A Reliability Modeling and Evaluation Method of Modular Multilevel Converters

Guangze Pan, Zheng Zhang*, Qin Luo
Reliability and Environmental Engineering Research Center
China Electronic Product Reliability and Environmental Testing Research Institute
Guangzhou, China
zhangzh@ceprei.com

Xiaobing Li, Yuanhang Wang
Guangdong Provincial Key Laboratory of Electronic Information Products Reliability Technology
China Electronic Product Reliability and Environmental Testing Research Institute
Guangzhou, China
530434071@qq.com

***Abstract*—The modular multi-level converter (MMC) is a key facility in voltage source converter based high voltage direct current (VSC-HVDC) transmission systems, and its reliability is related to the safe and stable operation of the entire VSC-HVDC transmission system. In this paper, a reliability modeling and evaluation method of modular multilevel converters are proposed. The modular multi-level converter components are sequentially decomposed into valve-level products, bridge-arm-level products, module-level products and basic-level products, and corresponding reliability modeling and evaluation methods are proposed for each level. From the bottom- to the top-level products, the reliability models are built up layer by layer, whereby finally, the reliability of the modular multi-level converters is evaluated. This case shows that the method is simple and effective, and can be used as an effective means for reliability modeling and evaluation of modular multi-level converters.**

Keywords- modular multilevel converters; reliability modeling; reliability evaluation

I. INTRODUCTION

In recent years, modular multi-level converter technology has become a research hotspot for use in medium and high voltage and large capacity power grids characterized by voltage source converter-based high voltage direct current transmission systems [1, 2, 3]. Compared to traditional switching tube series technology, MMC technology is easier to implement at higher voltage levels and with higher power requirements. Moreover, this multi-level technology can reduce the harmonic content of output voltage and the switching frequency of switching devices, thereby greatly reducing switching losses. At the same time, the modular design can improve the redundancy and operational reliability of the system, while also facilitating standardized large-scale production and reducing production costs. Therefore, MMC technology is widely used in the field of VSC-HVDC transmission.

With the development of information technology and the application requirements in the field of VSC-HVDC transmission, the voltage level and transmission capacity of VSC-HVDC transmission systems have been increasing, thereby making MMC more complicated in function and structure. In 2010, there were 216 sub-modules (SM) per bridge arm of the US Trans Bay Cable Project [4]. In 2014, there were 250 sub-modules per bridge arm of the Zhoushan Multi-terminal VSC-HVDC Transmission Project [5]. And in 2016, the number of sub-modules per bridge arm of the Luxi Mixed Back-to-Back HVDC Project reached 438 [6]. This dependence on MMC necessitates a high level of reliability. However, due to the complexity of MMC technology, the small batch production, and difficulty in carrying out reliability tests of the whole machine, it is difficult to evaluate the consistency of MMC. Therefore, it is important to carry out MMC reliability modeling and evaluation technology research.

At present, there are two main methods for reliability modeling and evaluation of MMCs, the reliability modeling and evaluation methods based on the $k/n(G)$ model [7, 8] and the reliability modeling and evaluation methods based on the Markov process [9, 10]. The first method assumes that the lifetime of the components of the MMC sub-module obeys an exponential distribution, uses the reliability block diagram to establish the reliability model of the MMC sub-module, and considers the MMC as a $k/n(G)$ model to evaluate its reliability level. However, due to the difference between the assumptions and the actual conditions of the method, not all lifetimes of the components of sub-modules are subject to the exponential distribution, resulting in a certain gap between the reliability evaluation results of the method and the actual system. The second method uses Markov's state transition method to construct the reliability model of the MMC sub-modules, and then considers the MMC as a $k/n(G)$ model to evaluate its reliability. However, when the number of sub-modules increases, the number of sub-module states increase, and the transition between sub-module states is likely to be extremely complicated, making the feasibility of the method extremely limited.

Based on these assumptions, this paper proposes a reliability modeling and evaluation method for basic-level products, module-level products, bridge-arm-level products and

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valve-level products of MMCs. From bottom-level MMC products to top-level ones, the reliability model is built up layer by layer to achieve the reliability evaluation of the MMC.

II. THE TOPOLOGY OF THE MMC

The topology of the MMC is shown in Fig. 1 [11]. Each phase unit of the MMC is composed of upper and lower bridge arms, and the three-phase units comprise a total of six bridge arms. Each bridge arm consists of a bridge arm reactor and several identical sub-modules. The topology of the MMC includes half-bridge topology, full-bridge topology, and hybrid topology. The MMC with full-bridge topology or hybrid topology has a certain capability of fault ride-through, but due to the increase in the number of sub-modules, the loss and cost also increase accordingly. Therefore, most of the current engineering applications use half-bridge topology. This paper uses half-bridge topology as an example to evaluate the reliability of MMCs.

The structure of the sub-module is shown in Fig. 2.

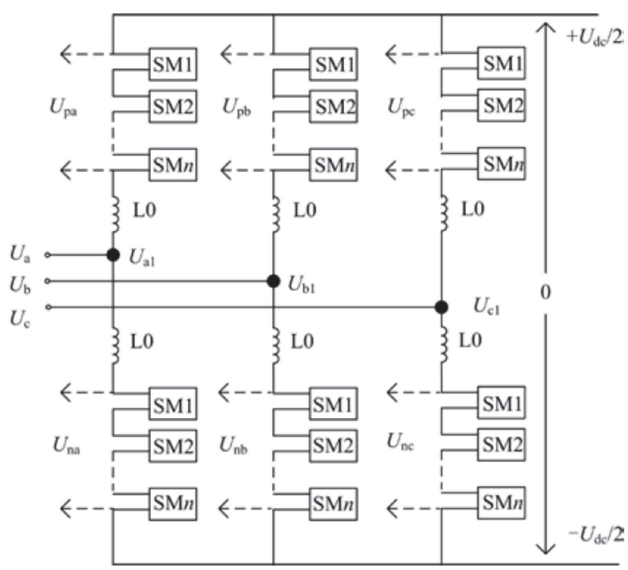

Figure 1. The topology of the MMC

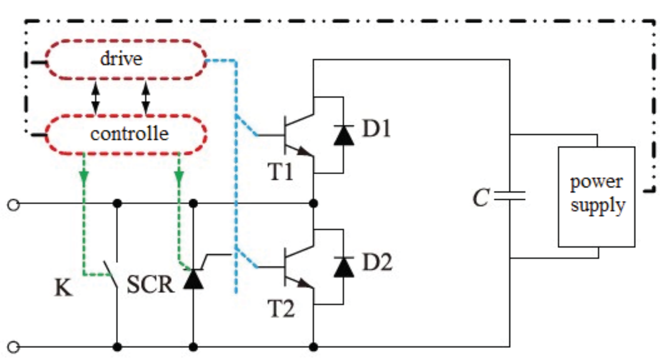

Figure 2. The structure of the sub-module

The sub-module consists of two insulated gate bipolar transistors (IGBTs), two drive boards, a capacitor, a bypass thyristor, a bypass switch, a power supply, and a controller. The function of the controller is to issue a trigger signal to control the state of each IGBT module, and to trigger the bypass thyristor and bypass switch in the event of a sub-module failure, causing the faulty sub-module to exit operation.

III. THE RELIABILITY MODEL OF THE MMC

A. *The Reliability Model of Basic-level Products*

MMC basic-level products mainly include IGBTs, driver boards, capacitors, bypass thyristors, bypass switches, power supplies, and controllers.

The reliability modeling of MMC basic-level products uses a method based on a statistical analysis of fault data. The flow is shown in Fig. 3. Firstly, combined with the fault data of the product, the product reliability model is analyzed, and key technologies such as model parameter estimation, a model goodness-of-fit test, and model optimization are studied. Then, combined with the commonly used reliability distribution model, such as the exponential distribution model, the Weibull distribution model, and the lognormal distribution model, the fault data is fitted and analyzed to obtain the life distribution of the basic-level products. Finally, the reliability function of each MMC basic-level product is calculated to achieve an accurate evaluation of the reliability of the basic-level products.

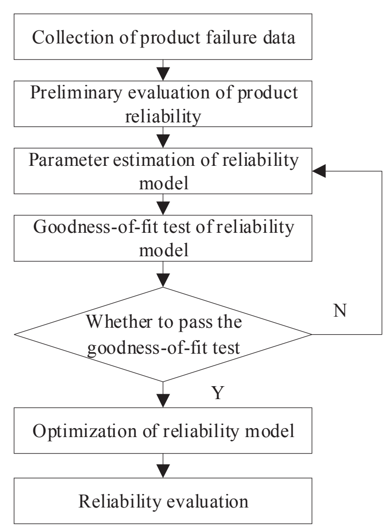

Figure 3. Reliability modeling and evaluation process for MMC's basic-level products

B. *The Reliability Model of Module-level Products*

MMC module-level products mainly refer to MMC sub-modules. Each component of the submodule is a series model, and if any component fails, the submodule fails. The reliability block diagram of the MMC sub-module is shown in Fig. 4.

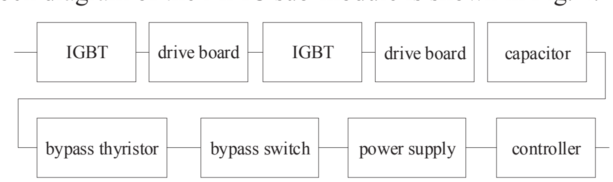

Figure 4. The reliability block diagram of the MMC sub-module

The reliability function of the sub-module $R_{SM}(t)$ is as follows:

$$R_{SM}(t) = [R_{IGBT}(t)]^2 \times [R_{DRI}(t)]^2 \times R_C(t) \times R_{SCR}(t) \times R_K(t) \times R_{Power}(t) \times R_{SMC}(t) \tag{1}$$

$R_{IGBT}(t)$、$R_{DRI}(t)$、$R_C(t)$、$R_{SCR}(t)$、$R_K(t)$、$R_{Power}(t)$ and $R_{SMC}(t)$ are the reliability functions of IGBTs, and the driver board, capacitor, bypass thyristor, bypass switch, power supply and controller, respectively.

If the MMC sub-module adopts other topologies such as full-bridge, the reliability block diagram can be established according to the component types and quantities of the sub-modules, and the reliability function is derived according to the above steps.

C. The Reliability Model of Bridge-arm- level Products

The MMC bridge arm consists of several sub-modules, each of which contains a certain number of redundant modules. In normal operation, the redundant modules are put into operation like other modules; if any sub-module fails, it is bypassed by the bypass switch, and the faulty module exits the operation and is replaced after it is repaired. When the number of faulty modules exceeds the number of redundant modules, the MMC bridge arm fails and a trip signal is generated.

Based on this, the reliability model of the MMC bridge-arm is well suited to be described by the $k/n(G)$ system model. The $k/n(G)$ system refers to a system consisting of n components. When k or more components work normally, the system works normally, and when $n-k+1$ components fail, the system fails. During the system failure, $k-1$ normal components stop working until the failed component is repaired, and the k normal components enter a working state at the same time as the system re-enters a working state. The reliability block diagram of the MMC bridge-arm is shown in Fig. 5.

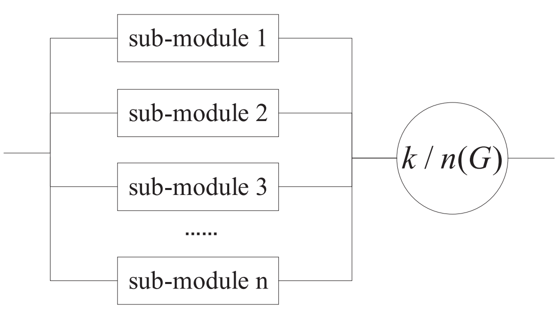

Figure 5. The reliability block diagram of the MMC bridge-arm

Assuming that the bridge arms are composed of sub-modules that are independent of each other and subject to the same life distribution, the reliability function of the MMC bridge arms $R_{ARM}(t)$ is as follows:

$$R_{ARM}(t) = \sum_{i=k}^{n} C_n^i [R_{SM}(t)]^i [1 - R_{SM}(t)]^{(n-i)} \tag{2}$$

where n is the total number of sub-modules in the bridge arm, and K is the number of sub-modules in the bridge arm without redundancy. Also,

$$C_n^i = \frac{n!}{i!(n-i)!} \tag{3}$$

D. The Reliability Model of Valve-level Products

The MMC consists of six bridge arms. In normal operation, all six bridge arms are in normal working condition. If any of the bridge arms fail, the MMC enters the fault trip state. The reliability block diagram of the MMC is shown in Fig. 6.

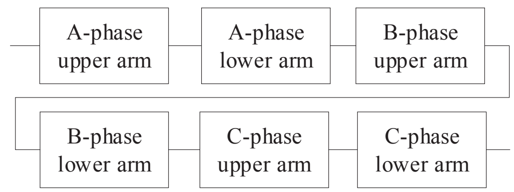

Figure 6. The reliability block diagram of the MMC

The reliability function $R_{\text{valve}}(t)$ of the MMC is:

$$R_{\text{valve}}(t) = [R_{ARM}(t)]^6 \tag{4}$$

The mean time between failures $T_{\text{valve}}(t)$ of the MMC is:

$$T_{\text{valve}}(t) = \int_0^{+\infty} R_{\text{valve}}(t)dt \tag{5}$$

IV. THE CASE

In this paper, a certain type of MMC is taken as an example to carry out the reliability modeling and evaluation, and its redundancy backup strategy is optimized to improve its reliability.

A. The Reliability Evaluation of Basic-level Products

The driver board of the MMC sub-module is taken as an example to carry out the reliability evaluation of the basic-level products.

1) Collection and statistics of fault data

By collecting the operating data of the MMC, a total of 16 failures of the driver board are obtained. The fault time (in hours) is sorted from small to large: 2124, 4760, 7163, 9563, 11748, 14007, 16245, 18373, 20407, 22467, 24588, 26591, 28613, 30695, 32626, and 34696.

2) Calculation of reliability

In combination with the total number of the drive boards n used for the MMC, the reliability is estimated according to the median rank estimation method for the sorted time. The formula is as follows:

$$R(t_i) = 1 - (i - 0.3)/(n + 0.4) \tag{6}$$

The trend of the unreliability $F(t)$ of the driver board is shown in the Fig. 7.

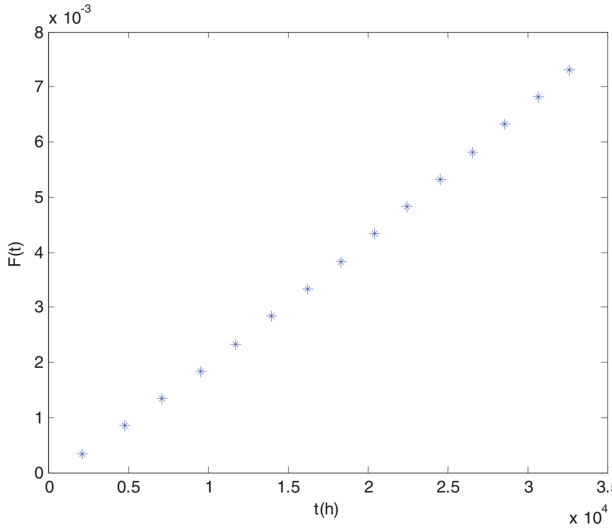

Figure 7. The trend of the unreliability of the driver board

3) Parameter estimation of the model

The exponential distribution, Weibull distribution and lognormal distribution are selected as the fitting model, and the model parameters are estimated according to the least squares method. The model parameter estimation results are shown in Table Ⅰ.

TABLE I. THE RESULT OF PARAMETER ESTIMATION

No.	Types	The results
1	Exponential distribution	$\lambda = 5.2\times10^{-5}$
2	Weibull distribution	α=2.655×10^6 , β=1.12
3	Lognormal distribution	μ=17.38 , σ=2.84

4) Goodness-of-fit test and optimization of the model

By performing the goodness-of-fit test and optimization of the model, the optimal fitting model is obtained. If multiple models are able to fit the data and pass the goodness-of-fit test, then optimization of the lifetime distribution model is needed. The optimization method is minimizing the sum of the squared residuals.In this case, the optimal fitting model is the Weibull distribution

$$F(t) = 1 - \exp[-(\frac{t}{2.655\times10^6})^{1.12}] \tag{7}$$

5) Reliability evaluation

According to the life distribution of the drive board, the reliability function can be obtained.

$$R_{DRI}(t) = \exp[-(\frac{t}{2.655\times10^6})^{1.12}] \tag{8}$$

The reliability evaluation of each component of the sub-module is carried out by the same reliability evaluation method or the reliability evaluation method of the point estimation. The evaluation results are shown in Table Ⅱ.

TABLE II. THE RELIABILITY EVALUATION RESULTS OF THE BASIC-LEVEL PRODUCTS

No.	The basic-level products	The evaluation results
1	IGBT	$R_{IGBT}(t) = \exp(-1\times10^{-8}\times t)$
2	driver board	$R_{DRI}(t) = \exp[-(\frac{t}{2.655\times10^6})^{1.12}]$
3	capacitor	$R_C(t) = \exp(-2\times10^{-8}\times t)$
4	bypass thyristor	$R_{SCR}(t) = \exp(-1\times10^{-7}\times t)$
5	bypass switch	$R_K(t) = \exp(-2.85\times10^{-8}\times t)$
6	power supply	$R_{Power}(t) = \exp(-3.5\times10^{-7}\times t)$
7	controller	$R_{DRI}(t) = \exp[-(\frac{t}{3.189\times10^6})^{1.04}]$

B. The Reliability Evaluation of Module-level Products

The reliability function $R_{SM}(t)$ of this type of MMC submodule is as follows:

$$\begin{aligned} R_{SM}(t) &= [R_{IGBT}(t)]^2 \times [R_{DRI}(t)]^2 \times R_C(t) \\ &\times R_{SCR}(t) \times R_K(t) \times R_{Power}(t) \times R_{SMC}(t) \end{aligned} \tag{9}$$

The mean time between failures $T_{SM}(t)$ of the sub-modules is as follows:

$$T_{SM}(t) = \int_0^{+\infty} R_{SM}(t)dt = 6.583\times10^5 h \tag{10}$$

C. The Reliability Evaluation of Bridge-arm-level Products

According to the voltage level of the MMC and the rated voltage of the sub-module, the number of sub-modules of each bridge arm is at least 250. Then the reliability function of the MMC bridge arm is as follows:

$$R_{ARM}(t) = \sum_{i=k}^{n} C_n^i [R_{SM}(t)]^i [1 - R_{SM}(t)]^{(n-i)} \tag{11}$$

D. The Reliability Evaluation of Valve-level Products

The reliability function $R_{\text{valve}}(t)$ of this MMC is:

$$R_{\text{valve}}(t) = [R_{ARM}(t)]^6 \tag{12}$$

The mean time between failures $T_{\text{valve}}(t)$ of this MMC is:

$$T_{\text{valve}}(t) = \int_0^{+\infty} R_{\text{valve}}(t)dt \tag{13}$$

When the redundancy schemes of the submodules are 0% redundancy, 6% redundancy, 8% redundancy, and 10% redundancy, the reliability evaluation results of this type of MMC are as shown in Table Ⅲ.

TABLE III. THE RELIABILITY EVALUATION RESULTS OF DIFFERENT REDUNDANCY SCHEMES

No.	The redundancy schemes	The number of sub-modules of each bridge arm	The mean time between failures $T_{\mathrm{valve}}(t)$ /h
1	0% redundancy	250	438.86
2	6% redundancy	265	6819.33
3	8% redundancy	270	8864.97
4	10% redundancy	275	10874.95

The function curves of MMC reliability for different redundancy schemes are shown in Fig. 8.

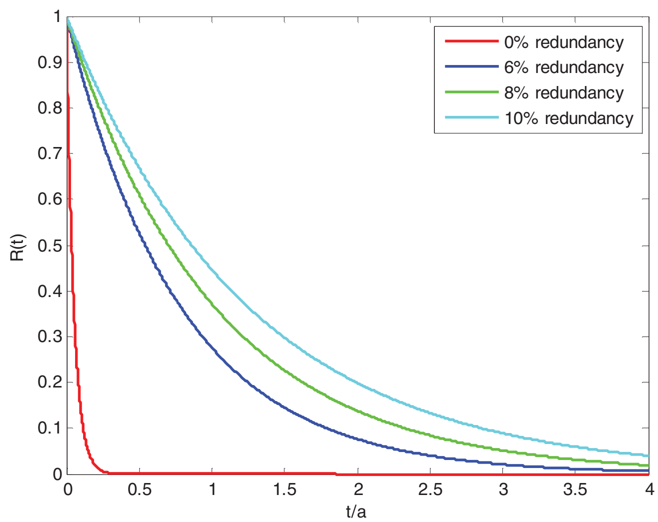

Figure 8. The function curves of MMC reliability for different redundancy schemes

It can be seen from Fig. 8 that in the case that the sub-module failure rate is constant, the reliability of the MMC increases as the redundancy of the MMC sub-module increases. In the same redundancy increment, the reliability increases significantly in the early stage of product use, and the increase in redundancy tends to reduce the reliability of the converter valve in the later stage of product use. Under the same period of use, the redundancy is increased, while the reliability increment of the converter valve tends to decrease and the benefit of the reliability improvement per unit investment is gradually reduced. Therefore, in practical engineering, the reliability and economy should be considered in order to select the most appropriate redundancy strategy.

This type of MMC adopts an 8% redundancy scheme of sub-modules. After reliability modeling and evaluation, the mean time between failures is 1.012 years. Since the design specification requirement is 1 year, this type of MMC meets the requirement of reliability.

V. CONCLUSION

First of all, in this paper, a reliability modeling and evaluation method for a modular multilevel converter are proposed. The structure of the MMC is decomposed layer by layer, and the reliability evaluations of basic-level products, module-level products, bridge-arm-level products and valve level products are carried out. The method is progressive and clear, and can be applied to a reliability evaluation of MMCs of various levels of complexity. Moreover, it can evaluate reliability of various product levels of MMCs, with strong applicability.

Secondly, this paper proposes a statistical analysis method for fault data to evaluate the reliability of MMC basic-level products. By selecting various life distributions to fit and optimize the reliability of the product instead of assuming that the lifetime is subject to the exponential distribution, the reliability evaluation results are more reasonable and the precision is higher.

Finally, the method proposed in this paper has a certain reference value for the reliability evaluation of other structural complex systems.

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