the battery fault tolerance of the MMC-based BESS depends on the active power capacity of the SMs with healthy batteries. This section first investigates the active power capability of the SMs with healthy batteries when redundant SMs are integrated, followed by the discussion on battery fault tolerance of the MMC with different numbers of redundant SMs.

A. Active Power Limits of the SMs

The active power of n SMs ($n \in [1, N + r]$) in one arm is calculated as:

$$\bar{P}^n = \frac{1}{T} \int_{t_0}^{t_0+T} v^n(t) i_{arm}(t) dt, \quad (6)$$

where a positive $\bar{P}^n$ indicates charging while a negative $\bar{P}^n$ indicates discharging of the batteries. T defines the fundamental period of the output voltage, v^n denotes the instantaneous output voltage of n SMs, and i_{arm} refers to the arm current, which can be either the upper or lower arm current in (2) and (3). A positive i_{arm} will charge the inserted SMs while a

negative i_{arm} will discharge the inserted SMs. Therefore, to obtain the maximum power that can be processed by n SMs, their output voltage must be maximum (represented as v_{max}^n) when the arm current is positive and minimum (represented as v_{min}^n) when the arm current is negative. Thus, the maximum active power is calculated as

$$\bar{P}_{max}^n = \frac{1}{T} \int_{t_0}^{t_0+T} v_{max}^n(t) i_{arm}(t) dt,$$

$$v_{max}^n(t) = \begin{cases} v_{max}^n(t) & \text{if } i_{arm}(t) \geq 0; \\ v_{min}^n(t) & \text{if } i_{arm}(t) < 0. \end{cases} \quad (7)$$

Similarly, to obtain the minimum active power, the output voltage of n SMs must be minimum when the arm current is positive and maximum when the arm current is negative. Thus, the minimum active power is calculated as

$$\bar{P}_{min}^n = \frac{1}{T} \int_{t_0}^{t_0+T} v_{min}^n(t) i_{arm}(t) dt,$$

$$v_{min}^n(t) = \begin{cases} v_{min}^n(t), & i_{arm}(t) \geq 0; \\ v_{max}^n(t), & i_{arm}(t) < 0. \end{cases} \quad (8)$$

The maximum and minimum output voltages of n SMs correspond to [14]:

$$v_{max}^n = \min[nV_C, v_{arm}], \quad (9)$$

$$v_{min}^n = \max[0, v_{arm} - MV_C], \quad (10)$$

where v_{arm} refers to the arm voltage, which can be either the upper or lower arm voltage in (2) and (3), and M represents the total number of SMs in this arm. Hence, considering N necessary SMs and r redundant SMs, (10) can be rewritten as

$$v_{min}^n = \max[0, v_{arm} - (N + r)V_C]. \quad (11)$$

According to (9) and (11), the presence of redundant SMs does not affect v_{max}^n but it does affect v_{min}^n . More specifically, v_{min}^n can be lower with redundant SMs, which means that the output voltage range is extended. Fig. 3 depicts the output voltage ranges of n SMs in one fundamental period. Fig. 3(a) displays the maximum and minimum output voltages of n SMs when no redundant SMs are employed, i.e., $r = 0$. The output voltage range is represented with the shaded region between v_{max}^n and v_{min}^n . Similarly, Fig. 3(b) depicts the output voltage range with r redundant SMs and Fig. 3(c) compares the two ranges. The shaded region in Fig. 3(c) represents the extended range when redundant SMs are implemented. As observed, with redundant SMs, the output voltage of n SMs can be lower between t_1 and t_4 , specifically, the minimum output voltage can be reduced by rV_C between t_2 and t_3 .

The extended output voltage range enables the SMs with healthy batteries to absorb/provide more active power, according to (7) and (8). Thus, a reduced number of SMs will be required to absorb/provide the required arm power, which means an enhanced battery fault tolerance.

Fig. 3. Allowed output voltage ranges of n SMs in one arm: (a) Allowed range without redundant SMs, (b) allowed range with r redundant SMs, and (c) comparison of the two ranges.

B. Enhanced Battery Fault Tolerance

The battery fault tolerance of an MMC-based BESS is defined as

$$F = \frac{n_{max}}{N} \times 100\%, \quad (12)$$

where n_{max} refers to the maximum number of SMs with faulty batteries per arm that the BESS can tolerate. Note that the normalization factor for F is N since the redundant SMs are not integrated with batteries. The derivation of n_{max} (and F) can be discussed in two conditions, viz. with a charging arm power ($\bar{P}_{arm} > 0$) and with a discharging arm power ($\bar{P}_{arm} < 0$), where $\bar{P}_{arm}$ represents the active power requirement of the arm.

If $\bar{P}_{arm} > 0$, n_{max} is decided as:

$$n_{max} = n, (\bar{P}_{max}^{N-n} \geq \bar{P}_{arm}) \wedge (\bar{P}_{max}^{N-n-1} < \bar{P}_{arm}). \quad (13)$$

The rationale behind this expression is as follows. Since n_{max} is defined as the maximum number of SMs with faulty batteries that the BESS can tolerate, the remaining $(N - n_{max})$

TABLE I
BATTERY FAULT TOLERANCE OF THE MMC-BASED BESS WITHOUT
REDUNDANT SMS UNDER DIFFERENT CONDITIONS

Condition	Modulation Index, m_a	Phase Shift, φ	Battery Fault Tolerance F with $r = 0$
1	0.8	0	51.5%
2	0.8	30°	38.5%
3	0.9	0	50%
4	0.9	30°	34%

Fig. 4. Increase of the battery fault tolerance with different redundant SMs.

SMs should be able to absorb the required arm power. Hence, the maximum power limit of the $(N - n_{max})$ SMs should not be lower than the active power requirement of this arm, i.e. $(\bar{P}_{max}^{N-n_{max}} \geq \bar{P}_{arm})$, which leads to the left-hand-side of (13). Meanwhile, if the batteries fail in $(n_{max} + 1)$ SMs, the remaining $(N - n_{max} - 1)$ SMs will fail to absorb the required arm power. Thus, the maximum power limit of the $(N - n_{max} - 1)$ SMs should be lower than the active power requirement of this arm, i.e. $(\bar{P}_{max}^{N-n_{max}-1} < \bar{P}_{arm})$, which leads to the right-hand-side of (13).

Similarly, if $\bar{P}_{arm} > 0$, n_{max} is decided as:

$$n_{max} = n, (\bar{P}_{min}^{N-n} \leq \bar{P}_{arm}) \wedge (\bar{P}_{min}^{N-n-1} > \bar{P}_{arm}). \quad (14)$$

To assess the improvement of battery fault tolerance of the MMC-based BESS with redundant SMs, four different conditions are investigated, as depicted in Table I. In these scenarios, the amplitude of the dc-link current of the MMC is considered as 40% of the peak of the ac-side output current, i.e. $I_{dc} = 0.4\hat{I}$. The battery fault tolerance of the MMC-based BESS with no redundant SMs is also provided in Table I.

Fig. 4 depicts the increase of the battery fault tolerance with an increasing ratio of redundancy. As observed, in all conditions, the battery fault tolerance will increase with the ratio of redundancy, which indicates that the implementation of redundant SMs can improve the battery fault tolerance of the MMC-based BESS. Moreover, according to Fig. 4, the rate of increase of tolerance diminishes and reaches zero eventually beyond a certain ratio of redundancy. For example, in Condition 4, the tolerance increases by around 5% when 10% of redundant SMs are implemented, but it only increases by 8% when 20% of redundant SMs are implemented. Hence, it is not

TABLE II
PARAMETERS OF THE SYSTEMS

Parameter	MMC 1	MMC 2
Necessary number of SMs per arm, N	5	5
Number of redundant SMs per arm, r	0	1
Capacitor voltage reference, V_C	2.4 kV	2.4 kV
DC-side current, I_{dc}	0.4 kA	0.4 kA
DC-side voltage, V_{dc}	12 kV	12 kV
AC-side current (Peak), $\hat{I}$	1 kA	1 kA
AC-side voltage (Peak), $\hat{V}$	5.4 kV	5.4 kV
AC-side phase shift, φ	30°	30°
Fundamental frequency, f	50 Hz	50 Hz

advisable to implement a large number of redundant SMs to improve the battery fault tolerance. Note that in this paper, the redundant SMs are not integrated with batteries. If batteries are integrated into the redundant SMs, the improvement of battery fault tolerance will be more significant.

IV. SIMULATION VERIFICATION

To verify the proposed analysis, simulation results are obtained on two MMCs, whose parameters are provided in Table II. The first MMC has five SMs per arm, which are all integrated with batteries. The second MMC has five SMs with batteries and one redundant SM without batteries in each arm. The operation of the first and second MMCs corresponds to the Condition 4 with $R = 0\%$ and $R = 20\%$ in Fig. 4, respectively. Hence, the battery fault tolerances of the two MMCs are 34% and 42%, respectively, which indicates that the first MMC can tolerate battery faults on one SM only while the second MMC can tolerate battery faults on two SMs.

Simulation results on the first MMC are provided in Fig. 5. In Fig. 5(a), $\bar{P}_{SMi}$ and $\bar{P}_{SMi}^*$ represent the measured active power and the active power reference of the i^{th} SM, respectively, which are normalized to the active power of this arm. Waveforms of the fifth SM are omitted because they are similar to the waveforms of the fourth SM. In Fig. 5(b), v_{Ci} represents the capacitor voltage of the i^{th} SM. Initially, the power reference is 20% for each SM, which means each of them is charging with 20% of the arm power. As observed, each SM can track the corresponding power reference and the capacitor voltages are balanced.

At $t = 0.1$ s, the batteries of the first SM are disconnected and consequently, its active power reference ($\bar{P}_{SM1}^*$) becomes zero. The active power of this arm is redistributed among the remaining four SMs. As observed, each SM can still track the corresponding power reference and the capacitor voltages are regulated to the references, which means the MMC can tolerate a battery fault on one SM.

At $t = 0.4$ s, batteries of the second SM are also disconnected. Accordingly, the power references of the first and second SMs are set to zero, hence, the active power of this arm should be redistributed among the remaining three SMs

Fig. 5. Simulation results on the MMC without redundant SM: (a) Power references and measured active powers of the SMs, and (b) SM capacitor voltages.

with batteries. However, as observed in Fig. 5(a), some active power are transferred to the first and second SMs. As a result, the capacitor voltages of these two SMs increase continuously and diverge, which verifies that the MMC cannot tolerate the battery faults in two SMs.

Simulation results on the MMC with a redundant SM per arm are provided in Fig. 6, where Figs. 6(a) and (b) depict waveforms of the SM powers and capacitor voltages, respectively. The redundant SM is denoted as the sixth SM. Since the redundant SM is not integrated with batteries, its power reference ($\bar{P}_{SM6}^*$) is strictly zero. Similar to the previous simulation scenarios, batteries of the first and second SMs are disconnected at $t = 0.1$ s and $t = 0.4$ s, respectively. As observed in Fig. 6, the SMs can track their corresponding power references and the capacitor voltages are properly regulated, which indicates that this MMC can tolerate battery faults in two SMs.

The obtained simulation results verify that the battery fault tolerance of the MMC-based BESS can be enhanced by implementing redundant SMs without batteries.

V. CONCLUSION

This paper has investigated the battery fault tolerance of MMC-based BESSs with redundant SMs. According to the investigation, even though the redundant SMs are not integrated

Fig. 6. Simulation results on the MMC with redundant SMs: (a) Power references and measured active powers of the SMs, and (b) SM capacitor voltages.

with batteries, the battery fault tolerance can be improved. However, since the rate of improvement diminishes with the increase in the number of redundant SMs, it may not be worth to implement a large number of redundant SMs to reach a desired battery fault tolerance. Simulation results have verified the analysis and confirmed enhanced fault tolerance of BESSs with redundant SMs.

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