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PAPERS

T-shaped hybrid alternate arm converter with arm energy balancing control for battery energy storage systems

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Multilevel voltage source converters (VSCs), such as modular multilevel converter (MMC), cascaded H-Bridge (CHB) and alternate arm converter (AAC), are competent topologies for battery energy storage systems (BESSs) due to modularity, scalability and low harmonic distortion. However, there is a lack of studies about interfacing AAC with a BESS due to the arm energy balancing issue. Redundant sub-modules (SMs) are inserted passively into MMC, CHB and AAC to achieve high reliability; consequently, some of them are constantly idling, resulting in low SM utilization. We propose a novel topology - T-shaped hybrid alternate arm converter (TSHAAC) for BESS applications. In addition to the aforementioned features, the proposed TSHAAC requires lower number of SMs than MMC and AAC, along with lower number of switches than CHB. Moreover, an adapted arm energy balancing control is proposed to take advantage of the redundant SMs that are idling to achieve faster balancing than in conventional AAC configuration. The simulation results validate the integration of TSHAAC configuration in a BESS; the adapted arm energy balancing control is able to improve the balancing duration by 27 %.

K e y w o r d s: battery energy storage system, cell balancing, hybrid modular multilevel converter, redundant sub-modules, state-of-charge balancing

1 Introduction

Renewable energy sources (RES) - solar, wind, hydro, geothermal, biomass, *etc* - have been in high demand due to the worldwide energy transition as the burning of fossil fuels emits carbon dioxide which makes up more than 50 % of global greenhouse gas emissions [1]. The goal of energy transition is to curb global warming by limiting average global temperature rise below 2 °C as stated in Paris Climate Agreement. Hence, the contribution of RES to the worlds energy is predicted to grow from 15 % in 2015 to 63 % in 2050 [1]. Studies carried out for the European [2] and Asian [3] regions verify that RES are the most feasible and critical solutions to achieve climate objectives [1]. To mitigate the intermittency issue faced by RES, Lithium-ion (Li-ion) based battery energy storage system (BESS) is a promising technology owing to its fast response time, flexible operation, prolonged lifespan and greater densities of energy and power [4]. The findings of [5] indicate that Li-ion based BESSs are the benchmark technology for future sustainable development, which will remain dominant in the energy storage market. Power conversion system (PCS) is an indispensable component of a BESS and is generally categorised into voltage source converters (VSCs) and current source converters (CSCs) [4].

Despite the fact that line-commutated CSCs have been well-developed for commercial applications - high voltage dc (HVDC) transmission and flexible ac transmission system (FACTS) - since 1950s , the emerging of self-commutated semiconductor power devices - gate turn-off thyristors (GTOs) and insulated gate bipolar transistors (IGBTs) - has made VSCs more prevalent since 1990s [4, 6]. The modular multilevel converter (MMC) is a topology belongs to multilevel VSCs and has come under the spotlight since its debut in 2003. Studies related to the MMC are for applications in HVDC transmission [7], BESSs [8] and both [9]. The alternate arm converter (AAC) is a topology derived from the MMC and introduced by Alstom Grid in 2010 [10]. The AAC has the potential to be applied in BESSs because the number of sub-modules (SMs)/cells required by the AAC is only half (50 %) of the MMC [10], not to mention the AAC possesses the prominent features of the MMC - modularity, scalability and low harmonic distortion [7]. However, studies related to the AAC are merely for HVDC applications [11–13]. The inherent energy balancing of the AAC is limited to an operating point named sweet-spot, which is a fixed modulation index of $4/\pi$ to achieve energy equilibrium at both dc and ac sides [14]. It is highly unreliable to attain energy balancing via sweet-spot since it is challenging to comply with the fixed operating point constantly. Hence, the arm energy balancing issue is the main concern for the AAC.

Augmenting multilevel VSCs - the MMC [15] and the cascaded H-Bridge (CHB) [16] - with redundant SMs is an approach to increase their reliability. The redundant SMs can be operated either in hot reserve/active [15] or cold reserve/passive modes [15, 16].

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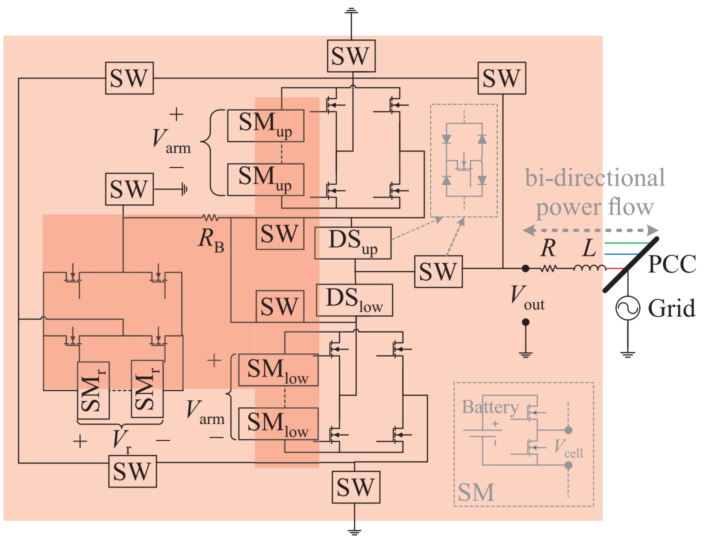

Fig. 1. Schematic of the proposed topology - TSHAAC - for BESSs

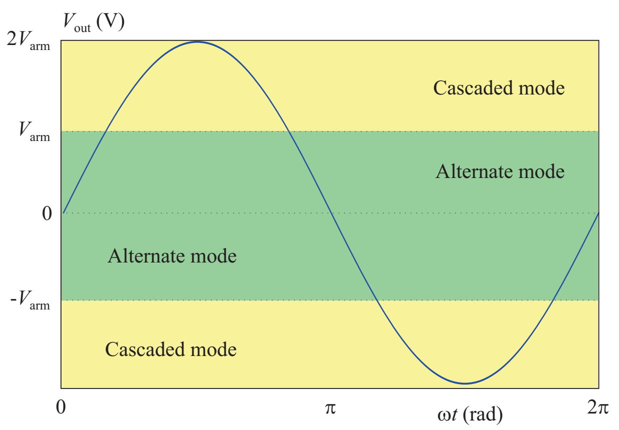

Fig. 2. V_{out} reference waveform displaying the regions of the cascaded and alternate modes

The prior serves the redundant SMs like regular SMs which is not practical as they lead to conduction loss and contribute trivially to the voltage quality, while the latter leaves the redundant SMs in idle state and thus they are not fully optimized.

This work proposes a novel topology – the T-shaped hybrid alternate arm converter (TSHAAC) – for BESS applications. There are three strings of SMs arranged like a character T rotated 90°clockwise as shown in Fig. 1, while the term "hybrid" refers to the combination of full-bridges (FBs) and half-bridges (HBs). In addition to the salient features of the MMC as aforementioned, the TSHAAC has the following novel features:

- Adapted with an arm energy balancing control to mitigate the arm energy balancing issue without the restriction of sweet-spot as in AAC.
- The redundant SMs are utilized to aid in the arm energy balancing control instead of staying idle.
- Reduced number of SMs compared to MMC and AAC, along with reduced number of switches compared to CHB.

These features are elaborated accordingly in Section 2, followed by the simulation results.

2 Operating principles of the TSHAAC

The SMs in both upper and lower arms ($\mathrm{SMs_{up}}, \mathrm{SMs_{low}}$) are symmetrical and used to generate the output voltage (V_{out}) thus, V_{out} is governed by the maximum voltage of each arm (V_{arm}), such that $-2\,\mathrm{V_{arm}} \leq V_{out} \leq 2\,\mathrm{V_{arm}}$.

The redundant SMs ($\mathrm{SMs_r}$) are used in arm energy balancing control and as reserved units. The TSHAAC can operate either in the cascaded or alternate modes by controlling the switches (SWs) and director switches ($\mathrm{DS_{up}}, \mathrm{DS_{low}}$).

The cascaded mode is in the yellow regions of $V_{arm} < |V_{out}| \leq 2V_{arm}$, as depicted in Fig. 2. During this mode, both DSs are switched on to enable the SMs in both arms to generate V_{out}, as shown in Fig. 3(a). If there are failed SMs - tinted in green color as depicted in Fig. 3(b) - in the arms, $\mathrm{SMs_r}$ are activated as shown in Fig. 3(b) to prevent breakdown of the TSHAAC. The sorting algorithm [4] is employed for state-of-charge (SoC) balancing between the SMs in both arms during this mode.

The alternate mode falls within the green region of $-V_{arm} \leq V_{out} \leq V_{arm}$, as shown in Fig. 2. In addition to the sorting algorithm [4], this mode is adapted with an arm energy balancing control to balance the average SoCs of $\mathrm{SMs_{up}}$ and $\mathrm{SMs_{low}}$. In the alternate mode, a difference of 2 % between the average SoCs of $\mathrm{SMs_{up}}$ and $\mathrm{SMs_{low}}$ is chosen as the threshold value for activating $\mathrm{SMs_r}$ to aid the arm energy balancing. This is because the threshold value - delta voltage - for cell balancing recommended by the industry is 0.01 V, *ie* Orion BMS by Ewert Energy Systems. Referring to the datasheet of the battery model

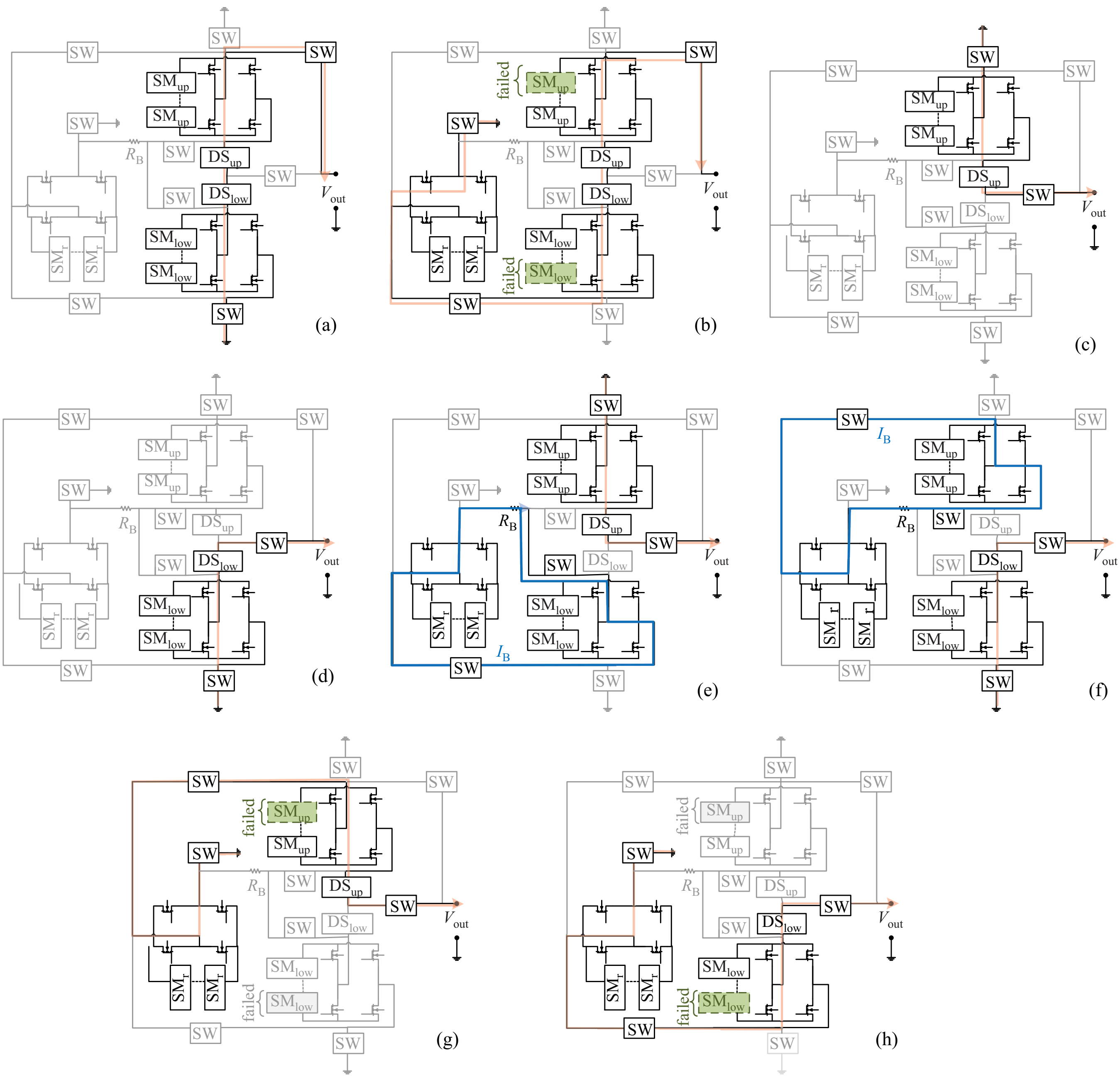

Fig. 3. Switching states of the TSHAAC during: (a) – cascaded mode, (b) – cascaded mode with SMs_r, (c) – alternate mode (upper arm), (d) – alternate mode (lower arm), and (e) – alternate mode (upper arm) with SMs_r, balancing lower arm, (f) – alternate mode (lower arm) with SMs_r balancing upper arm, (g) – alternate mode with SMs_r (upper arm), and (h) – alternate mode with SMs_r (lower arm)

employed in this work, about 2 % of SoC is corresponding to 0.01 V of battery voltage. Hence, it is considered a significant imbalance when the SoC difference is greater than 2 %. Moreover, similar threshold value of 2 % is used in [17] as well. Thus, either DS_{up} or DS_{low} is switched on to allow the respective SMs to generate V_{out}, depending on the following three conditions:

- Difference between the average SoCs = 0 %.

When the average SoCs are balanced, SMs_{up} and SMs_{low} are used to generate positive and negative half cycles of V_{out} respectively. The switching states are shown in Fig. 3(c) and (d).

- 0% < Difference between the average SoCs ≤ 2 %.

The BESS can discharge or charge since the power flow is bi-directional as shown in Fig. 1. For discharging/charging case, the arm with higher/lower average SoC is switched on respectively to generate V_{out}, as shown in Fig. 3(c) and (d).

- Difference between the average SoCs > 2 %.

Instead of staying idle, SMs_r are utilized to achieve balanced average SoCs in a shorter duration via discharg-

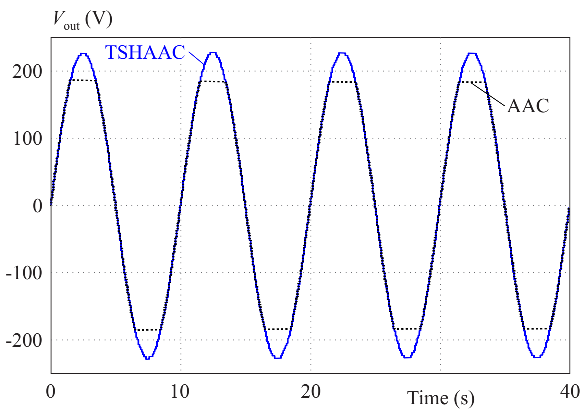

Fig. 4. V_{out} waveform generated by the TSHAAC and AAC

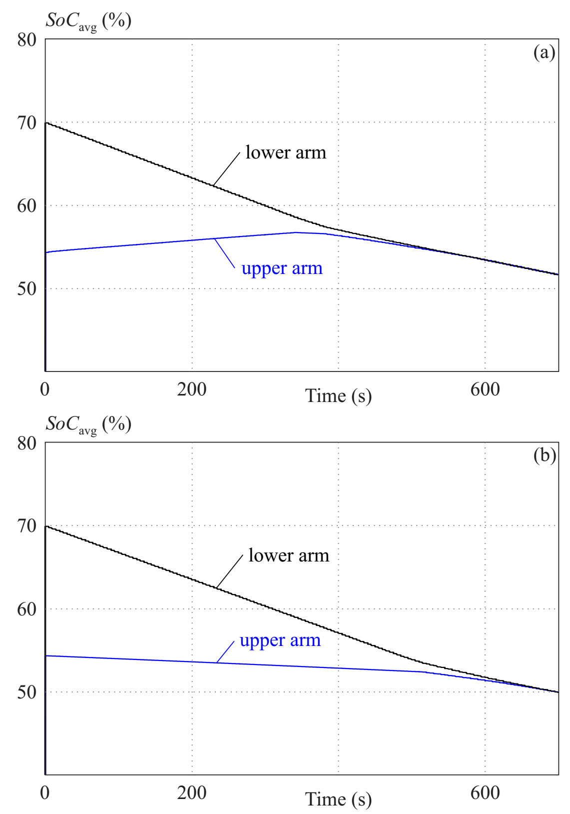

Fig. 5. Average SoCs of both arms when SMs_{r} are (a) – present, and (b) – absent

ing/charging the arm with lower/higher average SoC, while the other arm with higher/lower average SoC is generating V_{out} for discharging/charging, as indicated in Fig. 3(e) and (f). The balancing current (I_{B}) flowing between SMs_{r} and the inserted SMs for balancing is governed by

$$I_{\text{B}} = \frac{V_{\text{r}} - V_{\text{arm\_B}}}{R_{\text{B}}}, \tag{1}$$

where $V_{\text{r}}, V_{\text{arm\_B}}$, R_{B} represent the voltage across SMs_{r}, voltage across the inserted SMs for balancing and small resistor of $1\,\Omega$, respectively. I_{B} must not exceed the current limit of the connected battery cells [17]. Thus, I_{B} is regulated based on (1) by adjusting $V_{\text{arm\_}B}$ via inserting suitable number of SMs in the respective arm. The actual I_{B} is less than the current limit due to the internal resistance of the connected battery cells.

In case of failed SMs - tinted in green color as depicted in Fig. 3(g) and (h) - in the arms during the alternate mode, SMs_{r} are activated as backup units - subjected to the aforementioned conditions - in conjunction with SMs_{up} or SMs_{low} to generate V_{out}, as shown in Fig. 3(g) and (h), to avoid shutdown of the overall system, instead of aiding the arm energy balancing as shown in Fig. 3(e) and (f).

When generating a $(2n+1)$-level V_{out} [5], where $n = 1, 2, 3 \ldots$, the TSHAAC requires smaller number of SMs per phase leg (N_{SM}) than the MMC [8] and AAC [10] due to its operation principles, as well as lower number of switches in SMs per phase leg (N_{sw}) than the CHB [16] due to the combination of FBs and HBs. The comparison between the topologies in terms of N_{SM} and N_{sw} is depicted in Tab. 1. Hence, N_{SM} of the TSHAAC is approximately 25 % of MMC and 50 % of AAC, while N_{sw} of the TSHAAC will be less than the CHB substantially when n is getting larger.

Table 1. Comparisons of the TSHAAC with 3 existing topologies

	TSHAAC	MMC	AAC	CHB
N_{SM}	$n+1$, if n is odd n, if n is even	$4n$	$2n$	$1n$
N_{SW}	$2(n+1)+8$, if n is odd $2n+8$, if n is even	$2(4n)$	$4(2n)$	$4(n)$

3 Simulation results and discussion

A simulation model has been constructed in MATLAB Simulink to validate the proposed topology - TSHAAC. The simulation parameters are shown in Tab. 2.

Table 2. Simulation parameters

Battery model	Panasonic CGR 18650CG Li-ion cell
Current limit	4.2 A
N_{SM}	$50\,\text{SMs}_{\text{up}} + 50\,\text{SMs}_{\text{low}}$
Number of SMs_{r}	33
Reference voltage	$230\sin(0.2\pi t)$ V
Load	$50\,\Omega$, 0.9 H

In the simulation work, the TSHAAC with N_{SM} of 100 is able to generate an output voltage V_{out} similar to the reference voltage with a peak voltage of 230 V, as depicted in Fig. 4, since its maximum V_{out} is around 367 V. Conversely, the V_{out} generated by the AAC with

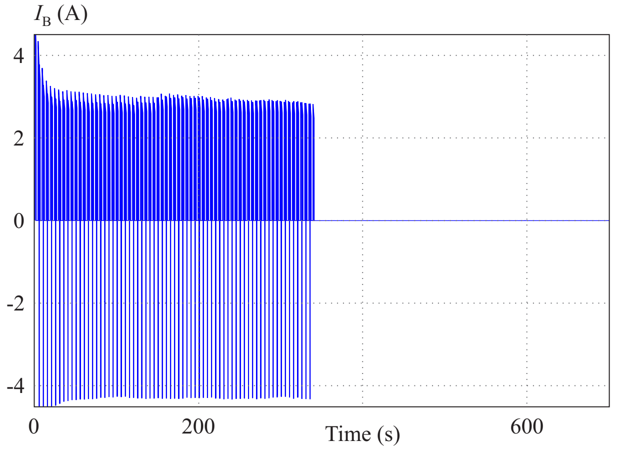

Fig. 6. I_B waveform maintains within the limit of 4.2 A

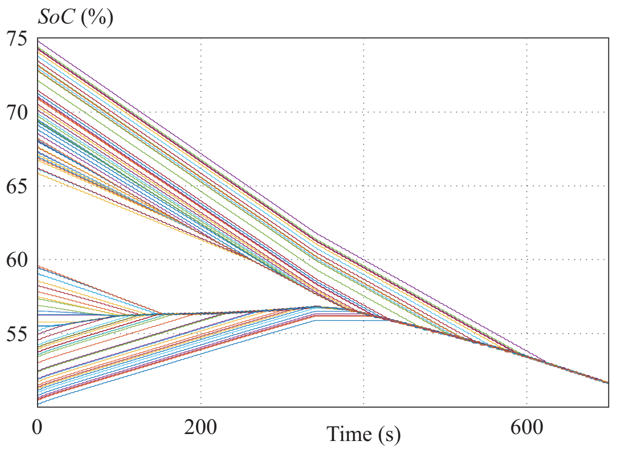

Fig. 7. SoCs of 100 SMs in both arms converge eventually

the same N_{SM} is distorted as the voltage is clipped at 186 V because this is the maximum V_{out} that can be generated by the AAC with N_{SM} of 100, about 50 % lower than the TSHAAC, thus higher N_{SM} is expected for the AAC to achieve V_{out} of 230 V. Hence, it is validated that the TSHAAC is capable of generating corresponding V_{out} using a lower N_{SM} than the AAC.

Since there is no fixed ratio of SMs_r, the number of SMs_r in the simulation is set at 33, which is about 33 % of N_{SM}. With idling cells, the system without the arm energy balancing control takes around 600 s to converge as shown in Fig. 5(b). Conversely, the system with the arm energy balancing control performs balancing faster with the aid of SMs_r because the average SoCs of both arms converge at 430 s as shown in Fig. 5(a), which is about 27 % faster than the system with idling cells. The magnitude of I_B is kept within the limit of 4.2 A by balancing control based on (1) as shown in Fig. 6 and I_B stops conducting after 330 s when it is beyond condition 3. Moreover, the SoCs of 100 SMs in both arms are kept balanced via the sorting algorithm [4] indicated by SoC convergence at around 650 s as illustrated in Fig. 7.

4 Conclusions

In this work, a novel topology - TSHAAC - is proposed for BESS applications. In addition to modularity, scalability and low harmonic distortion, the novel features of the proposed TSHAAC include:

- It is adapted with an arm balancing control to balance the average SoC between upper and lower arms without the restriction of sweet-spot in AAC;
- Instead of staying idle, SMs_r are utilized in the adapted arm energy balancing control to achieve balancing faster. Furthermore, they also act as reserved units, which aid in generating output voltage in the event of faulty SMs;
- It requires lower N_{SM} than MMC and AAC because it can operate in both the cascaded and alternate modes. The inclusive of HBs into a conventional AAC and CHB which employs only FBs resulted in lower N_{sw} compared to both conventional AAC and CHB topologies.

The TSHAAC has been validated in the simulation work. It has been proven that the TSHAAC requires lower N_{SM} than AAC to generate a designated V_{out} and the use of SMs_r have rendered the reduction of balancing duration as much as 27 %.

Acknowledgments

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References

[1] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, "The role of renewable energy in the global energy transformation", *Energy Strategy Reviews*, vol. 24, pp. 38–50, 2019.

[2] F. V. Bekun, A. A. Alola, and S. A. Sarkodie, "Toward a sustainable environment. Nexus between CO2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries", *Science of The Total Environment*, vol. 657, pp. 1023–1029, 2019.

[3] I. Hanif, B. Aziz, and I. S. Chaudhry, "Carbon emissions across the spectrum of renewable and nonrenewable energy use in developing economies of Asia", *Renewable Energy*, vol. 143, pp. 586–595, 2019.

[4] C. A. Ooi, *Balancing control for grid-scale battery energy storage system*, PhD Thesis, Cardiff University, 2016.

[5] L. J. Aaldering, J. Leker, and C. H. Song, "Analysis of technological knowledge stock and prediction of its future development potential" The case of lithium-ion batteries, *Journal of Cleaner Production*, vol. 223, pp. 301–311, 2019.

[6] T. Jing and A. S. Maklakov, "A Review of Voltage Source Converters for Energy Applications", *2018 International Ural Conference on Green Energy* (UralCon), pp. 275–281, 2018.

[7] R. Oliveira and A. Yazdani, "An Enhanced Steady-State Model and Capacitor Sizing Method for Modular Multilevel Converters for HVDC Applications", *IEEE Transactions on Power Electronics*, vol. 33, no. 6, pp. 4756–4771, 2018.

[8] Z. Ma, F. Gao, X. Gu, N. Li, Q. Wu, X. Wang, and X. Wang, "Multilayer SOH Equalization Scheme for MMC Battery Energy Storage System", *IEEE Transactions on Power Electronics*, vol. 35, no. 12, pp. 13514–13527, 2020.

[9] Z. Wang, H. Lin, and Y. Ma, "Improved capacitor voltage balancing control for multimode operation of modular multilevel converter with integrated battery energy storage system", *IET Power Electronics*, vol. 12, no. 11, pp. 2751-2760, 2019.

[10] M. M. C. Merlin, T. C. Green, P. D. Mitcheson, D. R. Trainer, D. R. Critchley, and R. W. Crookes, "A new hybrid multi-level voltage-source converter with DC fault blocking capability", *9 th IET International Conference on AC and DC Power Transmission* (ACDC 2010), pp. 1–5, 2010.

[11] H. R. Wickramasinghe, G. Konstantinou, S. Ceballos, and J. Pou, "Alternate Arm Converter Energy Balancing under Parameter Variation", *IEEE Transactions on Power Electronics*, vol. 34, no. 4, pp. 2996–3000, 2019.

[12] M. A. Abdel-Moamen, S. A. Shaaban, and F. Jurado, "France-Spain HVDC transmission system with hybrid modular multilevel converter and alternate-arm converter", *2017 Innovations in Power and Advanced Computing Technologies* (i-PACT), pp. 1–6, 2017.

[13] M. M. C. Merlin, D. Soto-Sanchez, P. D. Judge, G. Chaffey, P. Clemow, T. C. Green, D. R. Trainer, and K. J. Dyke, "The extended overlap alternate arm converter: A voltage-source converter with DC fault ride-through capability and a compact design", *IEEE Transactions on Power Electronics*, vol. 33, no. 5, pp. 3898–3910, 2018.

[14] Y. Y. Leow and C. A. Ooi, "Arm energy balancing control in AACs: A comparative analysis", *IET Power Electronics*, vol. 13, no. 6, pp. 1113–1128, 2020.

[15] J. Guo, X. Wang, J. Liang, H. Pang, and J. Goncalves, "Reliability modeling and evaluation of MMCs under different redundancy schemes", *IEEE Transactions on Power Delivery*, vol. 33, no. 5, pp. 2087–2096, 2018.

[16] P. Moamaei, H. Mahmoudi, and R. Ahmadi, "Fault-tolerant operation of cascaded H-Bridge inverters using one redundant cell", *2015 IEEE Power and Energy Conference at Illinois (PECI*,)pp. 1–5, 2015.

[17] A. B. Ahmad, C. A. Ooi, D. Ishak and J. Teh, "State-of-Charge Balancing Control for ON/OFF-Line Internal Cells Using Hybrid Modular Multi-Level Converter and Parallel Modular Dual L-Bridge in a Grid-Scale Battery Energy Storage System", *IEEE Access*, vol. 7, pp. 131–147, 2019.

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