11th International Conference on Power Electronics-ECCE Asia
May 22 - 25, 2023 / ICC Jeju, Jeju, Korea

Evaluation of Arm Reliability in Modular Multilevel Converters with Multiple Sub-modules for MVDC Applications

Yumeng Tian* and Georgios Konstantinou*
*School of Electrical Engineering and Telecommunications, UNSW Sydney, Australia.
e-mail: yumeng.tian@unsw.edu.au, g.konstantinou@unsw.edu.au

***Abstract*—Since the reduced number of sub-modules (SMs) in modular multilevel converters (MMCs) for medium-voltage DC (MVDC) applications cannot provide the same redundant design as high-voltage DC (HVDC) systems, reliability becomes a significant issue in MVDC systems. To evaluate the reliability performance of converters, arm reliability in MMC requires to be analysed and the design of redundancy can be further optimised. Considering the number of redundant SMs, redundancy operation schemes, and correlation coefficient between SMs, arm reliability are analysed in MMC for MVDC systems with multiple SM topologies. The aim of this paper is to provide a comprehensive evaluation of arm reliability in MMC with multiple SMs and identify the high-reliability options for SMs in different scenarios for MVDC applications.**

***Index Terms*—Arm Reliability, Modular Multilevel Converter, Sub-modules, MVDC systems.**

I. Introduction

MVDC systems have emerged as an attractive option for integrating renewable power generation and DC loads [1]. Compared with two-level and three-level converters, the use of MMCs in MVDC systems can provide several advantages, including increased financial benefits and reduced power losses [2]. Therefore, the MMC finds applications in MVDC systems, such as the Korea MVDC Pilot Project [3], the Baolong Industrial District, the Tangjiawan Science Park, and the Suzhou Industrial Park Pilot Project [4], just to mention a few.

Compared with HVDC systems, due to the reduction in the number of SMs in converters for MVDC applications, failure of a single SM has a greater impact on the operation of overall converter. The higher switching frequency of semiconductor devices in MVDC systems can further decrease the reliability of the converter [5]. Therefore, converter reliability has become a critical concern in MVDC applications.

Although the configuration of MMC provides flexibility and modularity to the converter, it also introduces a large number of semiconductor devices in MMC [6]. In order to improve the reliability in MMC, redundant design with additional SMs in an arm has been proposed in the literature [7]. However, the higher redundancy in converters also indicates higher financial investment. To achieve a balance between high reliability and effective cost, the number of redundant SMs in each arm needs to be properly evaluated. Compared with the base failure rate (BFR) of a single SM, the reliability of an MMC arm can represent the performance of the overall converter more appropriately. Therefore, based on the series connection of required and redundant SMs in one arm, the arm reliability and redundant design of the MMC need to be further analysed.

As far as the evaluation of arm reliability in MMC, the k-out-of-n model is a basic approach that has been widely applied in the literature [8]. However, with the consideration of redundant operation schemes in the converter, the BFR of SMs in one arm is not always identical. In this case, the k-out-of-n model is no longer suitable for all situations. To address this issue, Markov Chain has been implemented in the analysis [9], which can represent the different operation schemes through transition diagrams. Since the failure of one SM can cause waveform distortion in the converter arm, the lifetime of SMs in one arm is dependent on each other. To investigate the influence of the SM interdependence on arm reliability, Gumbel Copula has been used and correlation coefficient has been introduced in the evaluation of reliability [10].

More than 50 SM topologies have been proposed in the literature with different characteristics [11], indicating significant variations in the lifetime of SMs [12]. The multiple SM topologies can further result in differences in the arm reliability and the minimum number of redundant SMs in each arm, which are not yet evaluated in the literature. The influences of redundant operation schemes and correlation coefficient between SMs on the reliability of different SMs also need investigation. As a result, the evaluation and comparison of arm reliability in MMC with multiple SM topologies for MVDC systems require further research.

II. SM Base Failure Rate

There are three major stages in the investigation of reliability in MMCs (Fig. 1(a)): (1) identifying the component BFR, (2) calculating the SM BFR, and (3) evaluating the converter reliability.

The value of failures in time (FIT) of each component is shown in Table I, based on data of power circuit components provided by manufacturers [13], [14]. Furthermore, the BFR of control systems and power supply of [15] has been considered. Improved SMs introduce redundant structure in SM topologies, and a methodology was proposed in [12] for the evaluation of BFR in multiple SM topologies. Considering the open-circuit and short-circuit faults in components, the failures

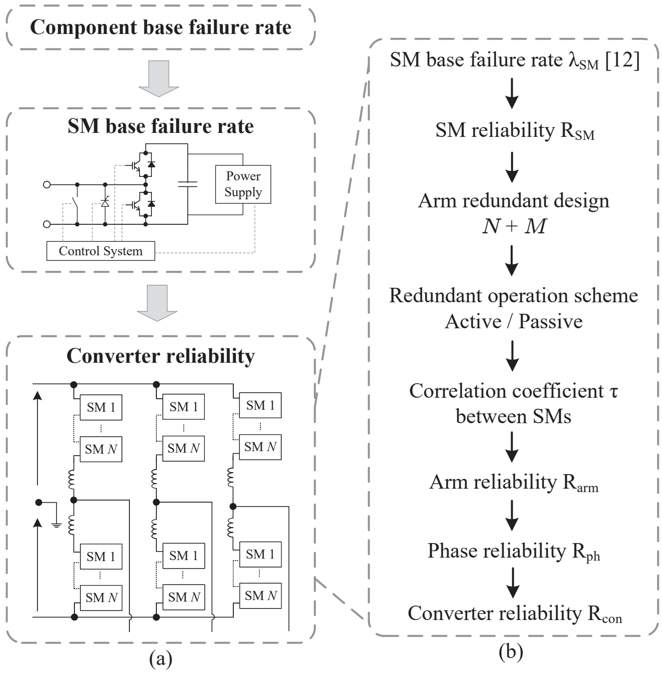

Fig. 1: The evaluation of MMC reliability at (a) system level and (b) converter level.

TABLE I: Base failure rate of components in a SM

	Component	FIT (occ /10^9 hours)
Power circuit	IGBT	200 [13]
	Diode	100 [13]
	Capacitor	300 [14]
Control system	Custom IC	150 [15]
	Optical Rx/Tx	200
	IC Circuit	13
Power supply	Ferrite Core	44 [15]
	Switching Power Supply	1000

of SMs have been classified into functional mode, degraded mode, and failed mode. The BFR in degraded and failed modes has been evaluated for 30 SMs suited to MVDC systems. Based on the results of [12], the BFR of certain SMs is double of other SM topologies, leading to significant differences in the lifetime of SMs and arm reliability in MMC.

III. Arm Reliability of MMC

With the identification of SM BFR, the reliability of an arm in MMC can be further evaluated. As illustrated in Fig. 1(b), by considering different aspects, three methodologies can be applied in the calculation of arm reliability.

A. *k-out-of-n model*

Based on the constant SM BFR, the reliability of an SM can be calculated by

$$R_{SM}(t) = e^{-\lambda_{SM} t} \tag{1}$$

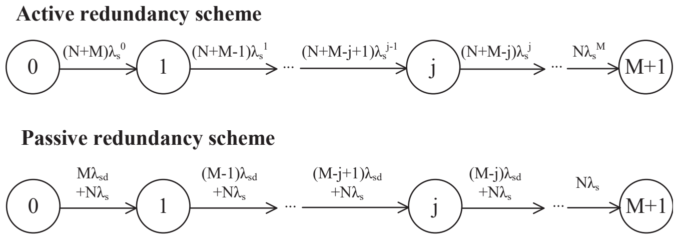

Fig. 2: Markov Chain for an MMC arm operating under active redundancy scheme and passive redundancy scheme.

For an arm that includes N required SMs and M redundant SMs with identical BFR, the k-out-of-n model can be utilized in the evaluation of arm reliability [8]. The arm reliability R_{arm_kn} in an MMC can be calculated as

$$R_{arm\_kn}(t) = \sum_{i=N}^{N+M} C_{N+M}^{i} (R_{SM})^i (1 - R_{SM})^{N+M-i} \tag{2}$$

where,

$$C_{N+M}^{i} = \frac{(N+M)!}{i!(N+M-i)!} \tag{3}$$

Under the traditional operating mode of MMCs, SMs in a single arm have the same BFR. Therefore, due to its low computational requirements, the k-out-of-n model has been widely applied in the analysis of converter reliability.

B. *Markov Chain*

In terms of redundant design of MMC, the operation of converters includes active and passive schemes. According to the number of participating SMs in each arm, the active scheme can be further classified into conventional mode and load-sharing mode [16]. Although all SMs are activated during the modulation of MMC, only N SMs participate in the generation of output voltages under conventional mode. However, in load-sharing mode, N+M SMs are active to share the DC voltage, leading to lower voltage stress in each SM than conventional mode [16]. Since the voltage stress has a direct impact on the lifetime of components, SM BFR in load-sharing mode is variable with different number of healthy SMs in an arm. In the operation of passive scheme, the redundant SMs are always bypassed until one healthy SM fails [17]. Thus, the required and redundant SMs in one arm have unequal BFR in passive mode.

In the k-out-of-n model, the BFR of all SMs in one arm is identical, which only suits to the traditional mode of active scheme. Therefore, Markov Chains have been introduced in the analysis [9], which use transition diagrams to evaluate arm reliability under all redundant operation schemes (Fig. 2). In the transition of BFR in total SMs, state 0 is the initial state that all SMs operate properly and state M+1 is the failed state of the arm. For the intermediate state, state j represents that j SMs are failed. In active scheme, λ_s^j is the BFR of SMs in j state, which is a constant under conventional mode, while depends on the number of participating SMs in load-sharing mode. The voltage stress factors of semiconductor devices and capacitors can be found in [18] and [19].

Based on the Markov Chain, by applying Laplace transforms and inverse Laplace transforms [9], probability of the arm in each state $P_j(t)$ in active scheme can be calculated iteratively:

$$P_0(t) = e^{-(N+M)\lambda_s^0 t}, \tag{4}$$

$$P_j(t)=\int_0^t (N+M-j+1)\lambda_s^{j-1} e^{-(N+M-j)\lambda_s^j \tau} P_{j-1}(t-\tau)d\tau, \tag{5}$$

$$P_{M+1}(t) = \int_0^t N\lambda_s^M P_M(\tau)d\tau. \tag{6}$$

The arm reliability under active scheme is the summation of probabilities in state 0 to M:

$$R_{arm\_MC}(t) = \sum_{j=0}^{M} P_j(t) \tag{7}$$

Since SMs in passive scheme have different BFR, as shown in Fig. 2, λ_{sd} represents the BFR of redundant SMs and λ_s is the BFR of operating SMs. Similar to the active scheme, probability of the arm in each state under passive scheme $P_j^*(t)$ can be calculated by

$$P_0^*(t) = e^{-(M\lambda_{sd}+N\lambda_s)t}, \tag{8}$$

$$\begin{gathered} P_j^*(t) = [(M-j+1)\lambda_{sd} + N\lambda_s]\times \\ \int_0^t e^{-[(M-j)\lambda_{sd}+N\lambda_s]\tau} P_{j-1}^*(t-\tau)d\tau, \end{gathered} \tag{9}$$

$$P_{M+1}^*(t) = \int_0^t N\lambda_s P_M^*(\tau)d\tau. \tag{10}$$

The arm reliability in passive scheme is

$$R_{arm\_MC}^*(t) = \sum_{j=0}^{M} P_j^*(t) \tag{11}$$

C. Gumbel Copula

In an arm of MMC, SMs operate under the same mission profile and the failure of one SM has effects on the remaining SMs. It indicates that the lifetime of SMs in one arm is related to each other. However, the BFR of SMs is assumed to be completely independent in the analysis introduced above. To address this issue, Gumbel Copula has been implemented in the evaluation of arm reliability [20].

According to the marginal probability distribution [10], Gumbel Copula is a joint function that can obtain the joint distribution function. The correlation coefficient ($\tau \in$ [0,1]) is introduced to represent the degree of correlation between SMs [21]. The BFR of SMs in one arm is independent when τ is zero, indicating that the failure of an SM does not affect the operation / failure of other SMs in the same arm. The greater the value of τ, the more significant impact of a failed SM on the lifetime of the remaining SMs.

Based on the N-dimensional joint Copula function [10], the reliability of required and redundant SMs in a single arm can be analysed separately. For an arm that only consists of required SMs, one failed SM can lead to the failure of the overall arm. Therefore, the N required SMs are performed in a logic series system. The reliability of N required SMs in one arm can be calculated as

$$R_N(t) = \sum_{p=0}^{N} (-1)^p C_N^p (1-R_{SM})^{p^{1-\tau}} \tag{12}$$

With regards to redundant SMs, the arm is failed until all redundant SMs are failed. A parallel system can be applied in this case and the reliability of M redundant SMs in an arm is calculated by

$$R_M(t) = 1-(1-R_{SM})^{M^{1-\tau}} \tag{13}$$

In a single arm of MMC, the required and redundant SMs are connected in series. With the combination of N required SMs and M redundant SMs, the arm reliability based on Gumbel Copula can be further calculated by

$$R_{arm\_GC}(t) = \sum_{q=N}^{N+M} C_{N+M}^i R_q(t) \tag{14}$$

in which,

$$R_q(t) = \sum_{k=0}^{q} (-1)^k C_q^k (1-R_{SM})^{(k+N+M-q)^{1-\tau}} \tag{15}$$

IV. Results and Comparison

Based on the methodologies introduced above, the arm reliability of MMC in MVDC applications has been evaluated separately. The analysis has been performed for all 30 SM topologies, however, due to the page limitations, only some SMs are shown in this section.

A. k-out-of-n model

Based on the k-out-of-n model, arm reliability of MMC with different number of redundant SMs is shown in Fig. 3 and Fig. 4. According to the level of positive output voltages, SMs can be classified into two-level and three-level SMs [11]. To achieve the same DC-link voltage in the converter, 30 two-level SMs or 15 three-level SMs per arm are utilized as required SMs in the analysis.

Although the HB-SM includes fewer number of semiconductor devices, the structure redundancy in FB-SM yields the same BFR of HB and FB-SM in failed mode [12]. Therefore, as shown in Fig. 3, FB-SM can provide the same arm reliability as HB-SM to the converter with DC fault ride-through (FRT) capability. In DCBSSM, the six discrete diodes provide DC FRT capability to the converter, but also lead to the greater SM BFR and the lowest arm reliability. For a certain SM topology, the reliability is always increased with more redundant SMs, demonstrating that the larger number of redundant SMs contributes to the improvement of arm reliability.

In terms of three-level SMs shown in Fig. 4, SFB-SM has the best performance in arm reliability because of the

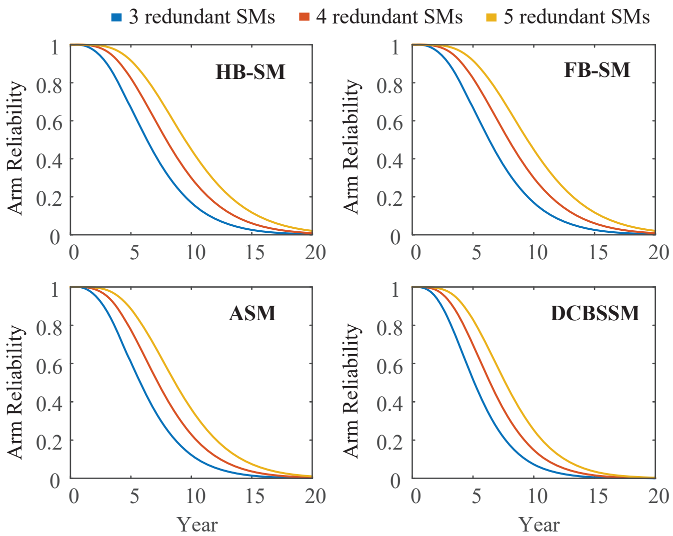

Fig. 3: Arm reliability based on k-out-of-n model for a converter including 30 two-level required SMs and redundant SMs in each arm.

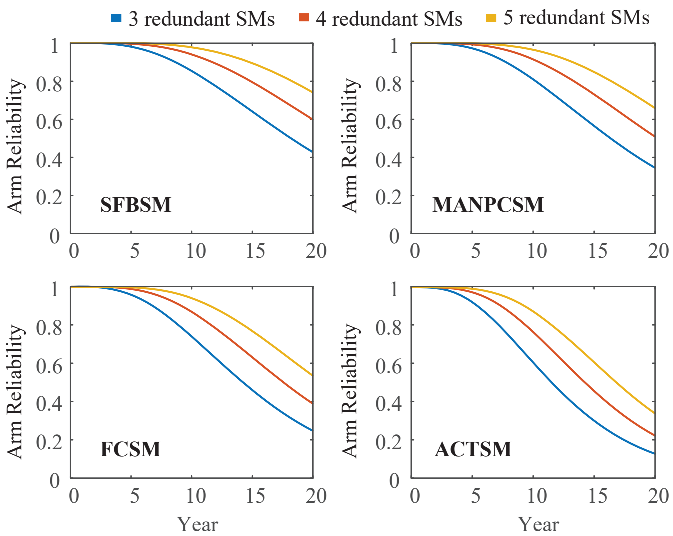

Fig. 4: Arm reliability based on k-out-of-n model for a converter including 15 three-level required SMs and redundant SMs in each arm.

redundant current paths and capacitors in SM structure. As far as the contribution of one more redundant SM, the increase of reliability is reduced when the number of SMs in each arm is greater, which is common across all SMs. Since the more redundant SMs indicates higher cost in the overall converter, the minimum number of redundant SMs can be identified for a proper aim of reliability.

Compared with two-level SMs, the redundant structure in three-level SMs normally leads to lower SM BFR [12]. The higher output voltage level of three-level SMs also reduce the number of required SMs in each arm. Consequently, the arm reliability of three-level SMs is commonly higher than two-level SMs. Among all SM topologies that are suited to MVDC applications, the highest reliability occurs in SFBSM, which remains more than 80% with 3 redundant SMs in 10 years. To achieve a specific percentage of arm reliability within a given period, the appropriate SM topology and redundant design in converters can be obtained based on the evaluation.

B. Markov Chain

With the use of Markov Chain, for an arm that involves 30 two-level or 15 three-level required SMs and 5 redundant SMs, Fig. 5 illustrates the arm reliability of multiple SMs under three redundancy operation schemes.

In the load-sharing mode, the reduced voltage stress of each SM leads to the decrease of failure rate in devices, further providing improved reliability than the conventional active mode. Because of the different power circuit components involved in the failure of each SM, the increased reliability observed in the load-sharing mode is different across multiple SMs. The two-level SMs commonly have simple structures and fewer devices, which indicates that the effect of decreased BFR in components is limited. Therefore, the increase of arm reliability in two-level SMs is lower than in certain three-level SMs, such as ACTSM and CDSM. However, for three-level SMs with sufficient structure redundancy (e.g. Mix-SM and MANPCSM), the components included in the SM failure is significantly fewer, leading to smaller improvement of reliability than two-level SMs. Due to the redundant structure in SFB-SM, the failure of one semiconductor device or capacitor cannot cause the SM failure and the SM BFR is only related to the power supply and control systems. Hence, the two active modes provide exactly the same arm reliability for SFB-SM.

During the operation of converters under passive scheme, the BFR of redundant SMs is quite low when they are bypassed. As a result, the arm reliability in passive mode is always higher than the conventional active mode. The improvement of arm reliability in passive mode is dependent on the BFR of SMs, in which the increase is greater for SMs with high reliability. Among the three different operation modes, the conventional active mode provides the worst arm reliability, which is consistent across all SM topologies.

In the comparison between load-sharing and passive modes, the optimal operating scheme depends on the failed components in the failure of SMs. For SMs that the failure can be caused by both failed semiconductor devices and capacitors, the load-sharing mode shows higher reliability. However, one failed capacitor in three-level SMs normally cannot result in the failure of the total SM. In this case, the arm reliability is higher under passive operation mode. In SFB-SM, since the reliability in load-sharing mode equals to the conventional active mode, the passive mode presents better reliability. By identifying the operation mode with high reliability, the arm reliability can be improved by up to 10% during the operating period. Due to the different components included in the calculation of SM BFR, the optimal operating schemes of SMs are different and need to be analysed individually.

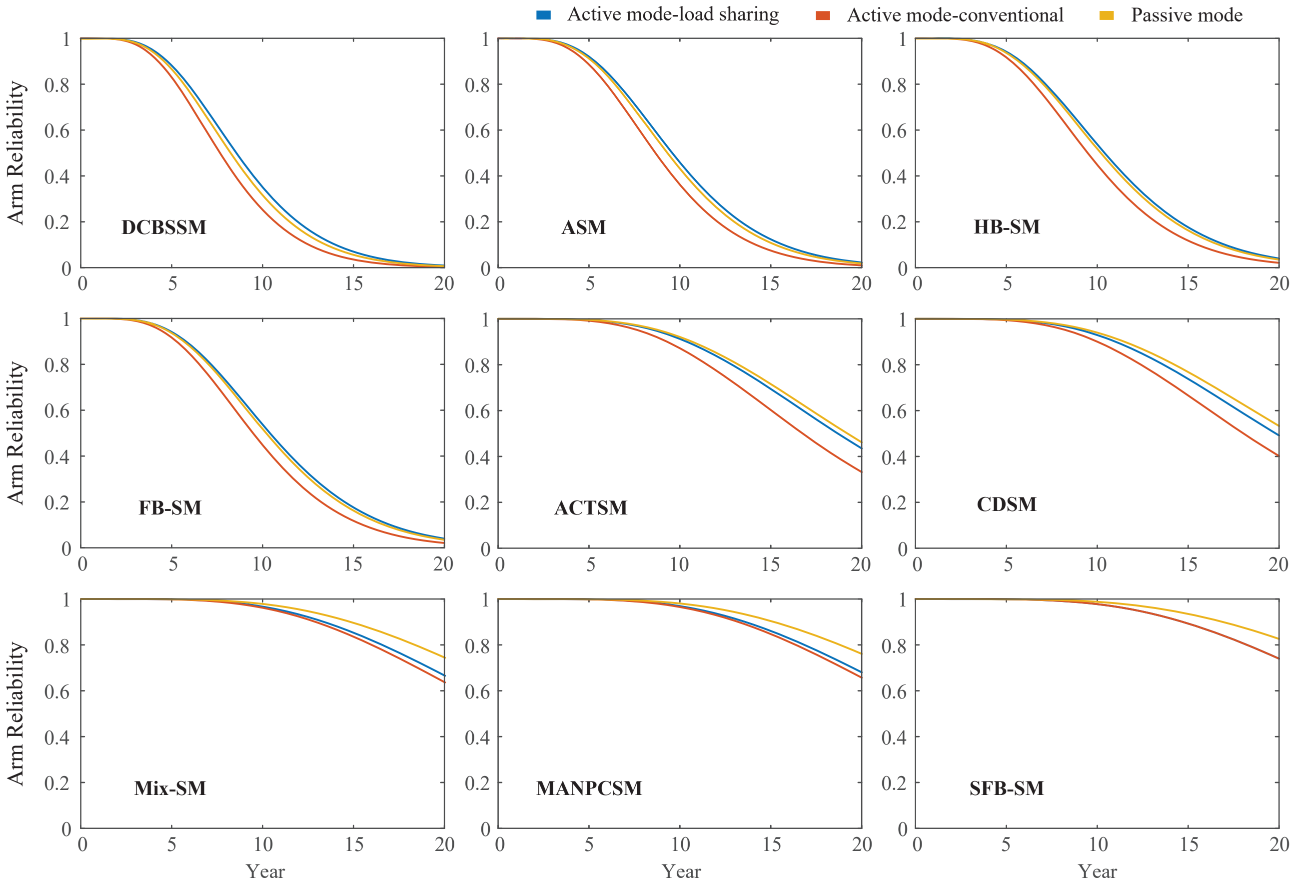

Fig. 5: Arm reliability based on Markov Chain for a converter including 30 two-level or 15 three-level required SMs and 5 redundant SMs in each arm.

C. Gumbel Copula

For converters that have the same redundancy design as in the above section, arm reliability obtained by Gumbel Copula is shown in Fig. 6. The value of correlation coefficient between SMs can be found in [21], [22] and the τ of 0 to 0.4 is applied in the analysis.

When the SMs are fully independent, arm reliability obtained by Gumbel Copula matches the results in above approaches. It can be observed that with different correlation coefficients, the variation of arm reliability is not liner. With the increase of τ, since the failure of one SM has a greater effect on the overall converter, the arm reliability is decreased in the initial stage. However, the trend is opposite over long-term operation as the redundancy of converter becomes insufficient. In order to guarantee the preventive maintenance of systems, the reliability of converters in the early service year is the primary concern in projects. Therefore, it can be concluded that the less correlation between SMs contributes to the improvement of arm reliability in MMC.

Assuming the same service year, the influence of correlation coefficient between SMs is smaller in SMs exhibiting higher reliability, indicating that these SMs can present better tolerance to the worse operating environment of MMC. Since the arm reliability is reduced over time, the correlation between SMs has a more significant effect on the reliability when the service year is larger. For projects with different SM topologies and time duration, the optimal design of SM correlation in MMCs should be evaluated for each application.

V. Conclusion

For SMs that are suited to MVDC applications, this paper provides a comprehensive evaluation of arm reliability with different considerations. Due to the redundant structure and high output voltage level, three-level SMs normally exhibit better performance than two-level SMs in arm reliability. Compared with conventional active operation mode, load-sharing mode and passive scheme always provide higher reliability to the converter. For an MMC that includes design of redundancy, the interdependence of SMs decreases the arm reliability in the initial service years. This analysis assists with identifying the redundant design and optimal redundant operation scheme in multiple SMs, and evaluating arm reliability with a given correlation coefficient between SMs.

Acknowledgment

The work was supported under Australian Research Council's Discovery Project (DP210102294).

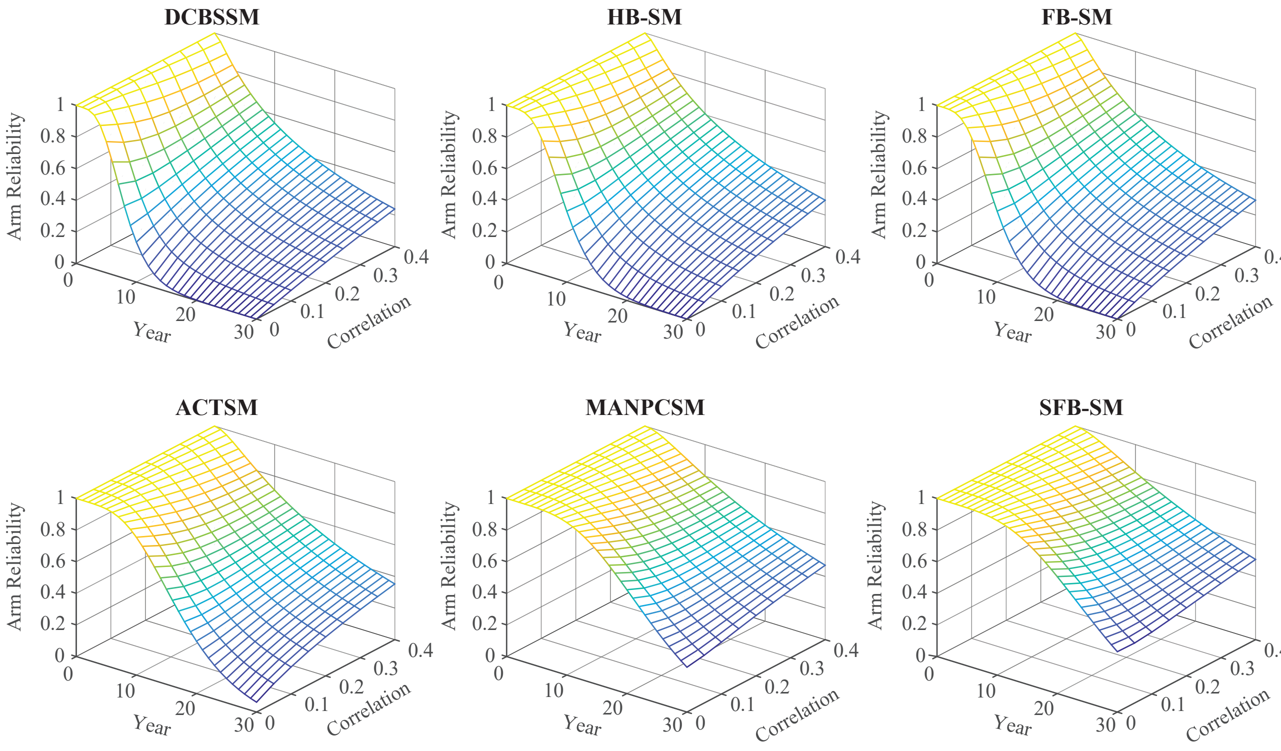

Fig. 6: Arm reliability based on Gumbel Copula for a converter including 30 two-level or 15 three-level required SMs and 5 redundant SMs in each arm.

REFERENCES

[1] J. C. T. B. 875, "Medium voltage dc system," *Cigre*, 2022.

[2] G. Abeynayake, G. Li, T. Joseph, J. Liang, and W. Ming, "Reliability and cost-oriented analysis, comparison and selection of multi-level mvdc converters," *IEEE Trans. on Power Delivery*, vol. 36, no. 6, pp. 3945–3955, 2021.

[3] M. Lee, "The first mvdc station project in korea," *Cigre*, 2023.

[4] Y. Fan, Y. Chi, Y. Li, Z. Wang, H. Liu, W. Liu, and X. Li, "Key technologies for medium and low voltage dc distribution system," *Global Energy Interconnection*, vol. 4, no. 1, pp. 91–103, 2021.

[5] J. O. Gonzalez, R. Wu, S. Jahdi, and O. Alatise, "Performance and reliability review of 650 v and 900 v silicon and sic devices: Mosfets, cascode jfets and igbts," *IEEE Trans. on Ind. Electron.*, vol. 67, no. 9, pp. 7375–7385, 2020.

[6] P. Yu, W. Fu, L. Wang, Z. Zhou, G. Wang, and Z. Zhang, "Reliability-centered maintenance for modular multilevel converter in hvdc transmission application," *IEEE J. of Emerging and Selected Topics in Power Electron.*, vol. 9, no. 3, pp. 3166–3176, 2021.

[7] G. Konstantinou, J. Pou, S. Ceballos, and V. G. Agelidis, "Active redundant submodule configuration in modular multilevel converters," *IEEE Trans. on Power Delivery*, vol. 28, no. 4, pp. 2333–2341, 2013.

[8] P. Tu, S. Yang, and P. Wang, "Reliability- and cost-based redundancy design for modular multilevel converter," *IEEE Trans. on Ind. Electron.*, vol. 66, no. 3, pp. 2333–2342, 2019.

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

[10] J. Xu, H. Jing, and C. Zhao, "Reliability modeling of mmcs considering correlations of the requisite and redundant submodules," *IEEE Trans. on Power Delivery*, vol. 33, no. 3, pp. 1213–1222, 2018.

[11] Y. Tian, H. R. Wickramasinghe, Z. Li, J. Pou, and G. Konstantinou, "Review, classification and loss comparison of modular multilevel converter submodules for hvdc applications," *Energies*, vol. 15, no. 6, p. 1985, 2022.

[12] Y. Tian and G. Konstantinou, "Base failure rate calculation for submodules in modular multilevel converters for mvdc applications," in *2022 7th IEEE Workshop on the Electronic Grid (eGRID)*, 2022, pp. 1–5.

[13] Infineon, https://www.infineon.com/cms/en/product/power/.

[14] TDK, https://www.datasheets.com/en/part-details/b25750h2448k004-tdk-54457966#datasheet.

[15] C. Kim and S. Lee, "Redundancy determination of hvdc mmc modules," *Electronics*, vol. 4, no. 3, pp. 526–537, 2015.

[16] G. T. Son, H.-J. Lee, T. S. Nam, Y.-H. Chung, U.-H. Lee, S.-T. Baek, K. Hur, and J.-W. Park, "Design and control of a modular multilevel hvdc converter with redundant power modules for noninterruptible energy transfer," *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1611–1619, 2012.

[17] B. Li, Y. Zhang, R. Yang, R. Xu, D. Xu, and W. Wang, "Seamless transition control for modular multilevel converters when inserting a cold-reserve redundant submodule," *IEEE Transactions on Power Electronics*, vol. 30, no. 8, pp. 4052–4057, 2015.

[18] MIL-HDBK-217F, "Military handbook for reliability prediction of electronic equipment," *Department of Defense*, 1990.

[19] Z. Li, H. Li, F. Lin, Y. Chen, D. Liu, B. Wang, H. Li, and Q. Zhang, "Lifetime investigation and prediction of metallized polypropylene film capacitors," *Microelectronics Reliability*, vol. 53, no. 12, pp. 1962–1967, 2013.

[20] J. Xu, L. Wang, Y. Li, Z. Zhang, G. Wang, and C. Hong, "A unified mmc reliability evaluation based on physics-of-failure and sm lifetime correlation," *International Journal of Electrical Power & Energy Systems*, vol. 106, pp. 158–168, 2019.

[21] D. Wu, C. Zhao, and J. Xu, "Reliability modeling and redundant design of mmc-hvdc converters considering direct-coupled sub-module correlations," in *2019 4th IEEE Workshop on the Electronic Grid (eGRID)*, 2019, pp. 1–6.

[22] J. Xu, L. Wang, D. Wu, H. Jing, and C. Zhao, "Reliability modeling and redundancy design of hybrid mmc considering decoupled sub-module correlation," *International Journal of Electrical Power & Energy Systems*, vol. 105, pp. 690–698, 2019.