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Analysis of the Inter-Submodule Active Power Disparity Limits of Modular Multilevel Converter-Based Battery Energy Storage Systems

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Abstract—In operation of the modular multilevel converter (MMC)-based battery energy storage system (BESS), different submodules (SMs) may be required to provide a different amount of active power, which is defined as inter-SM active power disparity in this paper. This happens in various conditions, for example, when some SMs have faulty batteries and thus, cannot process any active power. This paper proposes a general analysis of the inter-SM active power disparity limits of the modular multilevel converter-based battery energy storage systems. An analytical method is provided to derive the maximum/minimum power that any subset of SMs in one arm can provide. Based on the derived results, the active power limits of SMs are nonlinear with the number of SMs. Both simulation and experimental results are provided, which verify the proposed analysis and method. The proposed analysis facilitates the design and operation of the MMC-based BESSs.

Index Terms—Active power disparity, battery energy storage system (BESS), modular multilevel converter (MMC).

I. INTRODUCTION

Modular multilevel converter (MMC)-based battery energy storage systems (BESSs) are one of the promising solutions for the future power system, due to the intermittent nature of renewable energy resources [1], [2]. In the design and operation of an MMC-based BESS, uneven active power distribution among SMs is required in various conditions, such as 1) when batteries are only integrated into some of the SMs for each arm [3], 2) when the state of charge of batteries are unbalanced [4], 3) some SMs may have faulty batteries which cannot provide active power, etc. This uneven active power distribution among the SMs of an arm is referred to as inter-SM active power disparity in this paper.

When inter-SM active power disparity is required, it is necessary to know how uneven the power distribution can be, i.e. the inter-SM active power disparity limits. Without the knowledge of the inter-SM active power disparity limits, the controller of the system may set the power references of certain SMs beyond their limits, which means those SMs

cannot track their power references. Furthermore, knowing the inter-SM active power disparity limits is helpful to improve the design and implementation of the MMC-based BESS, like the design of a system with various battery chemistries or a system with partially integrated batteries (batteries are integrated into some SMs only). So far, only two special cases of this inter-SM active power disparity problem are discussed in the available literature while a general analysis is still lacked.

The first case calculates the minimum percentage of SMs in one arm that should be equipped with batteries of each arm, to provide the required active power [3], [5]–[7]. A numerical solution is given in [5] by testing whether one arm of the MMC-based BESS can provide the required active and reactive power when a certain percentage of SMs have faulty batteries, which means those SMs cannot process any active power. Based on the provided results, the system can meet all the power requirements when more than 67% of SMs can process active power. This means, the system can operate normally even when 33% of SMs in one arm are not integrated with batteries. In [3], a numerical and an analytical algorithm are proposed for an MMC respectively, where batteries are integrated into some SMs per arm to reduce the investment cost. To simplify the analysis, the numerical method assumes a certain number of bipolar SMs and redundant SMs without batteries per arm, which increases the construction cost. The numerical method does not have this assumption and is more accurate. However, numerical methods are computationally intensive. A graphical method is proposed in [6], with the assumption that the output voltage of each SM contains a dc component and a fundamental ac component only. However, to maximize/minimize the active power, the output voltage of one SM may contain ac components of different frequencies. For example, to achieve the maximum average active power, one SM should output its maximum voltage when the arm current is positive while output its minimum voltage when the arm current is negative. An analytical method is proposed

in [7], which assumes the SM output voltage as the average SM output voltage plus/minus a constant value, depending on the current direction and SM structure. In other words, an extra constraint is imposed on the output voltage of each SM. Both of the above-mentioned assumptions in [6] and [7] unnecessarily limit the SM output voltages, which results in underestimation of the system's ability to deal with active power disparity.

The second case analyzes the maximum difference between the power of one specific SM and the average power of all the SMs in that arm [8]. With the provided analysis, it is feasible to derive the active power limits of one SM in that arm. Similar to the analysis in [6], the SM output voltage is assumed to be a superposition of a dc component and a fundamental ac component. Furthermore, the proposed analysis does not consider the active power limits of multiple SMs. The active power limit of multiple SMs may not be a multiple of the limit of one SM. For example, under some operational conditions, the maximum active power of two SMs is less than twice of the maximum active power of one SM. This will be further illustrated in this paper.

To summarize, the above-mentioned papers consider specific cases of inter-SM active power disparity, instead of analyzing the general problem. Hence, the available analysis cannot answer some practical problems, like whether a specific unbalanced set of SM power references is viable for the system or not. A more general analysis is required to facilitate the design and operation of the MMC-based BESS. The main contribution of this paper is to propose a general analysis and an analytical method to derive the inter-SM active power disparity limits for the MMC-based BESS under various operation conditions. The proposed analysis facilitates the system to make full use of its ability to deal with the inter-SM active power disparity. The power disparity limits are represented as the maximum and minimum powers that a subset of SMs can provide. Based on the derived power limits, it is indicated that the quantitative change of the power limits is nonlinear with the change of the number of SMs. Both simulation and experimental results are provided to verify the proposed analysis and analytical method.

The remainder of this paper is organized as follows. Section II introduces the background of the MMC-based BESS. Section III analyzes the inter-SM active power disparity limits and proposes an analytical method to derive the limits. Based on the analytically derived results, the relationship between the power limits of SMs and the number of SMs is investigated. In Section IV, both simulation and experimental results are provided to verify the proposed analysis and method. Finally, Section V summarises the main conclusions from the paper.

II. MMC-BASED BESS

This section introduces the modeling of the MMC-based BESS and the implemented control schemes in this paper, which establishes the background for the subsequent analysis.

Fig. 1. Circuit diagram of a phase leg of an MMC-based BESS.

A. Modeling of an MMC-based BESS

The circuit diagram of a phase leg of an MMC-based BESS is illustrated in Fig. 1. The difference between a standard MMC and an MMC-based BESS lies in the embedded batteries. Batteries are integrated into SMs with an indirect active interface (IAI) [9], which provides voltage boosting capability. In addition to using the IAI, batteries can also be integrated into each SM directly. The system is connected to a dc terminal, whose voltage is denoted as V_{dc} . An optional dc current, denoted as I_{dc} , can be transferred from the dc terminal to the MMC, which exchanges active power between them. A phase leg of the MMC, shown in Fig. 1, consists of two arms with N identical series-connected SMs. Either half-bridge or full-bridge SMs can be used, although the depicted SMs in Fig. 1 are half-bridges. The reactor L inserted in the arm facilitates the control of the circulating current that flows through the arms of the phase leg. The two semiconductor switches S_{1ui} and $\bar{S}_{1ui}$, for $i = \{1, 2 \dots N\}$, operate in a complementary manner, producing a SM output voltage in the range $[0, v_{Cui}]$ or $[0, v_{Cli}]$ for the upper and lower arms, respectively. The variables v_{Cui} and v_{Cli} are the capacitor voltages of the i th SM in the upper and lower arms. For the sake of construction and operation of the system, capacitor voltages should be balanced and voltage ripples should be sufficiently suppressed [10], [11]. Assuming balanced capacitor

Fig. 2. The proposed sorting based SM power control algorithm in the upper arm.

voltages and negligible capacitor voltage ripples,

$$v_{Cui} = v_{Cli} = V_C = \frac{V_{dc}}{N}, \quad (1)$$

where V_C represents the average capacitor voltage. Assuming the voltage drop across the arm inductors is negligible, the upper and lower arm voltages (v_u and v_l) are:

$$v_u = \frac{V_{dc}}{2} - v_o; \quad v_l = \frac{V_{dc}}{2} + v_o, \quad (2)$$

where v_o refers to the output voltage of the MMC. The upper arm and lower arm currents (i_u and i_l) are:

$$i_u = \frac{i_o}{2} + i_{circ}; \quad i_l = \frac{i_o}{2} - i_{circ}, \quad (3)$$

where i_o and i_{circ} are the output current and circulating current of the converter, respectively.

B. Control Schemes

In the simulation and experiments of this paper, a circulating current controller described in [12] is implemented. The capacitor voltage balancing algorithm is unnecessary because the capacitor voltage is regulated by the batteries. SoC and SoH balancing controllers are omitted because they are not the main focus of this paper.

An additional control objective of the MMC-based BESS is to ensure that the active power of each SM tracks its reference. A sorting based SM power control algorithm is proposed and implemented in this paper, which is depicted in Fig. 2 for the upper arm. d_{SMui} and v_{SMui} represents the duty cycle and output voltage of the i th SM in the upper arm, respectively. A similar controller is applied to the lower arm. The moving average filter (MAF) computes the average active power of each SM in a fundamental period, $\bar{P}_{SMui}$. Then the error ΔP_{SMui} is derived by comparing $\bar{P}_{SMui}$ to the corresponding reference $\bar{P}_{SMui}^*$, i.e.

$$\Delta P_{SMui} = \bar{P}_{SMui}^* - \bar{P}_{SMui}. \quad (4)$$

With the knowledge of upper arm voltage reference v_u^* , upper arm current i_u and power error $\Delta \bar{P}_{SMui}$ of each SM, the sorting algorithm decides the output voltage reference for each SM, v_{SMui}^* , in such a way that: (1) if the current is positive (with the potential to charge inserted SMs), v_u^* will be distributed among SMs with highest ΔP_{SMui} as much as possible; (2) if the current is negative (with the potential to discharge inserted SMs), v_u^* will be distributed among SMs

with lowest ΔP_{SMui} as much as possible. For example, if there are five SMs in the upper arm and $v_{Cui} = 40$ V for all of them, when $v_u^* = 60$ V and i_u is positive, v_{SMui}^* of the SM with highest ΔP_{SMui} will be 40 V, v_{SMui}^* of the SM with second-highest ΔP_{SMui} will be 20 V and others will be zero. In the steady state, ΔP_{SMui} of all SMs will approach zero, which means $\bar{P}_{SMui}$ is equal to $\bar{P}_{SMui}^*$.

III. ANALYSIS OF THE INTER-SM ACTIVE POWER DISPARITY LIMITS

This section explains the proposed analysis of the inter-SM active power disparity limits and the analytical method to derive the limits. The proposed analysis hereinafter focuses on the upper arm of one phase of the MMC-based BESS but a similar analysis can be extrapolated to the other arms due to the symmetry. Furthermore, based on the derived limits, the relationship between the power limits of SMs and the number of SMs is investigated.

A. Derivation of the Inter-SM Active Power Disparity Limits

Representing the total active power of the upper arm as $\bar{P}_{armu}$, the sum of the active power of all SMs in this arm equals to $\bar{P}_{armu}$:

$$\bar{P}_{armu} = \sum_{i=1}^N \bar{P}_{SMui}, \quad (5)$$

where $\bar{P}_{SMui}$ represents the active power of the i th SM in the upper arm, as illustrated in Fig. 1. Naturally, there is a maximum and minimum limit on $\bar{P}_{SMui}$. More generally, there are maximum and minimum limits on the power that a subset of n SMs can provide ($n = [1, 2 \dots N]$), which are represented with $\bar{P}_{max}^n$ and $\bar{P}_{min}^n$, respectively. The power of a subset with n SMs is:

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

where T , $\bar{P}^n$ and v^n represent the fundamental period, average active power and instantaneous output voltage of this subset, respectively. Obviously, if v^n is at its maximum value (v_{max}^n) when i_u is positive and at its minimum value (v_{min}^n) when i_u is negative, the maximum power that this subset can provide ($\bar{P}_{max}^n$) is computed. The minimum power of this subset ($\bar{P}_{min}^n$) can also be derived in an opposite manner, i.e., v^n is at its minimum value (v_{min}^n) when i_u is positive and at its maximum value (v_{max}^n) when i_u is negative. Thus, $\bar{P}_{max}^n$ and $\bar{P}_{min}^n$ are:

$$\bar{P}_{max}^n = \frac{1}{T} \int_{t_0}^{t_0+T} v_{max}^n(t) i_u(t) dt, \quad (7)$$

$$\text{where } v_{max}^n(t) = \begin{cases} v_{max}^n(t) & i_u(t) \geq 0; \\ v_{min}^n(t) & i_u(t) < 0. \end{cases}$$

Fig. 3. The maximum and minimum output voltages of n SMs: (a) The maximum output voltage, and (b) the minimum output voltage.

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

$$\text{where } v_{minp}^n(t) = \begin{cases} v_{min}^n(t) & i_u(t) \geq 0; \\ v_{max}^n(t) & i_u(t) < 0. \end{cases} \quad (8)$$

The derived $\bar{P}_{max}^n$ and $\bar{P}_{min}^n$ imply the inter-SM active power disparity limits among one arm of the MMC-based BESS.

Considering unipolar SMs that can output positive voltage or zero only, intuitively $v_{max}^n = nV_C$ and $v_{min}^n = 0$. However, based on the operating point of the converter, there is one constraint on the output voltage of each SM. The summation of the output voltage of all the SMs in the upper arm should be equal to the voltage reference of this arm, as:

$$v_u^* = \sum_{i=1}^N v_{SMui}, \quad (9)$$

where v_u^* and v_{SMui} are the upper arm voltage reference and output voltage of the i th SM in the upper arm, respectively. Considering this limit, the allowed maximum and minimum output voltages of a subset of n SMs in a fundamental cycle are displayed in Fig. 3.

Fig. 3(a) depicts the maximum output voltage of n SMs in a fundamental cycle. During the interval $[t_1, t_2]$, where $v_u^*(t) \geq nV_C$, $v_{max}^n(t)$ is equal to nV_C as desired. However, during the intervals $[t_0, t_1]$ and $[t_2, t_3]$ when $v_u^*(t) < nV_C$, the allowed maximum output voltage v_{max}^n is reduced to v_u^* , to avoid the distortion of the output voltage. Similarly, Fig. 3(b) depicts the minimum output voltage of n SMs in a fundamental period. During the intervals $[t_0, t_1]$ and $[t_2, t_3]$, where $v_u^*(t) \leq (N-n)V_C$, the rest of $N-n$ SMs have sufficient capacity to generate v_u^* and thus, $v_{min}^n(t)$ is equal to 0. However, during the interval $[t_1, t_2]$, where $v_u^*(t) > (N-n)V_C$, the allowed minimum output voltage is

Fig. 4. The derived $\bar{P}_{max}^n$ and $\bar{P}_{min}^n$ of a subset of SMs in a specific case, with $R = \frac{n}{N}$.

increased to $v_u^* - (N-n)V_C$ (instead of the desired value of 0 V) because the rest of $N-n$ SMs do not have the sufficient capacity to generate v_u^* (the maximum output voltage of the rest $N-n$ SMs is $(N-n)V_C$). Consequently, $v_{max}^n(t)$ and $v_{min}^n(t)$ of n half-bridge SMs are obtained as:

$$v_{max}^n(t) = \min[nV_C, v_u(t)], \quad (10)$$

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

Hence, the maximum and minimum power limits of an arbitrary subset of SMs can be derived analytically with (7), (8), (10) and (11). It is worth to note that any active power distribution among SMs is viable for the system if and only if the sum of SM power reference of an arbitrary subset of SMs lies within the corresponding minimum and maximum limits.

B. Derived Limits of a Specific Case

In this paper, the output voltage, output current and the upper arm current are considered as:

$$v_o = m_a \frac{V_{dc}}{2} \cos(\omega t), \quad (12)$$

$$i_o = \hat{I}_o \cos(\omega t + \varphi), \quad (13)$$

$$i_u = I_{dc} + \frac{i_o}{2}, \quad (14)$$

where m_a , $\hat{I}_o$, ω , φ and I_{dc} denote the modulation index, amplitude of the output current, angular frequency, phase difference between the output current and voltage, dc input current, respectively. For the sake of easy reading, the power values hereinafter are all normalized based on $\bar{P}_{armu}$.

Fig. 4 provides the derived maximum and minimum limits of a subset with n SMs under a specific case, where R is proposed to represent the ratio of n versus N ($R = \frac{n}{N}$). The limits in Fig. 4 are derived when $m_a = 0.8$, $\varphi = 1.04$ (thus the power factor is 0.5) and $I_{dc}/I_o = 1/2$. Because the power values are normalized to $\bar{P}_{armu}$, the absolute values for V_{dc} , I_o and I_{dc} has no effect on the values of the derived $\bar{P}_{max}^n$ and $\bar{P}_{min}^n$.

TABLE I
PARAMETERS OF THE SIMULATED SYSTEM

Parameter	Value
DC terminal voltage, V_{dc}	200 V
DC input current, i_{dc}	10 A
Output current, I_o	20 A
Number of SMs per arm, N	5
SM capacitance, C_{ui} and C_{li}	5 mF
Capacitor voltage, v_{Cui} and v_{Cli}	40 V
Arm inductance, L	5 mH

Based on the results in Fig. 4, it is clearly indicated that the change of $\bar{P}_{max}^n/\bar{P}_{min}^n$ is nonlinear with n , which represents the number of SMs in that subset. For example, when $n = 0.2N$, $\bar{P}_{max}^n = 0.4451$, which means 20% of SMs in one arm can provide at most 44.51% of the total arm power. However, when $n = 0.4N$, $\bar{P}_{max}^n = 0.7120$ instead of twice of 0.4451, which means the maximum power limit of 40% of SMs is less than twice of the maximum power limit of 20% of SMs. The root cause of this nonlinear relationship between $\bar{P}_{max}^n$ ($\bar{P}_{min}^n$) and n is that the SM output voltages in one arm should sum up to the arm voltage reference, as indicated in (9). Hence, v_{max}^n (the allowed maximum output voltage of n SMs) can be saturated to v_u^* instead of nV_C , while v_{min}^n (the allowed minimum output voltage of n SMs) can be saturated to $v_u^* - (N - n)V_C$, as indicated in (10) and (11). If v_{max}^n is always nV_C and v_{min}^n is always 0, this nonlinear relationship will not exist.

Also, Fig. 4 indicates that $\bar{P}_{max}^n$ and $\bar{P}_{min}^{N-n}$ are complementary:

$$\bar{P}_{max}^n + \bar{P}_{min}^{N-n} = 1, \quad (15)$$

where 1 refers to the total arm power $\bar{P}_{armu}$ because both $\bar{P}_{max}^n$ and $\bar{P}_{min}^{N-n}$ are normalized based on $\bar{P}_{armu}$. For example, $\bar{P}_{max}^{0.2N}$ (0.4451) and $\bar{P}_{min}^{0.8N}$ (0.5546) sum up to 1 (small discrepancy occurs because of the truncation errors in the calculation of $\bar{P}_{max}^n$ and $\bar{P}_{min}^{N-n}$). The root cause of this complementary relationship of $\bar{P}_{max}^n$ and $\bar{P}_{min}^{N-n}$ is that the active power of all the SMs in one arm should sum up to the total arm power, as indicated in (5). Hence, when n SMs are providing their maximum power $\bar{P}_{max}^n$, the rest $N - n$ SMs must be providing their minimum power $\bar{P}_{min}^{N-n}$ and the summation of these two values is equal to $\bar{P}_{armu}$.

IV. SIMULATED AND EXPERIMENTAL RESULTS

In this section, both simulation and experimental results are provided to verify the proposed analysis.

A. Simulation Results

Simulation results are obtained on a single-phase MMC-based BESS with five SMs per arm. The parameters of the simulated system are provided in Table I. In this simulation, $m_a = 0.8$ and $\varphi = 1.04$. Thus, the derived limits in Subsection (III-B) and Fig. (4) are applicable to this simulated case.

Fig. 5. Simulation results: (a) Average active power waveforms of each SM and its reference, and (b) average active power waveforms of some subsets and their references.

Simulation results are provided in Fig. 5, where it is defined that $\bar{P}^n = \sum_{i=1}^n \bar{P}_{SMui}$ and $\bar{P}^{*n} = \sum_{i=1}^n \bar{P}_{SMui}^*$.

As one can see, before $t=0.2$ s, the SM power references are evenly set and each SM power $\bar{P}_{SMui}$ tracks the corresponding references $\bar{P}_{SMui}^*$. At $t=0.2$ s, the references become uneven but the sum of power for any subset of SMs lies between the corresponding $\bar{P}_{max}^n$ and $\bar{P}_{min}^n$ in Fig. (4). Thus, the references are viable and each $\bar{P}_{SMui}$ can track its reference.

At $t=0.6$ s, the power references of some SMs and subsets become beyond the corresponding derived limits and thus, the power distribution is unviable for the system. Instead of being able to track the new power references, the measured power of those SMs and subsets remains at the corresponding limits. For example, $\bar{P}_{SMu1}^*$ (0.60) is higher than the derived $\bar{P}_{max}^1$ (0.44) and thus, $\bar{P}_{SMu1}$ remains at $\bar{P}_{max}^1$, which is the best it can track the reference. Similarly, because $\bar{P}_{SMu5}^*$ (-0.10) is lower than the derived $\bar{P}_{min}^1$ (0.02), $\bar{P}_{SMu5}$ remains at $\bar{P}_{min}^1$. Considering the maximum and minimum power limits of one SM only, $\bar{P}_{SMu2}$, $\bar{P}_{SMu3}$ and $\bar{P}_{SMu4}$ should be able to track the corresponding reference because the references are between the derived $\bar{P}_{max}^1$ and $\bar{P}_{min}^1$. However, because the maximum power limit of 2 SMs is 0.71 and $\bar{P}_{SMu1}$ has already reached 0.44, $\bar{P}_{SMu2}$ can only reach 0.27, instead of being able to track $\bar{P}_{SMu2}^*$ (0.30). Similarly, because of $\bar{P}_{max}^3$ and $\bar{P}_{max}^4$, $\bar{P}_{SMu3}$ and $\bar{P}_{SMu4}$ cannot track the corresponding

TABLE II
PARAMETERS OF THE EXPERIMENTAL SETUP

Parameter	Value
DC terminal voltage, V_{dc}	150 V
Number of SMs per arm, N	2
SM capacitance, C_{ui} and C_{li}	5 mF
Capacitor voltage, v_{Cui} and v_{Cli}	75 V
Arm inductance, L	5 mH

Fig. 6. Picture of the experimental system.

references and remain at the recorded value. This interaction of power of different SMs is more clearly displayed in Fig. 5(b). As one can see, the recorded $\bar{P}^n$ remains at exactly the derived $\bar{P}_{max}^n$ for $n = [1, 2, 3, 4]$, because the power references are sorted in a descending order, i.e. $\bar{P}_{SMu1}^* > \bar{P}_{SMu2}^*$.

B. Experimental Results

Experimental results are obtained using a single-phase three-level MMC-based BESS, whose parameters are provided in Table II. No dc current is transferred from the dc terminal to the system and the circulating current is zero in the experiment. Batteries are directly connected in parallel with capacitors. In the experiments, the BESS works in discharging mode ($\varphi = 0$). Depending on the output power factor, it can also work in charging mode. It is worth noting that, in this specific case, $\bar{P}_{armu}$ is negative. Hence, the normalized value of $\bar{P}_{max}^1$ is smaller than the value of $\bar{P}_{min}^1$.

A picture of the setup is provided as Fig. 6. The Imperix B-Box RCP control platform is used to implement the proposed control strategy in the experimental setup. The MMC is built by the series connection of Imperix PEH 2015 full-bridge power modules, which are configured as half-bridge converters. Six series-connected RS 537-5488 lead-acid batteries are connected to the dc-side of each SM, while resistors are connected to the output as a load.

Experimental results are provided in Fig. 7, where $\bar{P}_{SMu1}^*$ and $\bar{P}_{SMu2}^*$ are set as 0% and 100%, respectively. Initially, the modulation index (m_a) is 0.7 and hence, the derived $\bar{P}_{max}^1$ and $\bar{P}_{min}^1$ are 9.01% and 90.99%, respectively. Since both of the power references are beyond the derived power limits, the power of these two SMs ($\bar{P}_{SMu1}$ and $\bar{P}_{SMu2}$) cannot track

Fig. 7. Experimental results: (a) The photo of the experimental setup, and (b) the experimental waveforms of $\bar{P}_{SMu1}$ and $\bar{P}_{SMu2}$.

the corresponding reference. Consequently, $\bar{P}_{SMu1}$ remains at the derived $\bar{P}_{max}^1$, while $\bar{P}_{SMu2}$ remains at the derived $\bar{P}_{min}^1$, as observed in Fig. 7. When $t = 0.04$ s, m_a changes to 0.8 and accordingly, the derived $\bar{P}_{max}^1$ and $\bar{P}_{min}^1$ change to 20.39% and 79.61%, respectively. Still, the power references are beyond the range of the derived power limits. Hence, $\bar{P}_{SMu1}$ and $\bar{P}_{SMu2}$ change to the changed $\bar{P}_{max}^1$ and $\bar{P}_{min}^1$, respectively. When $t = 0.22$ s, m_a changes to 0.9. Thus, the derived $\bar{P}_{max}^1$ and $\bar{P}_{min}^1$ change to 29.24% and 70.76%, respectively. $\bar{P}_{SMu1}$ and $\bar{P}_{SMu2}$ also change accordingly, as one can see.

V. CONCLUSION

This paper proposes an analysis of the inter-SM active power disparity limits for a general MMC-based BESS, which is helpful to improve the design and implementation of the MMC-based BESS. An analytical method is provided to derive the average active power limits of an arbitrary subset of SMs under any operational condition. With the proposed analysis, if the arm voltage, arm current, and capacitor voltages are known, the maximum and minimum active power limits of an arbitrary subset of SMs in this arm can be derived analytically. Based on the derived power limits, it is indicated that the maximum/minimum active power that multiple SMs can provide is nonlinear with the number of SMs. Both simulation and experimental results are obtained to verify the proposed analysis.

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