An Energy Absorbing Method for Hybrid MMCs to Avoid Full-Bridge Submodule Overvoltage During DC Fault Blocking

Xiongfeng Fang, Gen Li, *Member, IEEE*, Canfeng Chen, Dongyu Wang, Jian Xiong, Kai Zhang

Abstract- **The full-bridge submodules (FB-SMs) in hybrid modular multilevel converters need to absorb the enormous energy stored in dc side and arm inductors during dc fault blocking, which may lead to severe overvoltage. An energy absorbing branch (EAB) composed of metal oxide varistor (MOV) and thyristors is proposed in this letter. No extra power loss is produced by the EAB during normal operation. The EAB can absorb a part of the energy and reduce the energy absorbed by FB-SMs suffering from severe overvoltage by clamping the dc voltage. Thus, the maximum FB-SM overvoltage is reduced. Turning off the EAB several milliseconds after the blocking of the converter can accelerate the decaying of the dc fault in the transmission line and reduce the required energy volume of MOV with minimal effect on the maximum FB-SM overvoltage. The proposed EAB shows better technical and economic performance than existing methods. The proposed EAB is validated by simulations and experiments.**

I. Introduction

Dc fault blocking is a critical issue that limits the application of voltage source converter based high-voltage direct current (VSC-HVDC) transmission systems [1]-[2]. The widely employed modular multilevel converters (MMCs) based on half-bridge submodules (HB-SMs) can't block dc fault currents [3]. Alternative SMs that can block dc fault currents can be an effective solution to protect the system. For instance, the full-bridge SM (FB-SM), clamp-double SM, series-connected double SM, unipolar-voltage full-bridge SM, cross-connected SM, and diode clamp SM [4]-[6]. Hybrid MMCs composed of mixed HB- and FB-SMs can be a trade-off between dc fault protection and cost and power loss. In addition, hybrid MMC exhibits more flexible control than HB-MMC because its modulation index can be over 1 [7]-[8]. Due to the above features, the hybrid MMC has been deployed in the Kunliulong ±800 kV ultra HVDC project in China [9].

During the dc fault blocking process, hybrid MMCs may suffer severe capacitor overvoltage of the FB-SMs [10]. The FB-SM overvoltage should be avoided since it may threaten the safe operation of the devices. Factors affecting the FB-SM overvoltage have been analyzed in [11]. The studies show that the longer the transmission line, the more severe the FB-SM overvoltage. Methods have been proposed to deal with the FB-SM overvoltage. Increasing the proportion of FB-SMs (up to 100%) or the SM capacitance (usually several times larger than normal design to achieve significant improvement) can relieve the FB-SM overvoltage. However, this obviously results in higher cost. An active fault-clearing method has been proposed in [12]. During a dc fault, converters manage to regulate the fault current by controlling the dc voltage. By transferring the excess energy into the ac grid, the FB-SM overvoltage can be mitigated. However, a high proportion (over 70%) of FB-SMs is needed to achieve a fast dc fault blocking. Moreover, the ac grid is required to absorb the excess energy, which could be unacceptable in some situations, for example, when the ac side is connected to a wind farm. In [10], a dynamic model has been proposed to estimate the highest FB-SM overvoltage and fault blocking time. However, research on directly reducing the FB-SM overvoltage is still scarce.

Xiongfeng Fang, Canfeng Chen, Dongyu Wang, Jian Xiong, Kai Zhang are with the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: fangxiongfeng@foxmail.com; canfengchen@hust.edu.cn; m202071561@hust.edu.cn; xjhustwh@sina.com; kaizhang@hust.edu.cn). *(Corresponding author: Kai Zhang.)*

Gen Li is with the School of Engineering, Cardiff University, UK (e-mail: Lig9@cardiff.ac.uk).

An energy-absorbing branch (EAB) based on metal oxide varistor (MOV) and thyristors is proposed in this letter. The EAB is installed in the dc terminal of the converter. No extra power loss will be involved as the EAB is inactive during normal operation. By triggering the EAB, the MOV is inserted in the circuit to achieve two purposes. First, the MOV will absorb part of the excess energy. Second, by adjusting the turning-off instant of the EAB, the dc voltage can be adjusted. Thus, the charging speed of FB-SMs becomes controllable, and the energy absorption of those FB-SMs that are suffering from the most severe overvoltage can be reduced. Turning off the EAB earlier can accelerate the dc fault blocking and reduce the energy volume of MOV. The proposed method can significantly reduce FB-SM overvoltage at a low cost. Simulations and experiments on a scaled-down prototype have been made to validate the proposed method.

II. Energy-Absorbing Method Based On Metal Oxide Varistors

A. FB-SM Overvoltage during DC Fault Blocking

Absorbing the enormous energy from the dc side and the unbalanced energy absorption among arms are the main reasons that cause the FB-SM overvoltage. The dc fault current and steady-state dc current will have the same direction in an MMC operating in the rectifier mode. Therefore, such a converter is taken as an example because the fault current will be larger, and the FB-SM overvoltage will be more severe than in other cases. The energy absorbed by FB-SMs can be divided into three parts, as illustrated in Fig. 1(a). The first part is the pre-fault energy, which is determined by the circuit inductance and current. The second part comes from the ac gird. The third part is the discharging of the HB- and FB-SMs. Since the dc inductors are much larger than arm inductors, most of the energy is stored in the dc side.

The unbalanced energy absorption by the SM capacitors is caused by the current commutation among arms, as shown in Fig. 1(b). Assuming the ac-side three-phase voltages have the relationship of $u_a > u_b > u_c$ at the moment of converter blocking, then the ac arm currents and the dc fault current (i_{dc}) will have the same direction in the upper arm with the largest transient ac-side voltage (here is the upper arm of phase a) and the lower arm with the lowest transient ac-side voltage (here is the lower arm of phase c). The ac arm currents and the dc fault current are in opposite directions in the other four arms. Thus, the currents of the two arms will increase and reach the value of the dc current, and the currents of the other four arms will decrease to zero. Since the dc fault current will decrease once the converter is blocked, FB-SMs charged at the initial stage will be charged by a large current and suffer from severe overvoltage.

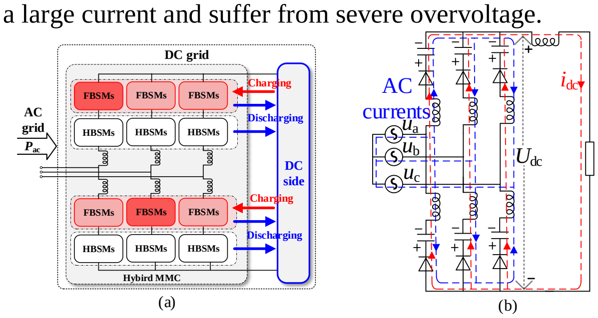

Fig. 1. FB-SM overvoltage. (a) Energy transferring of a hybrid MMC in the rectifier mode; (b) current commutation process among arms (when $u_a > u_b > u_c$).

B. Structure of the Proposed EAB

The proposed EAB consists of thyristors and MOVs, as shown in Fig. 2(a). During normal operation, thyristors are not triggered, and therefore, no power loss will be produced by the EAB. Once a dc fault is detected, the thyristors will be triggered, and SMs will be blocked. Blocked FB-SMs provide negative voltages [as shown in Fig. 1(b)] against the dc fault current. The inserted MOV will absorb the excess energy and clamp the dc voltage.

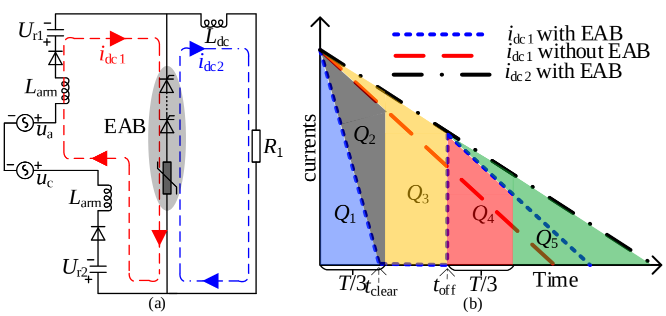

Fig. 2. Fault current paths and relationships. (a) Equivalent circuit during the dc fault blocking period after the current commutation; (b) dc fault currents with and without the EAB.

C. FB-SM Overvoltage Limiting

As shown in Fig. 2(a), FB-SMs in the two arms will be charged by the converter side dc fault current (i_{dc1}) after the current commutation. The FB-SM voltage U_{FB} can be calculated as

$$U_{FB} = U_0 + \frac{Q}{C}, \tag{1}$$

where U_0 is the initial FB-SM voltage, Q is the electric charge, C is the equivalent total FB-SM capacitance. Each arm will be charged for $T/3$ in one period without considering the current commutation overlap, where T is the period of the ac grid. i_{dc1} decreases from the initial value (i_{dc0}) to zero after the converter blocking, which can be expressed as follows:

$$i_{dc1} = \begin{cases} i_{dc0} - \int_0^t \frac{di_{dc1}}{dt} dt & (t < t_{clear}) \\ 0 & (t \geq t_{clear}) \end{cases}, \tag{2}$$

where t_{clear} is the time that i_{dc1} takes to decrease to zero. Thus, the FB-SMs charged at the very beginning of the converter blocking absorb the most electric charge, which is

$$Q_{max} = \int_0^{T/3} i_{dc1} dt. \tag{3}$$

If the dc fault clearing time is longer than T, the electric charge will accumulate. Since the charging time ($T/3$) in (3) is fixed, the decreasing rate of i_{dc1} decides the maximum FB-SM overvoltage, which can be expressed as follows:

$$-\frac{di_{dc1}}{dt} = \frac{u_c - u_a + U_{r1} + U_{r2} + U_{dc}}{2L_{arm}}, \tag{4}$$

where U_{r1} and U_{r2} are the negative capacitor voltages in the two arms [as shown in Fig. 2(a)], U_{ac} is the ac voltage, and U_{dc} is the dc voltage. When MOV is inserted, the negative dc voltage will be clamped by the MOV to U_{EAB}. In this case, the decreasing rate of i_{dc1} becomes:

$$-\frac{di_{dc1}}{dt} = \frac{u_c - u_a + U_{r1} + U_{r2} - U_{EAB}}{2L_{arm}}. \tag{5}$$

The dc fault current is assumed to decay linearly to simplify the analysis, as shown in Fig. 2(b). i_{dc1} with the EAB decreases faster than the i_{dc1} without the EAB. The electric charge absorbed by FB-SMs without using the EAB is Q_1 and Q_2. The electric charge absorbed by FB-SMs using the EAB reduces to Q_1. Thus, a low U_{EAB} will lead to a fast decrease of i_{dc1} and a low maximum FB-SM overvoltage.

The decreasing rate of the line side dc fault current (i_{dc2}) is

$$-\frac{di_{dc2}}{dt} = \frac{i_{dc2}R_1 - U_{dc}}{L_{dc}}, \tag{6}$$

where R_1 and L_{dc} are the equivalent resistance and inductance of the dc circuit. When MOV clamps the dc voltage, the decreasing rate of i_{dc2} becomes small. Thus, a low U_{EAB} will, at the same time, lead to a long line side dc fault current clearing time. The energy (E) absorbed by the MOV is

$$E = \int_0^{t_{off}} U_{EAB}(i_{dc2} - i_{dc1}) dt, \tag{7}$$

where t_{off} is the turn-off time of the EAB. If the EAB is inserted for the entire dc fault blocking process, E will equal to

$$E = U_{EAB}(Q_2 + Q_3 + Q_4 + Q_5). \tag{8}$$

D. Turn-off of the EAB

Only the arms charged at the initial stage will experience severe overvoltage, while the arms charged later may not. Thus, there is no need to keep the EAB being inserted during the whole dc fault blocking process. According to (6), turning off the EAB early can resume the negative dc voltage and therefore, accelerate the decreasing of i_{dc2}. Moreover, according to (7), reducing the time of inserting the EAB in the circuit can also reduce the required energy volume of the MOV.

Removing the firing signals of the thyristors and inserting all FB-SMs with positive output voltages into the circuit for a short while can block the EAB. Then, all FB-SMs will be blocked again to block the rest dc fault current in the transmission line. The energy released by re-inserting the FB-SMs during the EAB turning off process will be absorbed by FB-SMs finally. It should be mentioned that only the FB-SMs will participate in turning off the EAB. All HB-SMs will keep being blocked. Therefore, the action will not increase the total energy that FB-SMs need to absorb.

E. Design of the EAB

The thyristor branch needs to withstand the rated dc voltage, and the EAB should be able to withstand the dc fault current. A low MOV protection voltage helps to limit the FB-SM overvoltage, but it may lead to a longer dc fault clearing time and increased energy volume of the MOV. Since the priority here is to better protect the FB-SMs from overvoltage, the upper limit of the MOV protection voltage will be selected based on the expected maximum FB-SM overvoltage. Therefore

$$Q_1 \le \Delta U_{\mathrm{FB}} C, \tag{9}$$

where ΔU_{FB} is the expected maximum increase of FB-SM voltage. It is assumed that i_{dc2} remains constant during the EAB turning off process. When EAB is turned off after $T/3$, the impact on Q_1 will be slight. Moreover, the FB-SMs charged right after turning off EAB may suffer from high voltage, the electric charge of which is Q_4 in Fig. 2(b). To avoid increasing the maximum FB-SM overvoltage, Q_4 should satisfy

$$Q_4 = \int_{t_{off}}^{t_{off}+T/3} i_{dc1} dt \le Q_1 . \tag{10}$$

When the EAB is turned off, MOV will no longer absorb energy. Thus, the energy absorbed by MOV becomes

$$E = U_{EAB}(Q_2 + Q_3), \tag{11}$$

which is reduced compared with (8). When selecting the MOV, it should be ensured that the energy volume of the MOV is larger than the absorbed energy to satisfy thermal requirements.

F. Comparison with Existing Methods

The comparison of the proposed method with two existing methods is summarized in Table I. For the two methods, to reach the same limiting effectiveness of FB-SM overvoltage, the proportion of FB-SMs in the hybrid MMC should increase to 100%, or the SM capacitance should be increased to three times the original value [11]. The proposed method only employs one EAB, wherein the thyristors are the main cost. It is assumed that the cost of a thyristor is a quarter of an IGBT with the same voltage rating [13]. The cost of an SM capacitor is about three times of an IGBT, and the cost of the capacitor is proportional to the capacitance. In this study, it is assumed that thyristors are of the same voltage rating as the IGBTs in SMs. As the thyristor branch needs to withstand the rated dc voltage during normal operation, therefore the number (N) of required thyristors equals the number of SMs in each arm. $6N$ extra IGBTs are needed to increase the FB-SMs from 50% to 100%, the cost of which is 24 times that of thyristors. The additional cost of capacitance is 144 times of thyristors. To reach the same voltage limiting effect, the extra cost of capacitors and IGBTs is much higher than thyristors. Moreover, unlike the method using more FB-SMs, the proposed EAB does not bring power loss during normal operation.

It should be noticed that although increasing the SM capacitance (to several times larger) and increasing the proportion of FB-SMs (up to 100%) in the hybrid MMC can mitigate the FB-SM overvoltage, these methods will largely increase converter's capital cost, weight, and power losses as compared in Table I. Moreover, the method proposed in [12] may have limited application due to the strict requirement on the ac grid. Therefore, the proposed method is more promising than these methods thanks to its effectiveness and low cost.

TABLE I
COMPARISON WITH THE EXISTING SOLUTIONS BASED ON CONVERTER BLOCKING

Methods	**Extra loss**	**Extra Components**	**Extra Cost (p.u.)**
Proposed method	None	thyristors (N)	1
Larger SM capacitance	None	capacitance(double)	144
Higher FB-SM proportion	High	IGBTs ($6N$)	24

III. SIMULATION RESULTS

A symmetrical monopole hybrid MMC-HVDC link is built in Matlab/Simulink to verify the effectiveness of the proposed method. Parameters are given in Table II. A dc side pole-to-pole fault is set at t = 0.5 s. The converters are blocked 3 ms after the fault to block the dc fault.

Fig. 3 shows that when the EAB is kept being inserted, low protection voltage of MOVs will lead to small FB-SM capacitor overvoltage and long line side dc fault current clearing time, which is consistent with the analysis in Section II-C.

TABLE II
SETUP OF THE HYBRID MMC

Parameters	**Simulation**	**Experiment**
Dc voltage	±320 kV	200 V
Rated dc current	1.56 kA	5 A
AC line voltage	333 kV	90.4 V
Number of HB-SMs per arm	178	1
Number of FB-SMs per arm	178	1
SM voltage	1.8 kV	200 V
SM capacitance	17 mF	560 μF
Arm inductance	52.94 mH	4.62 mH
Dc inductance	1015 mH	125 mH
MOV protection voltage	130 kV	47 V

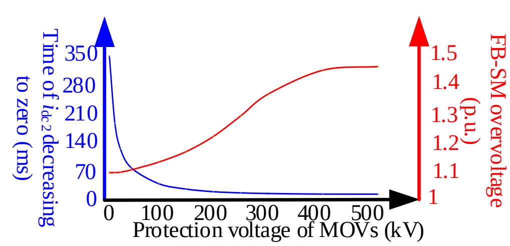

Fig. 3. Simulation results of the relationship between FB-SM capacitor overvoltage, line side dc fault current clearing time and the protection voltage of MOVs when the EAB is kept being inserted.

Simulation results without the EAB are shown in Fig. 4(a). The dc voltage U_{dc} is MMC's dc terminal (pole-to-pole) voltage. The negative dc voltage is up to 460 kV. The converter side fault current and the line side fault current are blocked simultaneously in 13 ms. The maximum FB-SM capacitor overvoltage reaches 1.45 p.u. The ac currents and arm currents are blocked simultaneously with the dc fault current.

Results of inserting the EAB for the entire dc fault blocking process are shown in Fig. 4(b). The MOV clamps the maximum negative dc voltage to 130 kV. The converter side fault current is blocked in 4 ms. The line side dc fault current is blocked in 33 ms. The maximum FB-SM voltage is limited to 1.1 p.u., which becomes acceptable. The ac currents and arm currents are blocked earlier than the line side dc current.

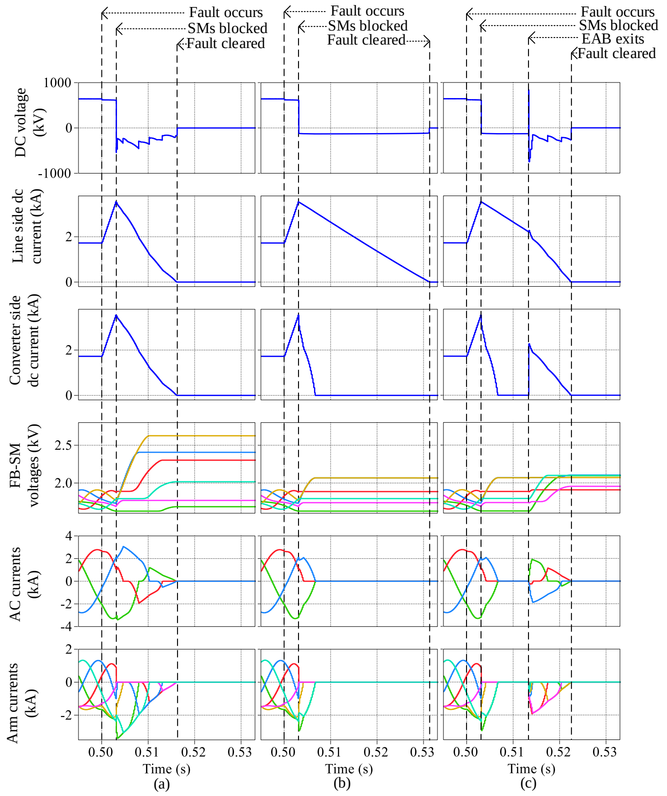

Fig. 4. Simulation results under different schemes. (a) Without the EAB, (b) EAB always being inserted, (c) EAB turned off 10 ms after the converter blocking.

Results when the EAB is turned off 10 ms after the converter blocking are shown in Fig. 4(c). Before turning off the EAB, the results are the same as the ones in Fig. 4(b). After the EAB exits, all FB-SMs remain positively inserted for a short while to ensure safe turn-off of the thyristors. Since some of the FB-SMs have been charged, the dc voltage is slightly higher than the rated value. The converter side dc fault current becomes the same as the line side dc fault current. The voltages of FB-SMs charged later increase, while the maximum FB-SM overvoltage is nearly the same. The line side dc fault current is blocked in 19.5 ms, which is much quicker than the second case. The ac currents and arm currents increase firstly and then decrease with the converter side dc fault current. Based on the above results, the effectiveness of the proposed EAB in mitigating the FB-SMs is demonstrated. It can be found that turning off the EAB has minimal impact on the maximum FB-SM overvoltage, and the clearance of the dc fault is quicker.

IV. Experiment Results

Experiments have been conducted using a three-phase hybrid MMC prototype, as shown in Fig. 5. Parameters of the MMC are given in Table II. Each arm consists of one HB-SM and one FB-SM. The dc terminal is short-circuited to create a dc fault. The converter is blocked when the dc current is larger than 20 A. The protection voltage of MOVs is 47 V. Results without the EAB are shown in Figs. 6(a) and (b). The negative dc voltage is not clamped during the dc fault blocking process. The line side dc current is blocked in 19 ms. The maximum FB-SM overvoltage reaches 1.4 p.u. Results of inserting the EAB for the entire dc fault blocking process are shown in Figs. 6(c) and (d). The negative dc voltage is clamped by the MOV. The line side dc fault current is blocked in 24 ms. The maximum FB-SM overvoltage is up to 1.11 p.u. Results of turning off the EAB 5 ms after the converter blocking are shown in Figs. 6(e) and (f). The dc fault current is blocked in 21 ms. The negative dc voltage is not clamped after turning off the EAB. The maximum FB-SM voltage reaches 1.12 p.u. Experiment results have validated the effectiveness of the EAB in limiting the FB-SM overvoltage. Turning off the EAB can reduce the fault clearance time with little impact on the maximum FB-SM voltage.

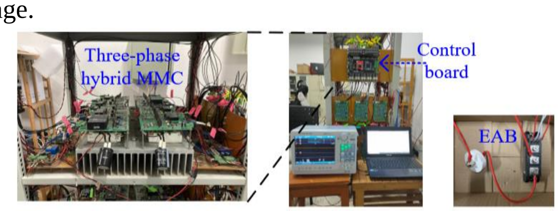

Fig. 5. Photography of the experiment setup.

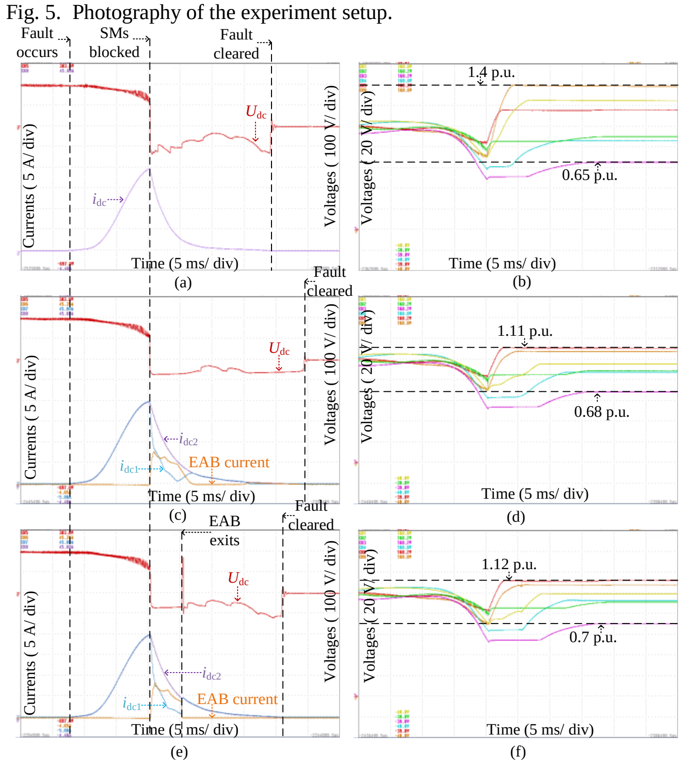

Fig. 6. Experiment results. (a) Dc voltage and currents without the EAB, (b) FB-SM voltages without the EAB, (c) dc voltage and currents of EAB always being inserted, (d) FB-SM voltages of the EAB always being inserted, (e) dc voltage and currents of turning off the EAB in 5 ms, (f) FB-SM voltages of turning off the EAB in 5 ms.

V. Conclusion

An energy absorbing branch (EAB) is proposed in this paper to mitigate the FB-SM overvoltage of hybrid MMCs during dc fault blocking. The EAB does not involve extra power loss during normal operation. The total cost of the proposed EAB shows better techno-economic performance than the existing methods. The proposed active control of the EAB can accelerate the line side dc fault blocking and, at the same time, reduce the required energy volume of MOV. The proposed method has been validated through both simulations and experiments. It proves that the proposed method would be a promising method to mitigate the FB-SM overvoltage for hybrid MMCs.

REFERENCES

[1] N. Flourentzou, *et al.*, "VSC-Based HVDC Power Transmission Systems: An Overview," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 592-602, March 2009.

[2] R. Marquardt, "Modular multilevel converter topologies with DC-short circuit current limitation," *Proc. 8th Int. Power Electron. ECCE Asia Conf.*, 2011, pp. 1425–1431.

[3] A. Lesnicar and R. Marquardt, "An innovative modular multilevel converter topology suitable for a wide power range," *Proc. of IEEE Power Tech Conf*., 2003, vol. 3, pp. 6.

[4] J. Qin, M. Saeedifard, A. Rockhill and R. Zhou, "Hybrid design of modular multilevel converters for HVDC systems based on various submodule circuits," *IEEE Trans. Power Del*., vol. 30, no. 1, pp. 385–394, Feb. 2015.

[5] J. Zhang and C. Zhao, "The research of SM topology with DC fault tolerance in MMC-HVDC," *IEEE Trans. Power Del*., vol. 30, no. 3, pp. 1561–1568, Jun. 2015.

[6] W. Lin, D. Jovcic, S. Nguefeu and H. Saad, "Full-bridge MMC converter optimal design to HVDC operational requirements," *IEEE Trans. Power Del*., vol. 31, no. 3, pp. 1342–1350, Jun. 2016.

[7] J. Hu, M. Xiang, L. Lin, M. Lu, J. Zhu and Z. He, "Improved Design and Control of FBSM MMC With Boosted AC Voltage and Reduced DC Capacitance," *IEEE Trans. Ind. Electron.*, vol. 65, no. 3, pp. 1919-1930, March 2018.

[8] R. Zeng, L. Xu, L. Yao and B. W. Williams, "Design and operation of a hybrid modular multilevel converter," *IEEE Trans. Power Electron*., vol. 30, no. 3, pp. 1137–1146, Mar. 2015.

[9] H. Ying, H. Weihuang, L. Ming and L. Tao, "Steady-state control strategy of multi-terminal hybrid UHVDC," in *19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe)*, Warsaw, Poland, 2017, pp. P.1-P.10.

[10] S. Xu, *et al.*, "Dynamic Model of the DC Fault Clearing Process of a Hybrid Modular Multilevel Converter Considering Commutations of the Fault Current," *IEEE Trans. Power Electron.*, vol. 35, no. 7, pp. 6668-6672, July 2020.

[11] Y. Gim, Z. Li, J. Meng, Z. Deng and Q. Song, "Analysis of submodule capacitor overvoltage during DC-side fault in hybrid MMC-based HVDC system," in *10th International Conference on Power Electronics and ECCE Asia (ICPE 2019 - ECCE Asia)*, Busan, Korea (South), 2019, pp. 2794-2799.

[12] Q. Song, S. Xu, Y. Zhou, Y. Gim, Z. Li and Z. Deng, "Active Fault-Clearing on Long-Distance Overhead Lines using a Hybrid Modular Multilevel Converter," in *IEEE 28th International Symposium on Industrial Electronics (ISIE)*, Vancouver, BC, Canada, 2019, pp. 2033-2038.

[13] H. Iman-Eini and M. Liserre, "DC Fault Current Blocking with the Coordination of Half-Bridge MMC and the Hybrid DC Breaker," *IEEE Trans. Ind. Electron.*, vol. 67, no. 7, pp. 5503-5514, July 2020.