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Impact of the Various Components Consideration on Choosing Optimal Redundancy Strategy in MMC

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***Abstract*—Power electronics converters will play a crucial role in power grid expansion. Superior advantages offered by MMC make it the most popular candidate amongst various converter topologies. However, due to a large number of components installed within MMC, reliability analysis is an unavoidable task that needs to be carried out to maximize the MMC's availability and positively affect the overall performance of the power system. To this end, applying redundancy at the converter level is one of the solutions to increase the reliability of the MMC. In this paper, the reliability of the MMC is evaluated during its useful lifetime according to various applied redundancy strategies. At the same time, it is proposed that optimal-decision making in redundancy strategy depends on the failure rate of which components are considered. It will be presented that the superiority of the applied redundancy can vary.**

***Index Terms*—MMC, Reliability, Redundancy, Failure rate.**

I. Introduction

Modular Multilevel Converter (MMC) has got worldwide consideration to be implemented in various applications from the medium voltage (MV) to high voltage (HV) in grid-connected power electronics converters [1]. MMC offers many advantages such as modularity, scalability, low harmonics, low power losses, etc. [2]. Nevertheless, within the structure of the MMC, a large number of components are used, including power switches, capacitors, indicators, breakers, sub-module (SM) controllers, SM power supply, etc. [3]. Therefore, the reliability of the MMC is lower than other types of converters. This study focuses on the reliability analysis at the converter level..

Reliability analysis of the MMC and grid-connected MMC falls into three main parts: components level [4]–[6], converter level [7]–[14] and system level [15]–[22] in which the converter level is the focus of this study.

At the converter level studies, [7] proposes an optimized design of the MMC by using half-bridge and full-bridge SMs that meets the reliability and cost requirements. In [8], authors compare two redundancy strategies (standby, active fixed-level) from a reliability and cost-efficiency perspective. In [10], the reliability of the voltage source converter multi-terminal DC (VSC-MTDC) is evaluated in which the effects of redundancy in MMC are shown; also, system-level reliability is analyzed by considering the penetration of wind farms with de-rated power. In detailed comparison among various redundancy strategies (standby, active load sharing, and active fixed-level) is carried out in [11]; furthermore, in [11], a novel redundancy strategy is proposed where the redundant SMs of each arm are shared with other arms through mechanical switches through the implementation of such redundancy strategy is not cost-effective. In [3], the redundancy strategies of MMC are compared by modeling the hybrid MMC. In [13], a thorough comparison of power electronics converters utilized in MV application is carried out. An optimal power converter and the number of redundant components based on the power converter rating of the system are specified in [13]. In [9], the reliability of the MMC by considering two types of Hipak and press-pack insulated-gate bipolar transistor (IGBT) is carried out to propose an optimal design of MMC.

In this paper, the reliability of the MMC at the converter level is analyzed, and the impact of various components within SM on reliability will be explained. This paper shows that a redundancy strategy's superiority depends on initial assumptions regarding which elements within SM are considered for reliability evaluation. The rest of the article is organized as follows; in section II, an overview of reliability and redundancy strategies within MMC is given. Section III explains the SM structure and the system's characteristics. Section IV shows the reliability results for different scenarios regarding the consideration of the components and discusses the facts that should be considered. Ultimately conclusions are presented in section V.

II. Reliability and redundancy overview of MMC

In the following, the general explanation is given to overview the MMC's reliability. Also, different redundancy strategies that are applied in MMC will be elaborated.

A. MMC reliability overview

MMC consists of many components, including power switches, capacitor bank, gate drive, fuses, power supply, etc. It operates properly if all the mentioned components function correctly. The reliability R(t) is an index to determine the probability of correct operation of the MMC for a specific period under a particular condition. R(t) can be calculated as (1).

$$R(t) = \frac{N(t)}{N(0)} \tag{1}$$

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Where, N(t) and N(0) are the total numbers of operational components at times t and 0, respectively. Hence, the reliability of MMC is the probability that MMC operates adequately during the period [0, t].

However, (1) for MMC requires long-term experimental data that is not available due to the confidentiality and novelty of MMC. If it is available, it exists only for a short period. Therefore, failure rate $\lambda(t)$ can be used, which describes the likeliness of a failure occurrence. For power electronics components, the well-known bathtub curve [10] is used to acquire the failure rate data. It is mainly considered in a useful lifetime where $\lambda(t)$ is almost constant. So, for calculating the reliability of MMC based on the failure rate, the mathematical equations (2) and (3) can be used as follows:

$$R(t) = e^{-\int_a^b \lambda(t)dt} \tag{2}$$

$$R(t) = e^{-\lambda t} \tag{3}$$

In this study, for comparison purposes, the reliability index B_{10} lifetime is applied, which calculates the reliability of the MMC where at least 90% of the MMC's components are operational and healthy.

B. MMC redundancy overview

Redundancy strategies are applied at the converter level to increase the MMC's reliability. In converters with redundancy, Additional SMs are used within the structure of the MMC during the designing and planning phase. However ,there are several modes with which an MMC having redundant SM's can operate namely, standby, active load-sharing, and active fixed-level [11]. In the following, the first two redundancy strategies are scrutinized, and analytical methods for calculating the reliability of the MMC with each specific redundancy strategy are explained.

1) Standby redundancy: In standby operation mode, if there are m additional SMs per arm, they remain idle and not operational until the first failure of one of the SMs occurs; then, the first redundant SM will take over and starts to operate. This process keeps continuing until there is no redundant SM left. Hence, if k are the minimum number of SM's required for each arm and n, the SM's installed with in the arm, then, the number of redundant standby SM's are m = n-k.. The minimum number of levels is dependent on the voltage level of the DC-link, switch and power rating of the MMC [13]. Therefore, the MMC always operates with k level; the reliability block diagram (RBD) model of standby redundancy is presented in Fig 1.

According to the RBD model of standby redundancy, an arm's reliability can be calculated using the Homogeneous Poisson Process with a constant failure of λ_s where λ_s is the failure rate of an arm with k operational SMs. The Homogeneous Poisson Process distribution for obtaining the reliability of MMC's arm is as follows:

$$\lambda_{\text{s}} = (\lambda_{SM}) \times k \tag{4}$$

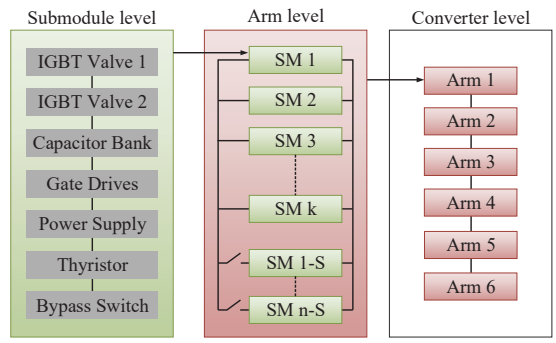

Fig. 1. RBD model of MMC with standby redundancy.

$$R_{\text{arm-S}}(t) = P[N(t) \leq (n-k)] = \sum_{i=0}^{n-k} \frac{(\lambda_s t)^i}{i!} e^{-\lambda_s t} \tag{5}$$

and λ_{SM} is the failure rate of a SM.

2) Active load-sharing redundancy: In active load-sharing redundancy, all the n SMs, including redundant SMs within the arm, are operational and share the load in normal conditions. Therefore, compared to the standby redundancy, the voltage across the SMs will be lower, consequently decreasing the risk of SM failure. In active load-sharing redundancy, in case of SMs failure, the faulty SM will be bypassed, and the remaining SMs will continue to operate. Nevertheless, in case of SMs failure in active load-sharing redundancy, the voltage across the operational SMs will increase, consequently changing the SM's failure rate. This fact is essential to be considered. The RBD model of the MMC with applied active load-sharing redundancy is shown in Fig 2.

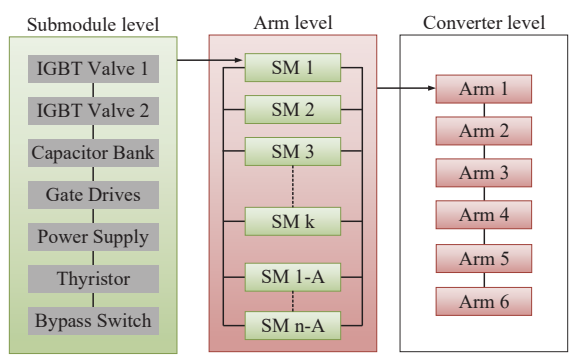

Fig. 2. RBD model of MMC with active load-sharing redundancy.

According to the RBD model and the fact that in active load-sharing redundancy, the voltage across the SMs changes in case of SM failure, Markov Chain is used for calculating the reliability of MMC's arm shown in Fig 2.

In the Markov Chain shown in Fig. 3, state 0 is the initial state in which all the n SMs are sharing the load, whereas, state n-k+1 is representative of the fail state in which more than k minimum required SMs failed. The differential equations obtained by Markov Chain are as (6)

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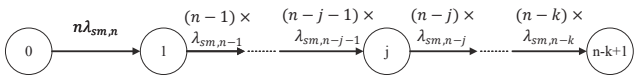

Fig. 3. Markov chain for an arm in active load-sharing redundancy mode.

$$\begin{aligned}
\frac{dP_0(t)}{dt} &= -n\lambda_{\text{SM,n}}P_0(t) \\
&= \\
\frac{dP_{\text{j}}(t)}{dt} &= (n-j-1)\lambda_{\text{SM,n-j-1}}P_{\text{j-1}}(t) \\
&\quad - (n-j)\lambda_{\text{SM,n-j}}P_{\text{j}}(t) \\
&= \\
\frac{dP_{\text{n-k+1}}(t)}{dt} &= k\lambda_{\text{SM,n-k}}P_{\text{n-k}}(t)
\end{aligned} \tag{6}$$

In which $P_{\text{j}}(t)$ is the state j, $\lambda_{SM,n-j-1}$ is the failure rate of SM upon the condition that n-j SMs are operational. The Laplace transform of (6) and then inverse transform will result in (7) as follows:

$$\begin{aligned}
P_0(t) &= e^{-n\lambda_{\text{SM,n}}t} \\
&= \\
P_{\text{j}}(t) &= \int_0^t (n-j-1)\lambda_{\text{SM,n-j-1}}e^{-(n-j)\lambda_{\text{SM,n-j}}\tau}P_{\text{j-1}}(t-\tau)d\tau \\
&= \\
P_{\text{n-k+1}}(t) &= \int_0^t k\lambda_{\text{SM,n-k}}P_{\text{n-k}}(\tau)d\tau
\end{aligned} \tag{7}$$

Therefore, the successful operation of the converter can be obtained by summing of successful states in (8)

$$R_{\text{arm-A}}(t) = \sum_{j=0}^{\text{n-k}} P_{\text{j}}(t) \tag{8}$$

At final stage, after calculating the arm's reliability of the MMC in active load-sharing and standby redundancy, the reliability of the MMC is calculated as (9) where subscript X can be replaced with either standby (S) or active load-sharing (A).

$$R_{\text{MMC-x}}(t) = [R_{\text{arm-x}}(t)]^6 \rightarrow x \in (\text{A}, \text{S}) \tag{9}$$

III. Impact of Components Failure Rate

SM is composed of many components, shown in Fig 4. As it can be seen, SM contains IGBT modules, capacitor bank, high-speed thyristor, bypass switch, power supply, gate drive, and control system, which all play a crucial role in the successful operation of the MMC.

However, in previous studies, various assumptions have been made regarding which components within the SM should

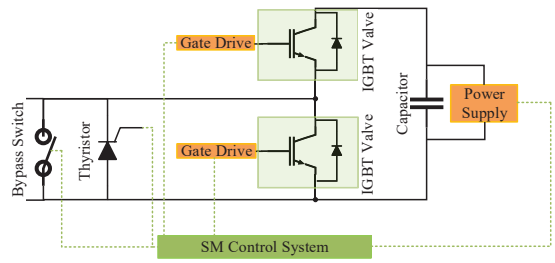

Fig. 4. Half-bridge SM structure

be considered for reliability analysis. Table I summarizes multiple studies that indicate which elements have been considered. In this paper, it will be shown that components consideration will change which redundancy strategy is superior. According to the previous studies, two major assumptions can be made as follows.

1) **Power components:** IGBT module and capacitor banks are the only power components within the SM structure, and their material deteriorates as time passes. Also, the failure rate of the IGBT module and capacitor banks depends on the arm's operational current, the voltage across the SM, and temperature.
2) **Auxiliary components:** Other components in the SM are essential, but they do not deteriorate, and their operation is not dependent on the operational current and voltage of the MMC. For example, the bypass switch is not functional almost most of its lifetime unless the SM is needed to be bypassed. In this case, the bypass switch operates, so the bypass switch can be considered 100% reliable. However, these components can experience statistical failure.

The MMC that is considered for this study has 10 MVA nominal capacity with pole-to-pole DC voltage of 17 kV. There are many IGBT options to be implemented in this system. However, the IGBT module from Infineon Technologies, FF450R33T3E3BPSA1-ND is used; the withstand voltage of this component is 3.3 kV. The base failure rate for this IGBT module is considered to be 0.000876 occ/year [8]. Considering the capacitor, the capacitor of KEMET, ALS71C133QT500-ND with 500 V and 11 mF is applied where its base failure rate is 0.000876 occ/year [8]. The used gate drive in this study is from Power Integrations SCALE-2 2SC0535T2A1-33. In Table II the characteristic of the considered system is shown.

As mentioned above, the failure rate of IGBT and capacitor is dependant on the temperature and voltage across them. Hence, these limitations need to be considered in failure rate formula of the IGBT and capacitors. Regarding the capacitor failure rate:

$$\lambda_{Cap} = \lambda_{\text{base-Cap}}\pi_{\text{T}}\pi_{\text{V}}\pi_{\text{SR}}\pi_{\text{Q}}\pi_{\text{E}}\pi_{\text{C}} \tag{10}$$

In (10), the base failure rate for film capacitor is equal to 0.000876 occ/year that is shown in Table I; for taking into account the effect of the series resistance of the capacitor, the

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TABLE I
COMPARISON OF THE EXISTING LITERATURE REGARDING SM'S COMPONENTS CONSIDERATION FOR RELIABILITY.

	Power Components		Auxiliary Components				
Reference	**IGBT module**	**Capacitor**	**Thyristor**	**Power Supply**	**SM control System**	**Gate Drive**	**Bypass Switch**
[10], [14]	✓	✓	✗	✗	✗	✗	✗
[13], [23]	✓	✓	✗	✗	✗	✓	✗
[12]	✓	✓	✓	✓	✓	✗	✓
[7]	✓	✓	✗	✗	✓	✗	✗
[8]	✓	✓	✗	✗	✗	✗	✗
[11]	✓	✓	✗	✓	✓	✗	✗
[3]	✓	✓	✓	✗	✓	✗	✗
[9]	✓	✗	✗	✗	✗	✗	✗

TABLE II
MMC CHARACTERISTICS AND FAILURE RATES

Symbols	Item	Value
n	Minimum number of SMs (k)	9
V_{dc}	Pole-to-pole DC voltage	17 kV
S_{MMC}	Rated power	10 MVA
V_{IGBT}	Withstand voltage of IGBT	3300 V
S_{f}	Safety factor of IGBT	0.6
E_{MMC}	Energy stored in the MMC	9.1 kJ/MVA
$\lambda_{\text{base-IGBT}}$	IGBT base failure rate	0.000876 occ/y [8], [13]
$\lambda_{\text{base-Cap}}$	DC capacitor base failure rate	0.000876 occ/y [8], [13]
λ_{PS}	Power supply failure rate	0.0023214 occ/y [12]
λ_{Thy}	Thyristor failure rate	0.000411 occ/y [12]
λ_{CS}	Control system failure rate	0.00318 occ/y [11], [12]
λ_{GD}	Gate drive failure rate	0.00438 occ/y [13]

π_{SR} is considered and it is equal to 0.1; quality aspect of the capacitor is π_Q that is 10 for commercialized capacitors; another factor in determining the failure rate of the capacitor is environmental factor π_{E} that is equal to 1 for the situations in which surrounding environment of the capacitor is controlled; π_C is the capacitance factor which is formulated as (11); voltage stress π_V is a variable factor in determining the actual failure rate of the capacitor that can be evaluated by (12), π_T is the temperature factor formulated as (13).

$$\pi_C = (C)^{0.09} \tag{11}$$

$$\pi_V = [\frac{V_{\text{operating}}}{0.6 \times V_{\text{rated}}}]^5 + 1 \tag{12}$$

$$\pi_T = exp[\frac{-0.15}{8.617 \times 10^{-5}}[\frac{1}{T_{vj} + 273} - \frac{1}{298}]] \tag{13}$$

In which T_{vj} is the ambient temperature of capacitor, and C in (11) is in μF. The failure rate of the IGBT is formulated as follows:

$$\lambda_{\text{IGBT}} = \lambda_{\text{base-IGBT}}\pi_{\text{T}}\pi_{\text{S}}\pi_{\text{A}}\pi_{\text{R}}\pi_{\text{E}} \tag{14}$$

$$\pi_{\text{T}} = exp[-2114 \times [\frac{1}{T_{\text{j}} + 273} - \frac{1}{298}]] \tag{15}$$

$$\pi_{\text{S}} = 0.045 \times exp[3.1\frac{V_{\text{applied}}}{V_{\text{rated}}}] \tag{16}$$

In (14), the base failure rate of IGBT is 0.000876 occ/year as presented in Table I; π_T is the temperature factor for determining the failure rate of IGBT that can be calculated as (15); Similar to the failure rate of the capacitor, voltage stress factor π_S is a variable element in determining the actual failure rate of IGBT, and it is formulated as (16); IGBTs can be used for various applications in which the π_A is determined, and it is equal to 0.7 for switching applications; π_R defines the power rating which is equivalent to 1; again like capacitors, surrounding environment factor π_E can affect the IGBT failure rate which is equal to 6 in situations that surrounding environment is controlled. T_j is the junction temperature of the IGBT which is varying between 80^oC to 90^oC according to the realistic internal measurements.

IV. RESULTS AND DISCUSSION

In this study, the reliability analysis of MMC is performed to compare the redundancy strategies by emphasizing that the superiority of each redundancy depends on which components within SM are considered. Worth mentioning that reliability analysis is carried out at the converter level, and the external parts, such as the cooling system, line transformer, AC filters, etc., are not considered. In the following, the reliability evaluation is carried out for two scenarios (according to the previous literature), with and without considering the auxiliary components of the SMs. IGBT modules and capacitor banks are the key components, and they should always be considered.

A. *Without auxiliary components:*

In this part, the quantitative evaluation is carried out to analyze the reliability of the MMC with specified characteristics presented in Table II and only by considering the IGBT module and capacitor banks. The reliability of the MMC with different redundancy levels is shown in Fig 5. As it can be seen, for the reliability calculations, if only IGBTs and capacitors are considered, active redundancy shows better performance than standby, and the B_{10} lifetime is higher. In this scenario, only IGBTs and capacitors are considered in the reliability analysis of the MMC, and reliability only depends on the IGBTs and capacitors' failure rate; in active load-sharing redundancy, the voltage across the SM will be lower than standby redundancy. Hence, according to the (10) (14), in active load-sharing redundancy, the failure rate of IGBTs and capacitors within the MMC will be lower than standby. Furthermore, it is evident that in this case, if there is

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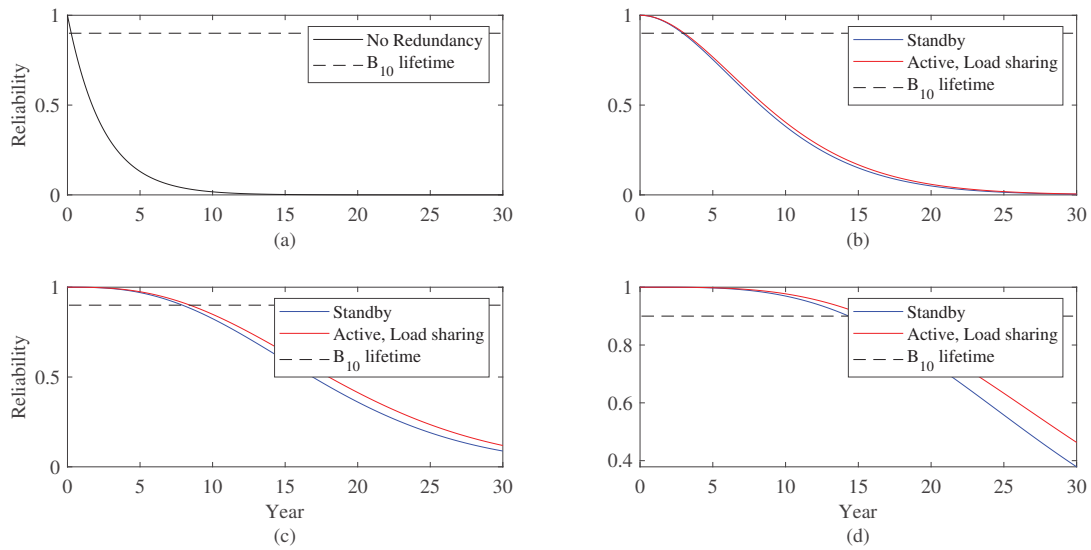

Fig. 5. Reliability of MMC without auxiliary components (a) No redundant SM, (b) 1 Redundant SM, (c) 2 Redundant SMs and (d) 3 Redundant SMs.

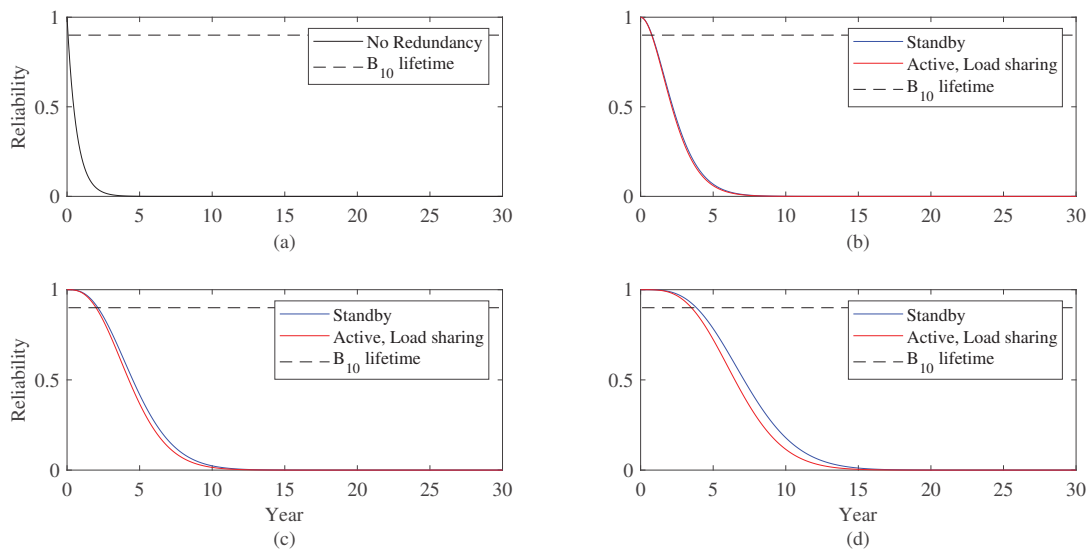

Fig. 6. Reliability of MMC with auxiliary components (a) No redundant SM, (b) 1 Redundant SM, (c) 2 Redundant SMs and (d) 3 Redundant SMs.

no redundancy applied, the reliability is much lower, and B_{10} lifetime is equal to 0.3 years.

B. With auxiliary components:

In this part, evaluation of the reliability of the MMC by considering auxiliary components within SM is performed. So, all the elements within SM (except bypass switch) are considered. The results are showed in Fig 6 where the standby shows a better performance than the active load-sharing strategy with different levels of redundancy. However, in general, the whole MMC's reliability is much lower than the case that auxiliary components are disregarded in reliability analysis. Additionally, the B_{10} lifetime of the MMC in the presence of the auxiliary components are presented in Table III.

TABLE III
B_{10} LIFETIME FOR MMC WITH DIFFERENT LEVEL OF REDUNDANCY.

	With Auxiliary Components		**Without Auxiliary Components**	
	Standby	**Active**	**Standby**	**Active**
No redundant SM	0.1	0.1	0.3	0.3
1 redundant SM	0.8	0.8	3	3.1
2 redundant SMs	2.2	2	8	8.5
3 redundant SMs	3.9	3.6	14.4	15.7

As it was presented, it is vitally important to make the assumptions as realistic as possible since, after the planning and design stage of the MMC, it is not possible to modify the

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structure of the MMC. The following facts can be drawn at the planning and design phase:

- If auxiliary components are considered in reliability analysis, standby redundancy shows a better performance than active load-sharing redundancy.
- If only power switches and capacitor banks are considered for reliability analysis, the active load-sharing redundancy shows a better performance than standby redundancy.
- In general, if all the SM's components, including IGBTs, capacitor banks, and auxiliary components, are considered, the reliability of the MMC is much lower than the case where only IGBT modules and capacitor banks are considered.
- In both scenarios, implementing redundant SM with the structure of the MMC can greatly increase the reliability of the MMC.

V. Conclusion

In this paper, the reliability of the MMC is developed based on various assumptions regarding the consideration of the components within the MMC's SM. Two redundancy strategies, namely standby and active load-sharing, are evaluated; and both redundancy strategies are compared using analytical expressions of homogeneous Poisson Process and Markov Chain, respectively. SM components are distinguished as power components, including IGBT modules, capacitor banks, and auxiliary ones, including high-speed thyristor, bypass switch, power supply, gate drive, and control system. Two scenarios are developed to calculate the MMC's reliability with applied redundancies with and without auxiliary components within the SM. It is evidenced that components consideration will change the superiority of the applied redundancy; if the additional components are considered, the standby redundancy shows a better performance, while on the other hand, if auxiliary components are not taken into account, the active redundancy has a higher reliability output. There are several directions for future studies. The impact of the aging failure of the power components can be evaluated based on the mission profile to compare the redundancy strategies. The effect of considering or not considering the auxiliary components can be analyzed at the system level, e.g., grid-connected power converters.

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