Reliability Model of MMC Considering Periodic Preventive Maintenance

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Abstract—Periodic preventive maintenance (PPM) is a significant measure to assure reliable operation of the modular multilevel converter (MMC), but to date has always been neglected in the reliability evaluation. A mathematical reliability model of MMC considering PPM is proposed in this paper. The model is derived rigorously by the reliability function and finally described by the indices equivalent failure rate and the forced outage rate (FOR). Two operation modes related to redundant SMs are considered and described by the standby mode and k-out-of-n model respectively. Employing this model, we can analyze the sensitivity of reliability to redundancy and maintenance interval and provide some reliability indices for planning, which is especially valuable for the offshore cases. The necessity of the considering PPM and the effectiveness of the proposed model are verified by case studies. A method to include PPM in reliability modeling is provided.

Index Terms—reliability; MMC; maintenance; HVDC

I. INTRODUCTION

The modular multilevel converter (MMC) has drawn considerable interest for its application to power systems over the last few years. It is particularly suitable for multi-terminal voltage sourced converter high-voltage direct current (VSC-HVDC) transmission system, which is taken as a promising option to connect remotely located offshore wind power plants and interconnect several isolated power systems. A five-terminal HVDC transmission system has been put into operation since July 2014 in Zoushan, China, in which MMCs are applied [1].

The salient advantages of the MMC over other multilevel topologies include: 1) its modularity and scalability with standardized sub-modules (SMs), 2) absence of multi-pulse transformers since the voltage output of each SM is provided by a floating SM capacitor, 3) flexible control of the voltage level and simple realization of redundancy if required, and 4) superior harmonic performance especially in high-voltage applications [2,3].

To realize the SMs of the MMC, numerous circuits have been proposed including the half-bridge, full-bridge, clamp-double three-level and five-level cross-connected circuit [4-7]. The mathematical model of the MMC has been explored for control purpose [8-11]. Based on it, the research effort toward control has increased. They focus on the pulse-width modulation (PWM) techniques [12-14], SM capacitor voltage balancing [15-17], circulating current control [18-20] and the SM capacitor voltage ripple reduction techniques [21-23]. There are also some works discussing the power loss calculation [24,25]. However, little attention has been paid to the reliability of the whole MMC.

The quantitative reliability evaluation of MMC helps to evaluate the whole HVDC system and provides some suggestions in the device selection. With the aid of it, the tradeoff between the reliability and the construction cost can be carefully considered in the optimal planning.

Redundant SM configuration and periodic preventive maintenance (PPM) are two useful methods to improve the reliability of MMC [26]. The provision of redundancy is of key concern in the design of MMC [2,27]. The operation modes of MMC can be described by both the standby model and the k-out-of-n model. Although the k-out-of-n model has been well adopted in other multi-level converters [26,28,29], there has been no published work on applying it to MMC.

PPM is a kind of maintenance program that replaces the faulty SMs before the number of them becomes large enough to result in a whole converter shutdown, with unscheduled repair afterwards [30]. It is practical, easy and do not rely on other technology compared with other common maintenance programs, such as predictive maintenance and reliability centered maintenance [31]. In addition, it is especially suitable for offshore cases for the following reasons. 1) The available period for offshore maintenance during one year is limited. For example it is only 150 days in the Southeast China sea area. It might be difficult to arrange an immediate maintenance when it is needed and the condition might turn worse during the waiting. 2) There are many types of equipment in the offshore wind plants or oil field, and all of them should be repaired or examined during maintenance since it is expensive and time-consuming to arrange one [32]. It is hard to decide the best time point for maintenance considering the conditions of so much equipment. Therefore PPM has great potential in offshore cases. Until now,
However, the most similar existing study to the PPM is the common replacement model [33], but it could hardly describe the PPM of MMC.

This paper pays special attention to the periodic preventive maintenance (PPM) and proposes a mathematical maintenance model derived rigorously using the reliability function. There are three main difficulties introduced by PPM in the reliability evaluation: 1) the reliability function becomes periodic and not continuous at the joint point between two cycles, 2) the lifetime of it is no longer exponential distributed, 3) all the SMs in one arm enjoy the same PPM and their states are not completely independent to each other. Thus the existing model based on exponential distribution and assumption of independence fails to describe it. Two operation modes depending on the redundancy strategy adopted are considered. The model is finally described by the indices equivalent failure rate and the forced outage rate (FOR), thus it can be adopted in the system evaluation together with the multi-state component model.

The contributions of this paper include the followings. 1) An equivalent maintenance model is developed considering two operation modes. 2) The sensitivity of the MMC reliability to the redundancy and maintenance intervals are carefully discussed. 3) The effect of redundancy and maintenance interval are discussed and a cost analysis is carried out based on the case studies, which may be helpful in the planning and system maintenance management. This paper provides a reliability modeling and analysis method to consider PPM.

The rest of the paper is organized as follows. Section II discusses the characteristics of MMCs. The reliability function of one arm considering redundancy is presented in Section III. The maintenance model of an arm is proposed in Section IV. Section V then develops maintenance model of the overall converter and analyzes the sensitivity. The case studies are carried out in Section VI. At last, the discussion is concluded in Section VII.

II. CHARACTERISTICS OF MMC

This section discusses the redundant SM configuration and maintenance of the MMC, and the premise that our study is based on. It is the first step in the reliability evaluation and forms the basis for our whole study.

A. MMCs with Redundant SMs

A typical configuration of the MMC topology [2] is shown in Fig.1. It requires \( l \) SMs per arm and can generate \( l+1 \) voltage levels in the output. \( l \) is the minimal number of SMs that must be functioning, otherwise the converter will be cut out. For redundancy purposes, there are \( n \) additional SMs inserted in each arm of the converter. The converter can detect and bypass the faulty SMs and keep its operation uninterrupted with the redundancy [34]. This is typically done by a fast mechanical switch within each SM.

There are two operational modes of the converter: Idle mode and Load-sharing mode, which are distinguished by the state of redundant SMs [35]. In Idle mode, the redundant SMs are bypassed and act as standby components in the normal state. When an SM failure occurs, one redundant SM will be put into operation, and the number of available redundant SMs \( N_{arSM} \) will be decreased by one. The converter can neglect the SM failures and continue working until the \( N_{arSM}=0 \). To achieve it, a switch must be included within each redundant SM that is capable of opening and shunting the arm current into the SM path. In this mode, the average output voltage that every SM generates is only related to the output voltage value and not affected by the \( N_{arSM} \).

In Load-sharing mode, the redundant SMs in the arms are considered active and operate normally. There is no differentiation between redundant and non-redundant SMs since all of the SMs in the arm are treated identically by the control and voltage-balancing algorithm. Considering the MMC in Fig.1, load-sharing mode can result in a total of \( l+n \) SMs per arm of the converter, but the number of output voltage levels is still \( l+1 \). When a SM failure occurs, the SM would be bypassed and the converter continues working until the number of operating SMs is lower than \( l \). Thus, the average voltage for every SM is equal to or lower than that one in Idle mode, and increases with the failures.

B. Periodic Preventive Maintenance

PPM is like the replacement policies [36] proposed decades ago, but the differences between them make the maintenance reliability model distinct.

The hazard rate of most power electronic and electric devices can be described by the well known bathtub curve, shown in Fig.2. This curve has three distinct regions known as the “Early failure period”, the “Constant failure rate period” and the “Wear-out failure period”. The devices are working during the second period, and the failure occurs at an approximately uniform rate. Apart from devices which operate in extreme circumstances, most power electronic devices can be regarded as possessing these characteristics [37]. Thus the life of every device is exponentially distributed, and the failure rate is equal to \( \lambda \) in
Fig. 2. We use a voltage factor for failure rate parameter modification and assume that the temperature variation could be neglected in this paper.

In the existing periodic replacement policy, the components are characterized by a failure rate that increases with age. So they are planned to be replaced before they have aged too greatly. The commonly Age Replacement is in force if a component is always replaced at the time of failure or $T$ hours after its installation, whichever occurs first. The $T$ could be a random variable. And under the Block Replacement policy, a block or group of components are replaced at times $kT$ ($k=1,2,\ldots$) and at failure independent of the failure history of the system. In the Periodic Replacement with minimal repair at failure model, it is assumed that the system failure rate remains undisturbed by any repair of failures between the periodic replacements. This model was proposed as an optimum maintenance policy to minimize total cost.

The main purpose of the maintenance policy considered in this paper is to ensure enough available standby or active redundancy for the converter. The faulty SMs are replaced at times $kT$ ($k=1,2,\ldots$), so are the aged SMs if necessary. If a converter failure caused by high-order SM failure or control system failure occurs, the maintenance will be organized immediately, and a new period starts.

In general, the main differences between the maintenance and the existing replacement policies include two points. Firstly, the failure rate of devices is constant in the maintenance, but increases with age in the existing policies. Secondly, the maintenance is mainly to replace the redundant SMs which have failed, while the existing policies are adopted to replace the aged components.

In order to distinguish from the existing “Periodic Replacement”, the maintenance derives its name from the purpose to provide the MMC with a preventive maintenance periodically, improve its reliability and decrease the maintenance cost. In addition, it provides no effect on non-redundant systems.

When failures occur in some other devices in the converter station such as the transformer, the preventive maintenance of the converter will be taken ahead of time together with the repair for convenience. It is not considered in this paper for its low probability and few effects.

III. RELIABILITY FUNCTION OF AN ARM WITH REDUNDANCY

This section presents the reliability function of a SM at first. And then, the standby model and $k$-out-of-$n$ model are adopted to describe an arm with redundancy respectively. The model in this section only discusses the operation during one lifetime period from once MMC is installed or repaired to the first failure after that, and the PPM is not considered in this section.

The MMC shown in Fig. 1 is considered in this section. $l$ denotes the number of non-redundant SMs, and $n$ denotes the number of redundant SMs. The definition of reliability function $R(t)$ references to [38]. The lifetime function $F(t)$ is the cumulative distribution function of the random variable lifetime. $F(t) = 1 - R(t)$.

A. Model of a SM

An SM consists of two IGBT modules and a capacitor bank as shown in Fig. 1, and an SM drive module. All of components have constant failure rates recorded as $\lambda_{\text{IGBT}}, \lambda_{\text{C}}$ and $\lambda_{\text{D}}$ respectively. $\lambda_{\text{IGBT}}$ is actually varied with its blocking voltage and working temperature, which is influenced by different voltage control strategies [39,40], operation modes and states of the MMC. [41] and [42] have calculated $\lambda_{\text{IGBT}}$ considering the effect of temperature and blocking voltage. And in Load-sharing mode, the blocking voltage of IGBT is related to the number of available SMs. Since the ratio of redundant SMs to non-redundant ones, which is recorded as redundancy ratio $r_{\text{SM}}$(%), is always small (<10%), the variation of average voltage for SM is low. Because this paper mainly pays attention to the whole MMC rather than IGBT, the types of IGBT and its dynamic characteristics are not discussed. An equivalent constant $\lambda_{\text{IGBT}}$ is used to reflect the total reliability of IGBT and a constant voltage factor $\pi_t$ for $\lambda_{\text{IGBT}}$ and $\lambda_{\text{C}}$ modification is applied in Load-sharing mode as an approximation and simplification. Some further study on the relationship between the $\lambda_{\text{IGBT}}$ and $r_{\text{SM}}$ might be carried out later.

The reliability block diagram of an SM is shown in Fig. 3, and it is a parallel system. The reliability function of an SM is

$$R_{\text{SM}}(t) = R_{\text{IGBT}}^2(t) \times R_{\text{C}}(t) \times R_{\text{D}}(t) = e^{-\lambda t}$$ (1)

where $R_{\text{SM}}(t)$ denotes the probability that an SM is still available at time $t$. $\lambda_{\text{SM}}$ denotes the failure rate of an SM. $\lambda_{\text{SM}}$ equals $2\lambda_{\text{IGBT}}+\lambda_{\text{C}}+\lambda_{\text{D}}$ in Idle mode and $\pi_t(2\lambda_{\text{IGBT}}+\lambda_{\text{C}})+\lambda_{\text{D}}$ in Load-sharing mode. Each of $l+n$ SMs is independent and identical.

B. Standby Model

In the standby model one unit is active and $k$ units are on cold standby. As soon as the operating unit fails, it is immediately replaced by one of the $k$ cold standby units [43]. The model can describe Idle mode exactly.

In our study, the bypass devices are considered to be perfect switches with zero failure rate, and the replace duration is short and regarded as 0.

First, the arm with $l$ active non-redundant SMs is a parallel system, and its lifetime is exponential distributed based on (1). Its lifetime function $F_1(t) = 1 - \text{exp}(-l\lambda_{\text{SM}})$.

We consider this parallel system as one operating unit. Once an operating SM fails and a cold standby SM is switched in, the operating unit could be regarded as a new one because of the exponential distribution’s memory-less property. Therefore, the $n$ cold standby SMs could be considered as $n$ cold standby units. The lifetime random variables of the $n+1$ units including the non-redundant one recorded as $X_1, X_2, \ldots, X_{n+1}$ are independent and identical. Let $X$ denote the random variable of lifetime of an arm. Then $X=X_1+X_2+\ldots+X_{n+1}$. Due to the property of exponential distribution, $X$ has a $\Gamma(n+1), \lambda_{\text{SM}}$ distribution [44]. The lifetime function of the an arm is
\[ F_{X_{\text{standby}}} (t) = 1 - e^{l \text{ SM} t} \]  

(2)

And the reliability function \( R_{X_{\text{standby}}} (t) = 1 - F_{X_{\text{standby}}} (t) \).

C. \textit{k-out-of-n} Model

In Load-sharing mode, at least \( l \) SMs out of \( l+n \) active SMs must function successfully for the MMC success. It is the \( k \)-out-of-\( n \) model in the reliability studies. Because each of the \( l+n \) SMs is independent and identical, the reliability function of the arm with the aid of binomial distribution is given by

\[ R_{X_{k/n}} (t) = \sum_{i=0}^{n} \binom{n}{i} R_{\text{SM}}^i (t) F_{\text{SM}}^{n-i} (t) \]

\[ = \sum_{i=0}^{n} \binom{n}{i} e^{l \text{ SM} t} (1 - e^{l \text{ SM} t})^{n-i} \]

(3)

IV. MAINTENANCE MODEL OF AN ARM

Based on the reliability function, the maintenance model of an arm is derived in this section. Different from that without maintenance, the reliability function of the arm \( R_{\text{arm}} (t) \) is not continuous but follows a \( T \)-hour cycle, which makes it much more difficult to obtain the mean time to the (first) failure (MTTF) especially in the \( k \)-out-of-\( n \) model. The derivation is presented in Appendix. It is necessary to emphasize that maintenance is to assure continuous operation and completely differs from the repair when the MMC is shut down. The former is adopted in planning while the latter is a response to contingency, due to what the loss and cost are very different. In part B the reliability indices, availability and mean steady failure rate of an arm are calculated.

A. MTTF of an Arm Considering PPM

MTTF of an arm equals to the expectation of the component lifetime without repair. Let \( E(X^*) \) denote the expectation, then

\[ E(X^*) = \int_{0}^{\infty} f_{\text{arm}} (t) dt = \int_{0}^{T} tdR_{\text{arm}} (t) \]

where \( f_{\text{arm}} (t) \) is the probability distribution function of the lifetime. Due to the PPM, the \( R_{\text{arm}} (t) \) is not continuous and follows a \( T \)-hour cycle. It can be given by

\[ R_{\text{arm}} (t) = R_{X}^i (T) R_{X} (t \ iT) \ i T \ t \ (i+1) T \]

where \( T \) denotes the maintenance interval, and \( i = 0, 1, 2, \ldots \). Thus, (4) can be rewritten as

\[ E(X^*) = \int_{0}^{T} R_{X} (t \ iT) \frac{t}{1} R_{X} (T) \]

With the aid of integration by parts, it simplifies into

\[ E(X^*) = \int_{0}^{T} R_{X} (t) dt \]

(6)

The integral of \( R_{X_{\text{standby}}} (t) \) can be calculated a little easier, while the derivation of the integral of \( R_{X_{k/n}} (t) \) is quite complicated and presented in the Appendix. They can be written as

\[ \int_{0}^{\tau} R_{X_{\text{standby}}} (t) dt = \sum_{k=0}^{n} \frac{1}{l \text{ SM}} \frac{k (l \text{ SM} T)^k}{k!} e^{l \text{ SM} T} \]

(8)

B. Availability and Failure Rate of an Arm

In the conventional reliability model of the equipment in the power system, the lifetime function is exponential distributed. Thus there is a constant failure rate of the equipment, the parameter \( \lambda \), and there are developed equations to calculate some other reliability parameters. However, in the model proposed in this paper, the failure rate varied with the time. Therefore, in this paper the reliability is described by the mean steady availability and mean steady failure rate, and the function is derived rigorously via the theory of stochastic process.

In this study, it is assumed that the arm can be put into operation immediately after repaired, and all the faulty SMs are replaced. Let \( X^*_i \) denote the random variables of arm lifetime between the \( i \)-th and \( i+1 \)-th repairs, and \( Y_i \) denote the random variables of \( i \)-th repair duration, where \( i = 0, 1, \ldots \). Then the process \( \{ N(t), t \geq 0 \} \) is known as a renewal counting process. According to the properties of renewal process, the availability \( A_{\text{arm}} (t) \) and the failure rate \( M_{\text{arm}} (t) \) of an arm satisfy the renewal equation [45]. Thus,

\[ A_{\text{arm}} (t) = 1 - F_{\text{arm}} (t) + Q(t) A_{\text{arm}} (t) \]

(11)

\[ M_{\text{arm}} (t) = F_{\text{arm}} (t) + Q(t) M_{\text{arm}} (t) \]

(12)

From (11) and (12) we obtain the Laplace transform of \( A_{\text{arm}} (t) \) and \( M_{\text{arm}} (t) \) as

\[ \hat{A}_{\text{arm}} (s) = \frac{1}{s} \frac{\hat{F}_{\text{arm}} (s)}{G (s)} \]

(13)

\[ \hat{M}_{\text{arm}} (s) = \frac{\hat{F}_{\text{arm}} (s)}{s G (s)} \]

(14)

Then the mean steady availability \( \bar{A}_{\text{arm}} \) and mean steady failure rate \( \bar{M}_{\text{arm}} \) are obtained with the aid of final value theorem

\[ \bar{A}_{\text{arm}} = \lim_{t \to \infty} \frac{1}{t} \int_{0}^{t} A_{\text{arm}} (u) du = \lim_{s \to 0} \frac{1}{1 - \hat{F}_{\text{arm}} (s) G (s)} = \frac{b}{a+b} \]

(15)

\[ \bar{M}_{\text{arm}} = \lim_{t \to \infty} \frac{M_{\text{arm}} (t)}{t} = \lim_{s \to 0} \frac{s \hat{F}_{\text{arm}} (s) G (s)}{1 - \hat{F}_{\text{arm}} (s) G (s)} = \frac{ab}{a+b} \]

(16)

where

\[ \frac{1}{a} = \int_{0}^{\infty} f_{\text{arm}} (t) dt = E(X^*) = \text{MTTF}_{\text{arm}} \]

(17)

\[ \frac{1}{b} = \int_{0}^{\infty} tdG (t) = \text{MTTR}_{\text{arm}} \]

(18)

\( \text{MTTR}_{\text{arm}} \) is the mean time to repair (MTTR) of the arm.
The reliability model of an arm considering PPM has been established by now. With the aid of mean steady failure rate, the reliability function of arm could be approximately equivalent to an exponential distribution whose failure rate equal to \(M_{\text{arm}}\). The approximation could greatly simplify the model of MMC and make it practical in the system evaluation.

V. MODEL OF THE MMC AND SENSITIVITY ANALYSIS

This section presents the maintenance model of the MMC based on the arm model first. And then part B and C discuss the sensitivity of \(\text{FOR}_{\text{MMC}}\) on the maintenance interval and the redundancy respectively. It helps to identify the critical issue and calculate economic indices in the planning.

A. Maintenance Model of the MMC

Apart from the failure of a converter arm, there are some other failures which would make the MMC shut down, such as central controller failure, cooling system failure, power supply failure as well as internal converter insulation failure and faults [46]. These failures are collectively called the converter level faults, and \(\lambda_{\text{Con}}\) and \(MTTR_{\text{Con}}\) denote the failure rate and MTTR of them. Then the mean steady availability \(A_{\text{Con}}\) and mean steady failure rate \(M_{\text{Con}}\) are

\[
A_{\text{Con}} = \frac{1}{1 + \frac{MTTR_{\text{Con}}}{Con}} \quad \quad M_{\text{Con}} = \frac{MTTR_{\text{Con}}}{1 + \frac{MTTR_{\text{Con}}}{Con}}
\]

The reliability block diagram of a MMC could be illustrated as Fig. 4. It is a parallel system consist of seven components that six arms and an abstract converter level component. Thus the forced outage rate (probability) and failure rate (frequency) of MMC are

\[
\begin{align*}
\text{FOR}_{\text{MMC}} &= 1 - A_{\text{Con}} \cdot A_{\text{arm}}^6 \\
M_{\text{MMC}} &= 6 \cdot M_{\text{arm}} + M_{\text{Con}}
\end{align*}
\]

By now, the maintenance model of the MMC has been established. The model is similar to the one which is commonly used to describe the electric devices. The outage rate and failure rate are provided which are the necessary parameters to calculate the outage table in the system reliability evaluation.

In addition when \(T\to\infty\) or \(n=0\), the model degrades to the one without PPM or redundancy. The proposed model is a more detailed and perfect one, and has a wide application.

B. Sensitivity Analysis on the Maintenance Interval

Let \(T\) denote the maintenance interval. The sensitivity of \(\text{FOR}_{\text{MMC}}\) with respect to \(T\) is

\[
S_M(T) = \frac{\text{FOR}_{\text{MMC}}}{T} = 6 \cdot A_{\text{arm}}^5 \cdot A_{\text{Con}} \cdot A_{\text{arm}}^T
\]

and the derivatives of \(A_{\text{arm}}\) is

\[
A_{\text{arm}} = \frac{\text{MTTR}_{\text{arm}}}{T} \quad \quad \frac{\text{MTTF}_{\text{arm}}}{T} = \left(\frac{\text{MTTF}_{\text{arm}}}{\text{MTTR}_{\text{arm}}}\right)^{\frac{1}{2}}
\]

In order to express more simply and clearly, let \(R_X\) and \(JR_X\) denote the \(R_X(T)\) and its integral respectively. Then

\[
\frac{\text{MTTF}_{\text{arm}}}{T} = \frac{1}{1 + \frac{R_X}{R_X} \left(1 + \frac{JR_X}{JR_X} \cdot \frac{R_X}{R_X}\right)^{\frac{1}{2}}}
\]

In the standby model, the derivatives of \(R_X\) and \(JR_X\) are

\[
R_{X,\text{standby}}(T) = l_{\text{SM}} e^{i\cdot suT} \left(\frac{l_{\text{SM}}}{T}\right)^{n!} \quad \quad JR_{X,\text{standby}}(T) = e^{i\cdot suT} \left(\frac{l_{\text{SM}}}{T}\right)^{n!}
\]

And in the k-out-of-n model, they are

\[
R_{X,k/n}(T) = \frac{n+l}{n!} \left(\frac{\text{MTTF}_{\text{arm}}}{\text{MTTR}_{\text{arm}}}\right)^n \left(i\cdot e^{suT}\right)^n \left(i\cdot e^{suT}\right)^{i+k} \left(\frac{1}{\text{MTTR}_{\text{arm}}}\right)^{i+k}
\]

C. Sensitivity Analysis on the Redundancy

The redundancy is reflected by the number of redundant SMs, which is \(n\) in our study. Since \(n\) is an integer variable, the difference quotient is applied. The sensitive of \(\text{FOR}_{\text{MMC}}\) with respect to \(n\) is

\[
S_R(n) = \frac{1}{2} \left(FOR_{\text{MMC}}[n+1,n] + FOR_{\text{MMC}}[n,n]ight)
\]

\[
= \frac{1}{2} \left(FOR_{\text{MMC}}(n+1) + FOR_{\text{MMC}}(n)ight)
\]

VI. CASE STUDY

The MMC shown in the Fig.1 is considered in the case study. Table I lists the values of the configuration, reliability and maintenance parameters. Some of them come from [26]. Quadruple precision computation is used in our study.
Table II shows the reliability indices. The voltage press modification factor \( \pi_r \) is set \( 1/(1+0.5 \times n(\%)) \). From the result, it can be seen that the arm is reliable with an availability of 0.99999987 under the standby model and 0.99996355 under the k-out-of-n model on the condition that 8% redundant SMs are installed with 5-years preventive maintenance intervals. The failure of the MMC is mainly caused by the converter level failures rather than the SM ones, about 0.02623250 and 0.02888442 \( \text{int}^{-1} \) and \( \text{VSC failure lower than to those in MMC high voltage is complicated and}
\) is not be put into practice. However, the reliability is improved rapidly with the increase of \( n \), as shown in Fig.5. When \( n<20 \), especially lower than 6, the improvement is much more obvious. It is reflected by the sensitivity index \( S_R \), which is always lower than 0. The \( S_R \) is 0.17772284 when \( n=1 \), that one more SM per arm can reduce \( \text{FOR}_{\text{MMC}} \) by 0.17772284.

Fig. 5 shows that the arm is reliable with an availability of 0.99996351 and the arm is more sensitive to the maintenance interval and redundancy. And it could hardly be improved by increasing the redundancy for standby model in the case study. This phenomenon leads to a discussion that whether a lower redundancy or a longer maintenance interval with lower cost is enough. The analysis on this is carried out in the following parts.

In order to illustrate the advantages brought by redundant SMs and PPM to MMC in reliability, a brief comparison between MMC and conventional VSC is carried out. The two-level VSC topology is used which has the least components. The design of the capacitor group of the VSC applied in such high voltage is complicated and is not discussed here. The failure of it is not taken into account tentatively. The VSC is modeled by a simple series system, \( \lambda_{\text{IGBT}}, \lambda_{\text{IGBT}}, \lambda_{\text{IGBT}} \) in VSC equal to those in MMC, and the MTTR of all components in VSC is 30 days. The availability of VSC is 0.8347575, which is much lower than \( \text{A}_{\text{MMC}} \) shown in Table II.

MMC shows great advantages than VSC even though the capacitor group failure of VSC is omitted, which take up a high percentage in VSC failure [47]. The contribution of SM redundancy and PPM is clearly showed in the following parts.

A. Redundancy Analysis

The k-out-of-n model is adopted in this part. Table III and Fig.5 show the results when \( 0\leq n \leq 32 \) and \( T=5 \) years. When there is no redundant SM, the \( A_{\text{arm}} \) is only 0.76198451 and the

| TABLE III | RELIABILITY INDICES FOR K-OUT-OF-N MODEL (0≤n≤32, T=5) |
|---|---|---|---|---|
| \( n \) | \( A_{\text{sm}} \) | \( A_{\text{MMC}} \) | \( S_R \) | \( S_M \) |
| 0 | 0.76198451 | 0.19531689 | 0.00000000 | / |
| 1 | 0.86491643 | 0.41774171 | -2.08607E-07 | -0.17772284 |
| 2 | 0.90569835 | 0.55076256 | -1.63788E-06 | -0.10889244 |
| ... | ... | ... | ... | ... |
| 6 | 0.95730097 | 0.76798715 | -3.29900E-04 | -0.02863236 |
| 7 | 0.96246769 | 0.79319489 | -8.03206E-04 | -0.02283506 |
| 8 | 0.96562029 | 0.81365727 | -0.00173550 | -0.01880521 |
| 9 | 0.96992775 | 0.83080531 | -0.00336663 | -0.01601233 |
| 10 | 0.97280102 | 0.84568194 | -0.00590350 | -0.01413908 |
| ... | ... | ... | ... | ... |
| 19 | 0.99231181 | 0.95269068 | -0.03992334 | -0.00903559 |
| 20 | 0.99393785 | 0.96209585 | -0.03739566 | -0.00881268 |
| ... | ... | ... | ... | ... |
| 30 | 0.99988556 | 0.99715973 | -0.00195047 | -3.85572E-04 |
| 31 | 0.99993451 | 0.99745265 | -0.00118977 | -2.33378E-04 |
| 32 | 0.99996355 | 0.99762648 | -7.03305E-04 | -1.36929E-04 |

For MMC, the \( A_{\text{MMC}} \) is 0.99999962 and the \( S_R \) is 0.17772284 when \( n=1 \), that one more SM per arm can reduce \( \text{FOR}_{\text{MMC}} \) by 0.17772284.

Fig. 6 shows the sensitivity of the maintenance interval and redundancy. It is obviously that there are proper intervals of \( n \) in which \( S_R \) or \( S_M \) is much higher and the reliability of MMC is easier to improve by increasing redundant SMs or organizing more frequent PPM. \( S_R \) is higher when \( n\leq10 \), in which cases the system has fewer SMs, and redundancy is the more significant point for reliability. However, with \( n \) growing, redundancy has increased to a quite high level and the contribution of adding \( n \) decreases, and the PPM becomes important. When \( 10\leq n\leq32 \), \( S_M \) is higher and reaches a peak at \( n=18 \). When \( n \) is higher than enough to provide necessary redundancy between the maintenance intervals \( (28n) \), shorter interval makes less sense. Thus \( n \) and \( T \) affect the reliability simultaneously and the interaction of their effects will be discussed in the following parts.

B. Maintenance Interval Analysis

The steady model is adopted in this part to examine sensitivity of the reliability to the maintenance interval. Two cases that
$n=10, 32$ respectively are considered and the value of $T$ is raised from 0.5 to 10.5 by 0.5 one time. Table IV shows a part of $A_{\text{arm}}$ only for simplification and the complete ones are presented in Fig. 7 in curves. The influence of redundancy and maintenance interval are reflected by $S_R$ value and curves of $F\text{OR}_{\text{MMC}}$ in TABLE IV and Fig. 7 respectively.

The results show that the maintenance is effective to improve the reliability. The $A_{\text{arm}}$ can be improved from less than 0.97200681 to 0.99999962 when $n=10$. And a more frequent one makes better effects. The $|S_R|$ is higher when $3 \leq T \leq 4$ in the case that $n=10$ and when $7 \leq T \leq 10$ in the case that $n=32$. In another word, more frequent PPM makes more sense when redundancy is a little lower, however the contribution of PPM could not be ignored even the $n$ is as high as 32.

From Fig. 7 it can be seen that when the maintenance interval is short enough, a more frequent maintenance policy can hardly improve the reliability. In the case study, 1.5-years and 6.5-years intervals are short enough for two cases respectively. And when the maintenance interval is too long to replace available SMs timely, the maintenance loses its meaning. As shown, when $T \geq 5.5$ for the case that $n=10$, $A_{\text{arm}}$ and $\text{FOR}_{\text{MMC}}$ are less affected by the maintenance. Comparing the curves $\text{FOR}_{\text{MMC}}$, when $n=10$ the curve is sharper than the one when $n=32$. It means that when $n=10$ the reliability is more sensitive to the maintenance interval, which is in accordance with Fig. 6.

Therefore, there is an interval for $T$, [$T_{\text{min}}, T_{\text{max}}$], in which the $|S_R(T)|>d$ and $d$ is a constant small enough. The values within the interval need special attention in determining the maintenance policy. Both $T_{\text{min}}$ and $T_{\text{max}}$ are functions of $n$, and they can be calculated by (23)-(29).

C. Cost Analysis

According to the previous studies, the reliability of MMC is influenced by both the redundancy levels and the maintenance interval. A fewer number of redundant SMs can be compensated by more frequent maintenance, and vice versa. In this part, the cost and the quantitative effects of this are analyzed. We only discuss the uniform annual value (UAV) increment when the reliability of a converter is improved by increasing $n$ or decreasing $T$. The UAV represents a uniform amount that extends through consecutive periods, considering the time value of money. The general equation for this method is [48]

$$W_{\text{UAV}} = W_p \cdot \frac{i(1+i)^n}{(1+i)^n - 1}$$  \hspace{1cm} (31)

where $W_{\text{UAV}}$ denotes the UAV, $W_p$ denotes the present worth of total cost, $W_n$ denotes the lifetime and $i$ denotes the discount rate.

Fig. 7 Curves of reliability indices for standby mode ($n=10$ and $n=32$)

Because converter is only a component in the transmission system, the cost of its failure is difficult to analysis separated from the whole. The model proposed in this paper can exactly be applied to the system evaluation and the cost due to converter failures can be estimated by sensitivity analysis then. Here the price of an SM is set 27k$, according to data in Chinese markets. The discount rate is set 10%, and the rated lifetime of the SM is set 25 years. Thus the UAV of an SM is 2.975k$ obtained by (31). The cost of one maintenance is set 60k$ for an offshore case [32].

The cost of losses added by additional SMs should be included in Load-sharing mode. In our study, the rated capacity of a SM is 0.8MW, and 0.5% losses are assumed. The capacity factor of a converter is decided on its applications. In the system transmitting wind power, its capacity factor is around 0.4-0.5, while in the critical transmission system it could be as high as 0.9. When the price of electricity is 0.165/kWh, the increased cost caused by an additional SM is about 2.5k$ per year. The cost of losses of an additional SM is as high as the UAV of an SM, thus it can’t be neglected in the cost analysis.

Furthermore, the higher volume of the converter due to redundant SMs might increase the cost, particularly in offshore applications. As the range of redundant SM number discussed in our study is small (0-32), this part of cost is not considered.

The standby model is adopted in this part to discuss the UAV increment for increasing the MMC reliability. The case that $n=0$ and $T=\infty$ (no redundancy and no maintenance) is taken as a cost reference of which the UAV increment ($W_{\text{UAV},0}$) is 0. In the analysis, $n$ is raised from 0 to 32 and $T$ is decreased from 10.5 to 0.5 year. The results are summarized in Fig. 8, in which the height of the bars represents the $W_{\text{UAV},1}$ and the color of them shows the reliability. An $A_{\text{MMC}}$ higher than 0.9950 is considered the minimum required reliability and the cases which satisfy the condition are shown using a light green. Among the cases, the one in which $n=13$ and $T=2.5y$ has the minimal UAV increment that is 62.675k$. It is regarded as the best case under the reliability requirement. From Fig.8 it can be seen that simply increasing the redundancy or organizing frequent maintenance unilaterally is neither efficient in reliability improvement nor economical. The cases with low redundancy corresponding to grey bars have the lowest reliability while still having high investment in terms of maintenance. And the cases that $n=32$ and $T=10.5$ has a much higher UAV increment of about 100k$ and a lower $A_{\text{MMC}}$ than the best case.

Based on this analysis, it can be concluded that it is necessary
to include the influence of PPM in the reliability analysis of MMC, as well as the redundancy levels.

VII. CONCLUSION

A novel reliability model is proposed for MMC to consider the PPM in this paper. First, the reliability function of an arm considering two operation modes is presented. Then the maintenance model of an arm is developed and the reliability indices, available and mean steady failure rate, are derived via renewal process. Based on it, the maintenance model of the whole MMC is proposed. The model can be adopted in the system evaluation together with other component. And the sensitivity of reliability is also analyzed with the aid of the model. Finally, the proposed model is verified in the case study, and some discussion on the redundancy, maintenance interval and cost are carried out. The results indicate some issues as follows. 1) The comparison between Idle mode and Load-sharing mode is greatly related to voltage press modification factor $p_r$. When $p_r$ is high, Idle mode performs better reliability. 2) The sensitivity to the number of redundant SMs is much high when the redundancy is low and decreases with its increment. And there is a closed interval of the maintenance interval $T$, in which the MMC is sensitive to it. 3) The cost of MMC can be properly analyzing the interaction between maintenance interval and the required redundancy levels.

The proposed reliability model, the method to consider PPM in the reliability function, could also be extended to other equipment and the whole system including offshore wind plants and the transmission system connected it. It would be studied in our future work.

APPENDIX

The integral of $R_{X, kn}(t)$ which is described as (3) is derived as

$$
\int_0^\tau R_{X, kn}(t) \, dt = \int_0^{n+l} i \, i \, e^{i \omega t} \left( 1 + e^{i \omega t} \right)^{n+l} \, dt
$$

Let $H(k)$ denotes the integral as (A2)

$$
H(k) = \int_0^\tau e^{(ik) \omega t} \left( 1 + e^{i \omega t} \right)^{n+l} \, dt, \quad k \leq n+l, \quad i
$$

Then the integral in the right of the (A1) equals $H(0)$

$$
\int_0^\tau R_{X, kn}(t) \, dt = \int_0^{n+l} i \, H(0)
$$

With the aid of integration by parts, $H(k)$ can be deduced as

$$
H(k) = A(k) + \frac{n+l}{i+k} \left( k+1 \right) H(k+1)
$$

where

$$
A(k) = \frac{1}{i+k} e^{(ik) \omega t} \left( 1 + e^{i \omega t} \right)^{n+l} \omega t
$$

for $0 \leq k \leq n+l-1$, and

$$
H(n+l) = \frac{1}{(n+l) \omega t} e^{(n+l) \omega t}
$$

Hence $H(0)$ can be obtained by (A4)-(A6)

$$
H(0) = A(0) + \frac{n+l}{i} \frac{A(1) + \frac{1}{(i+1)} (A(2) + \frac{2}{n+l} A(n+l) i)}{i+1} + \frac{1}{n+l} H(n+l) i
$$

which simplifies into

$$
H(0) = \frac{1}{\omega t} \sum_{k=0}^{n+l} \left( e^{(ik) \omega t} \left( 1 + e^{i \omega t} \right)^{n+l} \right) \frac{1}{i+k} \frac{n+l}{1} \frac{i}{i+k} \frac{1}{n+l} i
$$

So that the $H(0)$ in (A3) can be substituted for (A8). Then the integral of $R_{X, kn}(t)$ can be written as

$$
\int_0^\tau R_{X, kn}(t) \, dt = \int_0^{n+l} i \, \int_0^{n+l} i \, e^{i \omega t} \left( 1 + e^{i \omega t} \right)^{n+l} \, dt
$$

(A9)

(A9) can simplifies into

$$
\int_0^\tau R_{X, kn}(t) \, dt = \int_0^{n+l} i \, \int_0^{n+l} i \, e^{(ik) \omega t} \left( 1 + e^{i \omega t} \right)^{n+l} \, dt
$$

REFERENCES


