Reliability Analysis of MMCs Considering Submodule Designs with Individual or Series-Operated IGBTs

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***Abstract*—The half-bridge-based modular multilevel converter (MMC) has emerged as the favored converter topology for voltage-source HVDC applications. The submodules within the converter can be constructed with either individual insulated-gate bipolar transistor (IGBT) modules or with series-connected IGBTs, which allows for different redundancy strategies to be employed. The main contribution of this paper is that an analytical method was proposed to analyze the reliability of MMCs with the consideration of submodule arrangements and redundancy strategies. Based on the analytical method, the relative merits of two approaches to adding redundancy, and variants created by varying the submodule voltage, are assessed in terms of overall converter reliability. Case studies were conducted to compare the reliability characteristics of converters constructed using the two submodule topologies. It is found that reliability of the MMC with series-connected IGBTs is higher for the first few years but then decreases rapidly. By assigning a reduced nominal voltage to the series valve submodule upon IGBT module failure, the need to install redundant submodules is greatly reduced.**

***Index Terms*—Modular multilevel converter (MMC), redundancy analysis, reduced nominal voltage operation, reliability assessment, voltage capability.**

I. Introduction

MULTILEVEL voltage source converters (VSCs) have been widely used in the High Voltage Direct Current (HVDC) applications. Numerous multilevel converter topologies have been reported, including Neutral Point Clamped (NPC) VSC [1], Flying Capacitor Converter (FCC) [1], Cascaded H-Bridge converter (CHB) [2] and Modular Multilevel Converter (MMC) [3]–[5]. Among these multilevel converters, the MMC has come to dominate HVDC applications because of its superior characteristics with respect to operational power losses, industrial scalability and failure management under severe fault conditions. The MMC is a modular converter, a schematic of which is shown in Fig. 1. Each arm of the MMC is comprised of a series arrangement of submodules, whose switching is coordinated to generate a highly sinusoidal output voltage. Each submodule (SM) is typically comprised of a half-bridge arrangement of power electronic switches, with a floating submodule capacitor. Since the concept of MMC was proposed by R. Marquardt in 2001 [3], various topologies based upon the modular multilevel concept have been developed for high voltage applications for both dc-ac conversion [4], [5] and dc-dc conversion [6]. In the HVDC transmission application, researchers have mainly focused their efforts on improving the performance of MMCs, including topology optimization [7], modulation [8], voltage balancing [9] and power loss evaluation [10]. However, availability, and therefore reliability, is also a key feature in selecting between HVDC converter station offerings. Published research on reliability of VSC-HVDC covers analytical methods [11], [12] and simulation methods [13]. Reliability analysis of semiconductors used in VSC-HVDC has also been carried out either on the end-of-life tests [14] or on analytical models of the lifetime of IGBTs [15].

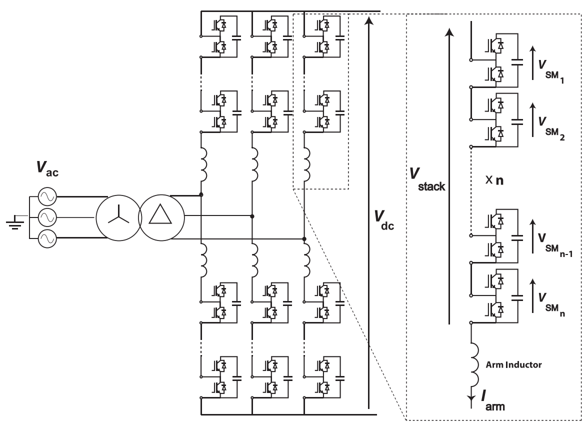

Fig. 1. Circuit schematic of Modular Multilevel Converter.

In [16], the reliability of a two-level converter was modelled, and [17] conducted an industry-based survey about converters'

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reliability, in which the equivalent model of the converter is topology-blind. There has been little work reported on the reliability analysis of MMCs, especially that of MMCs with different submodule topologies.

Two distinct types of half-bridge MMCs have been brought forward by vendors, differing in the ways of using IGBTs in SMs, either single IGBTs [4] or series-connected IGBTs [5]. These two types of SMs are denoted as Individual Device Submodule (**ID-SM**) and Series Valve Submodule (**SV-SM**) in this paper. Their corresponding MMC variants are named as $\mathrm{MMC_{ID}}$ and $\mathrm{MMC_{SV}}$ respectively. The overall electrical characteristics of MMC built using either option are the same and have the same electrical circuit representation [18]. The differences are in the nominal voltage at which each SM is operated, and the number of SMs. The **ID-SM** has a smaller nominal voltage than **SV-SM**. For the same rated dc terminal voltage, more SMs are required in $\mathrm{MMC_{ID}}$. Numerous other potential SM arrangements, such as the Double Clamped Submodule (DCSM), have also been proposed but are not considered in this paper [19].

Due to the high financial costs associated with unscheduled outages of HVDC systems, converters are designed with redundancy. In MMCs designed with single IGBTs within each SM valve, redundancy can be provided by including additional SMs within each arm of the converter [20]. Any faulted SMs need to be quickly bypassed by a mechanical switch. In MMCs that contain series connected devices within each SM, redundancy can also be provided by including additional IGBT devices within each valve inside the SM [5].

This paper intends to make a contribution of proposing an analytical method for the reliability assessment of MMCs with different submodule arrangements and different redundancy strategies. Reliability models of MMCs are presented based upon the failure rate of IGBTs within individual submodules, considering the cases where each submodule valve contains either individual devices, or series connected devices. Using this analytical model, the impact that the submodule arrangement will have on the overall converter reliability is evaluated, and the relative merits of the two approaches are compared in terms of reliability and voltage capability. Sensitivity analysis is conducted to consider the possible difference in the reliability of different IGBT packages used in the two topologies. The influence of a reduced nominal voltage operating mode of the submodule type containing series devices, on the converter reliability is also assessed.

II. Structure and Operating Principle

Fig. 2 shows a per-phase representation of an MMC, which has a nominal dc voltage V_{dc} and an ac voltage v_o. Each phase in an MMC is divided into two arms: the positive arm and the negative arm. A series stack of SMs and one inductor are series connected to constitute each arm. Each SM contains a capacitor and a half-bridge SMs. Two types of SMs, **ID-SM** and **SV-SM** are represented in Fig. 2(b) and (c) respectively. Each valve in **ID-SM** contains single IGBT module, while that in **SV-SM** is composed of several IGBT modules, i.e., l connected in series in Fig. 2(c). The nominal voltage of each SM is denoted by V_{SM}, and the voltage blocking capability of each IGBT module is represented by V_D.

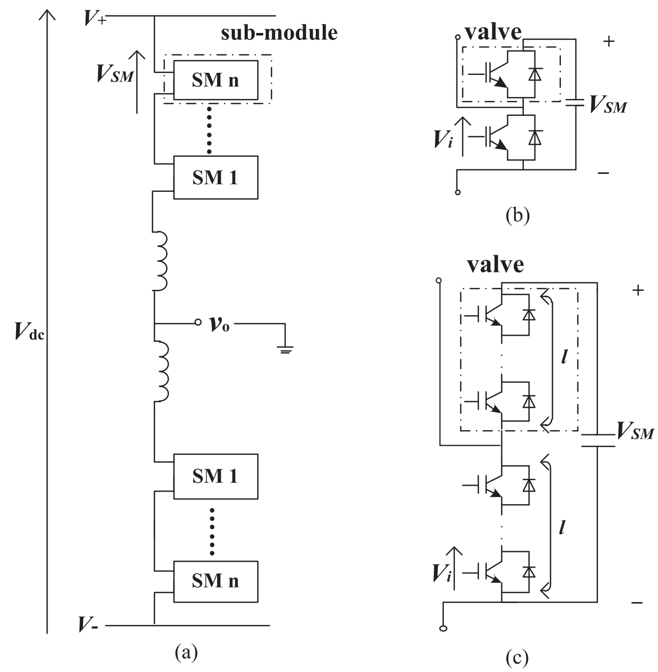


Fig. 2. Configuration of one phase of a Modular Multilevel Converter (a) with two different SMs: (b) **ID-SM** with single IGBT module in each valve or (c) **SV-SM** with series-connected IGBT modules.

The IGBTs used within **ID-SMs** are typically a HiPak style case [21]. This style of package is comprised of an electrically isolated base-plate upon which insulating layers of ceramic material provide electrical isolation of silicon semiconductor dies. These dies are then connected together using bond-wires to internal bus bar structures to form the overall device. This type of package typically forms an open-circuit upon failure. This necessitates a fast mechanical bypass switch to be integrated into the SM to short-circuit the output terminals of the SM in the event of a failure.

The IGBTs used within **SV-SMs** are press-pack devices, designed for series operation. Series operation of IGBTs requires good dynamic voltage sharing performance of the devices, leading to more complicated gate-drive arrangements, and potential need for snubber circuits. Press-pack devices are designed in a vertical manner in which the Collector of the device is connected to one cooling plate of the package, and the Emitter is connected to other cooling plate. The devices are then clamped between heat-sinks to form a series valve. As the cooling plates are not electrically isolated, the heat-sinks form part of the conduction path. This double-sided cooling plate arrangement allows for more efficient cooling of the semiconductors. In addition, press-pack devices eliminate the need for internal bond-wires, which are a major source of failure within HiPak modules [22]. These press-pack devices are also designed to form a stable short-circuit in the event of a device failure. This allows redundancy to be built into each valve as in the event of a device failure, the remaining healthy devices within the valve split the voltage between them. As long as remaining devices have sufficient blocking voltage between them, the SM can continue to operate as normal. If enough IGBTs within a valve fail such that the remaining healthy IGBTs can no longer support the nominal voltage of the SM, the SM must either be taken out of service, or as proposed in [5], a Reduced Nominal Voltage (**RNV**) could be assigned to that SM. An MMC that uses this **RNV** mode will be referred to as $\mathrm{MMC}_{\mathrm{SV\,RNV}}$ in this paper.

By installing redundant IGBT modules in a SM, its reliability is improved. The power loss of the SM, however, is increased. Similarly, when the number of redundant SMs in an MMC increases, the converter tends to be more reliable but with more power loss and higher cost. The number of IGBT modules and the number of SMs are related with the reliability and the power loss of MMCs. In this section, these concepts as the basis of the reliability modelling of MMCs have been discussed.

A. Number of IGBT Modules in a SM

Each valve in a SM should be able to safely operate at the nominal voltage of the SM. Otherwise, the IGBT modules might fail due to over-voltage. In real practices, a voltage margin for the IGBT module is needed, and the operation voltage V_i is typically set as $1/2 \sim 2/3$ of the IGBT module's withstanding voltage V_D. η denotes the de-rating factor of the IGBT module voltage, that is, $\eta = V_i/V_D$. In the **ID-SM**, each SM is comprised of 2 IGBT modules. In the **SV-SM**, which composes of a series of IGBT modules in each valve, IGBT modules share the SM voltage. The minimum number of IGBT modules required in one valve r can be obtained by

$$r = \left\lfloor \frac{V_{\mathrm{SM}}}{\eta \times V_D} \right\rfloor \tag{1}$$

where V_{SM} is the nominal voltage of each SM; η is the de-rating factor of the IGBT module voltage; V_D is the IGBT module's withstanding voltage.

B. Number of SMs in an Arm

The number of SMs in each arm of the converter is determined by the voltages at both dc and ac terminals.

The total nominal voltage of each phase leg should equal to the dc voltage. Let *SW* be a switching function to denote the SM's state. When $SW = 1$, the SM's output voltage is V_{SM}. When $SW = 0$, the SM's output voltage is 0. Then, n, the number of SMs in each arm, should be subjected to the following equation.

$$V_{\mathrm{dc}} = V_+ - V_- = \left(\sum_{i=1}^{n} SW_{\mathrm{pi}} + \sum_{i=1}^{n} SW_{\mathrm{ni}} \right) V_{\mathrm{SM}} \tag{2}$$

where V_{dc} is the nominal dc voltage of the converter; SW_{pi} and SW_{ni} are the switching functions for the i-th SM in the positive arm and the negative arm respectively.

In all phase units of an MMC, SMs can be controlled separately and selectively so that it is possible to adjust the arm voltage by controlling the number of "active" SMs. Each SM is capable of either bypassing itself or inserting its capacitor voltage. By controlling the number of inserted SMs within each arm of the converter, a sinusoidal stepped voltage waveform can be generated. Each arm has to be able to generate a voltage between the dc terminal voltage and zero volts [23]. In order to be capable of generating the required peak voltage, the required number of SMs in each arm is calculated as follows.

$$n \geq \left\lfloor \frac{V_{\mathrm{dc}}/2 + \hat{V}_o}{V_{\mathrm{SM}}} \right\rfloor \tag{3}$$

where $\hat{V}_o$ is the peak ac voltage.

In order to generate an ac voltage with an amplitude of $V_{\mathrm{dc}}/2$, the sum of SM voltages in one arm should be equal to the dc voltage. Then, the minimum requirement of SMs k can be calculated as follows.

$$k = \left\lfloor \frac{V_{\mathrm{dc}}}{V_{\mathrm{SM}}} \right\rfloor \tag{4}$$

The SM capacitance C is estimated by [24]:

$$C = \frac{2 \times S \times E_{\mathrm{MMC}}}{6 \times n \times V_{\mathrm{SM}}^2} \tag{5}$$

where S is the nominal capacity of the MMC; E_{MMC} is the nominal energy per MVA stored in the MMC, and it should be in the range of 30–40 kJ/MVA [5]; n is the number of SMs in each arm; V_{SM} is the nominal voltage of a SM.

C. Redundancy

The voltage capability of an arm can be considered to be the sum of the healthy SM voltages within that arm. In both $\mathrm{MMC}_{\mathrm{ID}}$ and $\mathrm{MMC}_{\mathrm{SV}}$, the failure of an IGBT module can result in a reduction to the voltage capability. If the voltage capability of an arm decreases to a point whereby the arm is no longer capable of generating its required peak voltage, the converter will no longer be able to operate properly and forced shutdown and maintenance may become necessary.

HVDC systems are expected to have high reliability and availability. It is therefore required that the system have sufficient redundancy so that it may continue to operate until the next scheduled maintenance period, where repair and replacement can take place.

Let n_1 and n_2 represent the number of installed SMs in each arm of an $\mathrm{MMC}_{\mathrm{ID}}$ and of an $\mathrm{MMC}_{\mathrm{SV}}$ respectively. Then the number of assembled IGBT modules in the converters with **ID-SM** and **SV-SM** can be obtained by (6) and (7) respectively.

$$M_1 = 12 \times n_1 \tag{6}$$

$$M_2 = 12 \times n_2 \times l \tag{7}$$

where l is the number of series-connected IGBT modules in each valve of a **SV-SM**.

D. Series Valve Operation Modes

Given that l IGBT modules are installed in each valve of $\mathrm{MMC}_{\mathrm{SV}}$ and at least r IGBT modules $(r \leq l)$ are required to endure the nominal voltage, $l - r$ among them are redundant components. In normal mode, when the SM is in healthy state, its operation voltage is set as its nominal voltage. The voltage of a SM with p IGBT modules surviving in the up valve and q in the bottom valve is given by:

$$V_{\rm sc}(p,q) = \begin{cases} V_{\rm SM}, & r \le \min\{p,q\} \le l \\ 0, & \min\{p,q\} < r \end{cases} \quad (8)$$

where $V_{\rm SM}$ is the nominal voltage of the **SV-SM**.

In the **RNV** operation mode, the SM can operate in the nominal voltage $V_{\rm SM}$ if the number of surviving IGBT modules is not less than r in both valves. If there are more than $l-r$ faulty IGBT modules in any of the two valves, the SM will be assigned a lower voltage. It may not be realistic to expect a SM to continue operating if an excessive amount of IGBTs within its valve have failed. To account for this case, a minimum number of healthy IGBTs can be given by r_d. When the surviving IGBT modules is less than r_d, the SM fails and will be bypassed. Assuming that the operation voltage of an valve in a **RNV** mode is proportional to the number of surviving IGBT modules, the voltage of a SM is calculated as:

$$V_{\rm sd}(p,q) = \begin{cases} V_{\rm SM}, & r \le \min\{p,q\} \le l \\ \frac{\min\{p,q\}}{r} V_{\rm SM}, & r_d \le \min\{p,q\} < r \\ 0, & \min\{p,q\} < r_d \end{cases} \quad (9)$$

III. Reliability Modelling of MMCs

There are many items of a plant that have significant impacts on the reliability of an HVDC system beyond the converter electronics, such as the transformers and cables. Even within the electronics, it must be acknowledged that both active components and passive components have impacts on the reliability of MMCs [17]. But this work aims to clarify how variations in the modular construction of the converter influence the reliability. This paper is, therefore, focused on the reliability of the converters with the arrangements of the IGBT modules and their operating modes taken into consideration. All IGBT modules in an MMC are assumed mutually independent. The assumption is made based on the modular operation of the MMC, which means each SM essentially operates as an independent power-converter that sees an identical loading to every other SM within the overall converter [8]. Based upon the analysis of converter structure and operating principle illustrated in Section II, the reliability model of MMCs and the calculation procedure of voltage capability are proposed in this section.

Let $\lambda_d(t)$ be the failure rate of an IGBT module:

$$\lambda_d(t) = \lim_{\Delta t \to 0} \frac{R_d(t) - R_d(t+\Delta t)}{\Delta t R_d(t)} = -\frac{1}{R_d(t)} \frac{d[R_d(t)]}{dt} \quad (10)$$

where $R_d(t)$ is the reliability function of an IGBT module, that is the probability of the IGBT module operating without failure to time t.

From (10), the reliability function of an IGBT module is derived as:

$$R_d(t) = e^{-\int_0^t \lambda_d(t)dt} \quad (11)$$

Note that the electronic equipment's failure pattern is typically demonstrated by a Bathtub curve, in which the normal operating period is characterized by a constant failure rate [25].

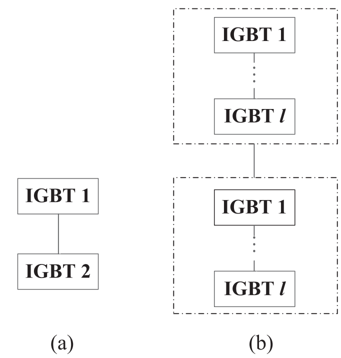


Fig. 3. Reliability diagram of (a) **ID-SM** and (b) **SV-SM**.

The reliability function of an IGBT module is calculated by:

$$R_d(t) = e^{-\lambda_d t} \quad (12)$$

where λ_d is the failure rate of the IGBT module.

A. Impact of Redundant Structure on the Reliability of MMCs

The redundant structure contributes to the improvement of the reliability of MMCs. First, the lifetime of IGBT modules is extended. When redundant submodules are assembled in a converter arm, a lower voltage and cycle frequency are applied to each submodule. In an $\mathrm{MMC_{SV}}$, if redundant IGBT modules are included within a valve, each IGBT module is subjected to a lower voltage. The lifetime of IGBT modules is influenced by various factors, including junction temperature, blocking voltage and cycle frequency [26]. Moreover, different types of IGBT modules are used in the two variants of MMCs, and the failure mechanisms of these two types of IGBTs are quite different [15]. Thus, redundant structure has different impact on the two variants of MMCs. Secondly, the lifetime of a converter arm, as well as that of a converter, is extended. In an MMC with redundant submodules, the faulty submodule is bypassed by a highly reliable high-speed switch when it fails during the operation. The converter will continue to operate. In the $\mathrm{MMC_{SV}}$, the valve will continue to operate upon failures of some IGBT modules, as long as the remaining IGBT modules can endure the rated voltage of the valve. Some work has been done on the impact analysis of various factors on the reliability of IGBT modules. In [14], [26], damage accumulation experiments or numerical simulations were carried out for the considered type of IGBTs, and the lifetime of IGBTs was estimated by analytical models. This paper is focused on the system-level reliability analysis.

B. Reliability Model of MMCs in Normal Operation Mode

1) Reliability of a SM: Based on its topology and operating principle, the reliability diagram for the SM can be obtained. As shown in Fig. 3, IGBT modules in two valves are series connected in terms of reliability, which depicts that the SM works only if both valves are working.

For the **ID-SM**, of which each valve contains one IGBT module, the reliability is given by:

$$R_{s-ID}(t) = R_{\text{du}}(t) \times R_{\text{db}}(t) \tag{13}$$

where $R_{\text{du}}(t)$ and $R_{\text{db}}(t)$ are the reliability function of the IGBT module in the up valve and that of the IGBT module in the bottom valve respectively.

For the **SV-SM**, which consists of a series of IGBT modules, more IGBT modules are usually assembled than required. In a normal operation mode, each valve should be able to withstand the nominal voltage of the SM. If each valve is composed of l IGBT modules and $l - r$ are redundant, the valve will operate as long as any r IGBT modules work. The valve fails at the instant of the $(l - r + 1)$-th IGBT module's failure. Hence, each valve can be regarded as a r-**out-of**-l **system**, which is suitable for the system that continue to operate as long as any r out of l components are working [27]. The reliability of a valve is given by adding the probability of exactly r IGBT modules surviving to time t to the probability of exactly $r + 1$ IGBT modules surviving, and so on up to the probability of l IGBT modules surviving to time t. Given that all IGBT modules have the identical reliability function $R_d(t)$, the reliability of one valve can be calculated as follows.

$$R_v(t) = \sum_{i=r}^{l} C_l^i [R_d(t)]^i [1 - R_d(t)]^{l-i} \tag{14}$$

where r is the minimum number of IGBT modules required in a valve and is calculated using (1). A SM works only if both valves work. The reliability of one **SV-SM** is given by:

$$R_{s-SV}(t) = R_{\text{vu}}(t) \times R_{\text{vb}}(t) \tag{15}$$

where $R_{\text{vu}}(t)$ and $R_{\text{vb}}(t)$ are the reliability function of the up valve and that of the bottom valve respectively.

2) Reliability of an Arm: Note that redundant SMs are operating all the time, even when there have been no failures. The redundant SMs are assembled without any differences from other SMs. Without the consideration of **RNV** operation mode of SMs, the arm will operate as long as k out of n SMs are working. Thus, the arm can be represented by a k-**out-of**-n **system model**. The arm's reliability is given by:

$$R_a(t) = \sum_{i=k}^{n} C_n^i [R_s(t)]^i [1 - R_s(t)]^{n-i} \tag{16}$$

where $R_s(t)$ is the reliability function of the SM (in (13) and (15)); k is the minimum number of SMs required in each arm and is calculated using (4); n is the number of assembled SMs in each arm.

3) Reliability of a Converter: According to the reliability diagram shown in Fig. 4, a phase leg operates only if both the positive arm and the negative arm work. The reliability of one phase leg of an MMC can be calculated by:

$$R_p(t) = R_{\text{ap}}(t) \times R_{\text{an}}(t) \tag{17}$$

where $R_{\text{ap}}(t)$ and $R_{\text{an}}(t)$ are the reliability of positive arm and that of negative arm respectively, as shown in (16).

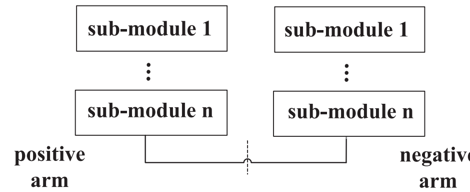


Fig. 4. Reliability diagram of one phase of an MMC.

Then, the reliability of a converter, which is composed of three phases, is obtained by:

$$R_c(t) = [R_p(t)]^3 \tag{18}$$

The mean time to failure (MTTF) of the converter is calculated by:

$$MTTF = \int_0^{+\infty} R_c(t)\, dt \tag{19}$$

And the failure rate of the converter is given by:

$$\lambda_c(t) = -\frac{\mathrm{d}[lnR_c(t)]}{\mathrm{d}t} \tag{20}$$

This paper is focused on the reliability evaluation of two variants of half-bridge MMCs. However, the proposed analytical method and models can be applied to other MMC topologies with minor changes on the reliability function of submodules. Based on the analysis of submodule structure and operating principle, the reliability function of the submodule is derived firstly. By substituting the reliability function of submodules into (16)–(18), the reliability model of MMCs is established. For example, a DCSM contains 5 IGBT modules, and its reliability function is calculated by:

$$R_{s-DC}(t) = \prod_{i=1}^{5} R_{\text{di}}(t) \tag{21}$$

where $R_{\text{di}}(t)$ is the reliability function of the i-th IGBT module. The reliability modelling procedure for MMCs with CDSMs is the same as that for MMCs with **ID-SM**s.

C. Reliability Model of MMC_{SV} *With Reduced Nominal Voltage Mode*

With the consideration of the **RNV** operation mode, the reliability of $\text{MMC}_{SV_{\text{RNV}}}$ can be modelled as follows.

1) Reliability of a SM: If a SM composes l IGBT modules in each valve, the operation voltage of the SM with p IGBT modules surviving in the up valve and q in the bottom valve is given by (9), and its corresponding probability can be calculated by:

$$P_s(t, p, q) = C_l^p C_l^q [R_d(t)]^{p+q} [1 - R_d(t)]^{2l-p-q} \tag{22}$$

where $R_d(t)$ is the reliability function of the IGBT module.

2) Reliability of an Arm: In an $\text{MMC}_{\text{SV}_{\text{RNV}}}$ which can operate with a lower voltage, the arm can be considered to be functional as long as the sum of the voltages of all SMs in the arm is greater than the rated dc voltage. The reliability of an arm can be calculated by summing up the probabilities of the arm in healthy states.

$$R_a = \sum_{\Phi} \prod_{j=1}^{n} P_{\text{sj}}(t, p_j, q_j)$$
$$\Phi = \left\{ (p_1, \ldots, p_n; q_1, \ldots, q_n) \;\middle|\; \sum_{i=1}^{n} V_{\text{si}}(p_i, q_i) \geq V_{\text{dc}}, p_i, q_i \in \{0, 1, \ldots, l\} \right\} \quad (23)$$

where P_{sj} is the probability of SM j operating with p_j IGBT modules surviving in the up valve and q_j in the bottom valve; V_{si} is the SM voltage ((9) for **RNV** mode); V_{dc} is the rated dc voltage; l is the number of IGBT modules in each SM; n is the number of SMs in the arm.

3) Reliability of a Converter: According to the reliability diagram shown in Fig. 4, the reliability of one phase leg and that of an MMC can be calculated by substituting the reliability function of an arm into (17) and (18) respectively. And the reliability indices, MTTF and the failure rate of the converter, can be obtained by (19) and (20).

D. Voltage Capability of MMCs

If redundant IGBT modules or redundant SMs are installed in an arm, the arm can generate a higher voltage than the nominal arm voltage. If the number of faulty SMs within an arm increases, the peak voltage which can be generated at the ac side will be reduced. In terms of the number and the location of faulty SMs, the arm has many possible states at time t. The expected voltage capability of an arm is defined as:

$$V_c(t) = \sum_i V_{\text{ai}} \times P_{\text{ai}} \quad (24)$$

where V_{ai} is the voltage capability of the arm when it is in state i; P_{ai} is the probability of the arm being in state i. The values of V_{ai} and P_{ai} are different for the two variants, MMC_{ID} and MMC_{SV}.

For the MMC_{ID}, given that each arm is composed of n SMs and $n-k$ of them are redundant, the expected voltage capability of an arm at time t is calculated by:

$$V_{c-ID} = \sum_{j=0}^{n} j V_{\text{SM}} C_n^j [R_{s-ID}(t)]^j [1 - R_{s-ID}(t)]^{n-j} \quad (25)$$

where V_{SM} is the nominal voltage of an **ID-SM**; $R_{s-ID}(t)$ is the reliability of the **ID-SM**, namely, the probability of the **ID-SM** working at time t.

Suppose that each arm in an MMC_{SV} is composed of n SMs among which $n-k$ are redundant. The expected voltage capability of an arm at time t can be obtained by:

$$V_{c-SV} = \sum_{\Theta} \left[\left(\sum_{j=0}^{n} V_{\text{sj}}(p_j, q_j) \right) \prod_{j=0}^{n} P_{\text{sj}}(t, p_j, q_j) \right]$$
$$\Theta = \{ (p_1, \ldots, p_n; q_1, \ldots, q_n) \mid p_i, q_i \in \{0, 1, \ldots, l\}, \forall i \in \{1, \ldots, n\} \} \quad (26)$$

where P_{sj} is the probability of SM j operating with p_j IGBT modules surviving in the up valve and q_j in the bottom valve; V_{sj} is its corresponding operation voltage ((8) for normal mode and (9) for **RNV** mode); l is the number of IGBT modules in each SM; n is the number of SMs in the arm.

The standard deviation of the voltage capability is calculated by:

$$\sigma(t) = \sqrt{\sum_i V_{\text{ai}}^2 P_{\text{ai}} - V_c^2} \quad (27)$$

where V_{ai} is the voltage capability of the arm in state i; P_{ai} is the probability of the arm being in state i; V_c is the expected voltage capability.

E. Model Extension

In the previous subsections, it is assumed that the failure of an IGBT module is independent of the failure of any other IGBT modules. Note that some failures, in practice, might cause the outage of two or more IGBT modules, which are called common cause failures. The main common cause failures we have identified for the MMC include internal flash-over, isolation failure, control system failure and cooling system failure, and are independent of the submodule arrangement. To take the common cause failure into consideration, the proposed model needs minor modifications. Common cause failures are considered as virtual components and connected in series with other components/systems. With adequate information, including the failure rate and influenced components/systems, common mode failures are included in the reliability analysis of MMCs. For example, if the cooling pumps in a converter station fail, some or even all IGBT modules in the converter will fail due to overtemperature. As a consequence, the MMC might fail. This common mode failure is regarded as a virtual component with a failure rate of λ_{CMF}, and the corresponding reliability function $R_{\text{CMF}}(t)$ is assumed as $e^{-\lambda_{\text{CMF}} t}$. The reliability function of an MMC in (18) is then modified as:

$$R_c(t) = [R_p(t)]^3 R_{\text{CMF}}(t) \quad (28)$$

where $R_p(t)$ is the reliability function of one phase leg of the MMC.

Moreover, external factors, such as control systems, have impacts on the reliability of MMCs. On one hand, the operation condition of IGBT modules might be influenced. For example, control strategies affect the cycle frequencies, voltage and temperature of IGBT modules. As a consequence, the reliability of IGBT modules is affected. Impacts of control strategies on IGBT reliability and lifetime prediction models of IGBT modules have been analyzed in [14], [15], [26], [28]. On the other hand, MMCs might fail due to failures in control systems. Particular submodules will fail as a consequence of failures of submodule level control systems. The submodule level control system is then regarded as an extra component which is connected in series with the influenced submodule. By multiplying (13) by the reliability function of the submodule level control system, the reliability function of the submodule is obtained. Failures of system-level, station-level and converter-level con-

TABLE I
PARAMETERS OF CONVERTERS

Symbol	Quantity	Value
S	system capacity	1000 MVA
V_{dc}	rated dc voltage	±320 kV
$\widehat{V}_o$	peak ac phase voltage	320 kV
V_D	withstanding voltage of IGBT module	4.5 kV
η	de-rating factor of IGBT module's voltage	56%
V_{ID-SM}	nominal voltage of **ID-SM**	2.52 kV
V_{SV-SM}	nominal voltage of **SV-SM**	17.6 kV
E_{MMC}	energy stored in the MMC	30 kJ/MVA
λ_d	failure rate of the IGBT module	0.004 occ/year

TABLE II
COMPARISON OF TWO VARIANTS OF MMCS

	MMC_{ID}	MMC_{SV}
Levels	259	38
No. of SMs in each arm	258	37
No. of IGBT modules in each SM	2	16
No. of IGBT modules in each arm	516	592
SM Nominal Voltage (kV)	2.52	17.6
SM Capacitor (mF)	6.1	0.87
Redundant SMs per Arm	4	0
Redundant IGBTs per SM	0	2
MTTF (year)	1.25	2.04(non-**RNV** mode 9.07(**RNV** mode)

trol systems cause the outage of the converter, and they are considered as extra components that are connected in series with the MMC. The reliability function of MMCs is derived by multiplying (18) by the reliability function of control systems. Thus, the impacts of control systems on the reliability of MMCs are included in the proposed model.

IV. CASE STUDY

MMC designs with a nominal capacity of 1000 MVA and a nominal dc voltage of ± 320 kV were used in reliability evaluation. The peak ac phase voltage was set to 320 kV. IGBT modules with a blocking voltage of 4.5 kV were considered and a de-rating factor of 56% for the voltage of IGBT modules was applied in both SM types. Therefore, the nominal voltage of the **ID-SM** with single IGBT module in each valve is 2.52 kV. Each **ID-SM** is composed of two IGBT modules. Each **SV-SM** is composed of 16 IGBT modules with one redundant IGBT module included in each valve [5]. Therefore, the **SV-SM** is rated at 17.6 kV nominal. For SMs that operate using the **RNV** mode, a minimum number of healthy IGBTs (r_d) of 5 is imposed. This removes unrealistic cases where SMs operate with nominal voltages that are significantly away from their healthy state voltage. This means that the lowest voltage an SM can be assigned is $\frac{5}{7}$ of the nominal voltage. The failure rate of the IGBT module was assumed as 0.004 occ/year based on statistical data in practical projects [29]. Parameters of the converters used in this comparison are shown in Table I. Simulations were conducted using MATLAB R2014a. The maintenance as well as the repair of components is not considered in this paper.

A. Reliability Comparison of MMCs

Three variants of MMCs, $\mathrm{MMC_{ID}}$, $\mathrm{MMC_{SV}}$ and $\mathrm{MMC_{SV_{RNV}}}$ are compared in terms of reliability and arm voltage capability in this subsection. The basic information of MMCs, including the number of IGBT modules, the number of SMs and the SM capacitance, is calculated according to Section II. Reliability, as well as the voltage capability, of MMCs is then evaluated based upon the modelling procedure in Section III.

In the $\mathrm{MMC_{SV}}$, one redundant IGBT module is included in each valve, but no redundant SMs are included. At least 37 SMs are required in each arm to generate a dc voltage of ± 320 kV. The number of IGBT modules in each arm is $37 \times 16 = 592$, and

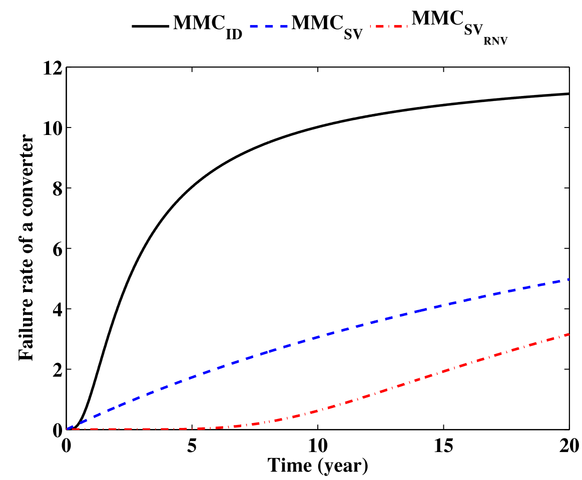
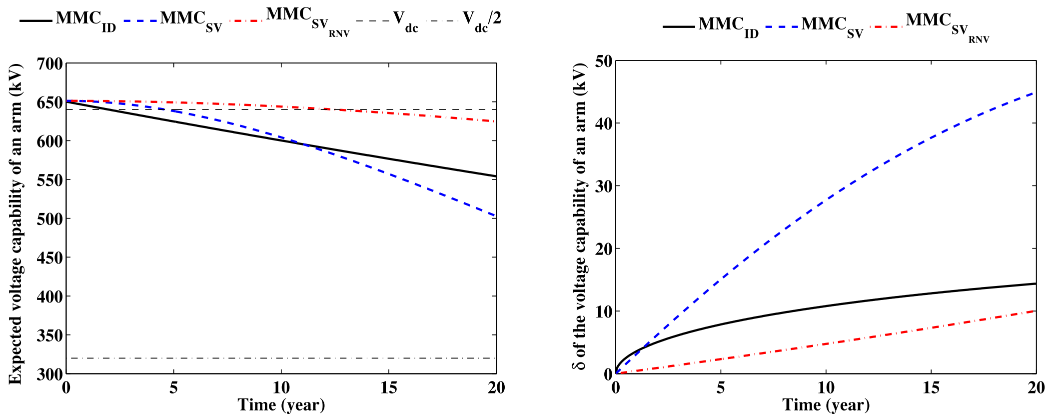


Fig. 5. Failure rate of MMCs.

the initial voltage capability is 651.2 kV. For the same voltage level, each arm of an $\mathrm{MMC_{ID}}$ must contain at least 254 SMs, and here 4 redundant SMs are added to meet the same initial voltage capability as $\mathrm{MMC_{SV}}$. There are $258 \times 2 = 516$ IGBT modules in each arm of an $\mathrm{MMC_{ID}}$. Basic parameters of the two variants, i.e., SM number and IGBT module number, are presented in Table II. Two operation modes are applied to the $\mathrm{MMC_{SV}}$. The allowable number of IGBT modules to be failed in a valve is one in the normal mode and 3 in the **RNV** mode respectively.

Reliability indices of MMCs, MTTF and the failure rate, are calculated using (19) and (20) respectively. MTTF of each variant is shown in Table II, while the failure rate is illustrated in Fig. 5. X-axis is time t, while Y-axis is MMCs' failure rate at time t. 1.6% redundant IGBT modules are added in the $\mathrm{MMC_{ID}}$, and the redundant rate of IGBT modules in the $\mathrm{MMC_{SV}}$ is 14.3%. The MTTF of the $\mathrm{MMC_{ID}}$ is 1.25 years, which is less than that of the $\mathrm{MMC_{SV}}$. The failure rate of the $\mathrm{MMC_{ID}}$ increases rapidly over time in the first few years. Moreover, the $\mathrm{MMC_{SV}}$ operating in **RNV** mode is more reliable than that in the normal mode.

The expected arm voltage capability and the corresponding standard deviations of the variants over time are calculated using (24)–(27) and shown in Fig. 6(a) and (b) respectively. In the



(a) (b)

Fig. 6. (a) Expected voltage capability of an arm and (b) the corresponding standard deviation.

TABLE III
COMPARISON OF MMCs WITH DIFFERENT FAILURE RATES

	MMC_{ID}	MMC_{SV}	$\text{MMC}_{\text{SV}_{\text{RNV}}}$
Levels	259	38	38
No. of SMs in each arm	258	37	37
No. of IGBTs in each SM	2	16	16
No. of IGBTs in each arm	516	592	592
Voltage capability at $t = 0$ (kV)	650.16	651.2	651.2
Energy Storage at $t = 0$ (kJ/MVA)	30	30	30
Redundant SMs per Arm	4	0	0
Redundant IGBTs per SM	0	2	2
MTTF (year)}	1.25	2.04 ($\lambda_{SV} = 0.004$) 2.91 ($\lambda_{SV} = 0.0028$) 5.09 ($\lambda_{SV} = 0.0016$)	9.07

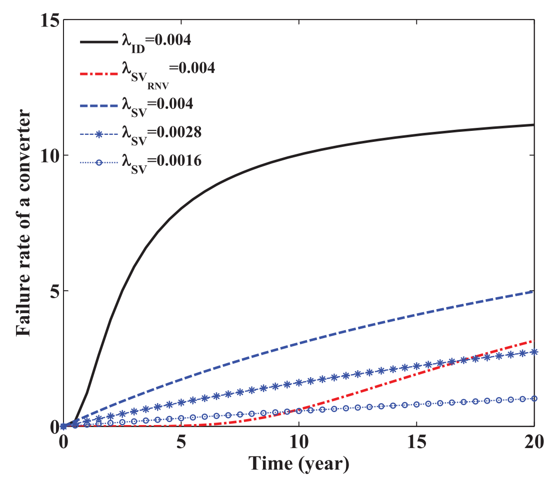


Fig. 7. Failure rate of MMCs ($\lambda_{\text{ID}} = \lambda_{SV_{\text{RNV}}} = 0.004; \lambda_{\text{SV}} = 0.004, 0.0028, 0.0016$).

first 10 years, the expected voltage capability of an arm in the MMC_{SV} in the normal operation mode is greater than that in the MMC_{ID}. IGBT modules have high reliability in the first few years. The probability of the **SV-SM** with redundant IGBT modules being in healthy state is greater than that of the **ID-SM**. Thus, the expected remaining voltage of the arm in MMC_{SV} in the first few years is greater than that in the MMC_{ID}. If the **RNV** mode of operation is not used, then the decrease in expected voltage capability of an MMC_{SV} increases over time and at some point exceeds that of the MMC_{ID}. The MMC_{SV} also has the most rapidly increasing standard deviation.

With greater expected values and smaller standard deviation, the voltage capability of an arm of the MMC_{SV} operating with the **RNV** mode is substantially better than that in non-**RNV** mode. This is because the **SV-SM** in the **RNV** mode can operate with 3 faulty IGBT modules in each valve, while that in the normal mode will be out of service if more than one IGBT module fails in a valve. The profile of the voltage capability of the **SV-SM** and the arm is much improved by **RNV** mode.

Monte Carlo-based simulations have been undertaken to validate the proposed analytical method. Simulations were conducted 30000 times to calculate the MTTF of converters. The MTTF of MMC_{ID} and that of MMC_{SV} are 1.25 years and 2.03 years respectively, which are approximately equal to the results obtained by using the proposed analytical method. Compared with the Monte Carlo-based simulation, the analytical method obtains more accurate values of MTTF. Moreover, except for MTTF, the failure rate of MMCs is calculated in the proposed analytical method, which provides more information about the reliability of converters and how redundancy influences the system reliability.

B. Influence of IGBT Module'S Failure Rate

It is important to note that different IGBT modules, HiPak and Press-pack style cases respectively, are used within **ID-SMs** and **SV-SMs**. It is therefore useful to collect the failure rate of different types of IGBT modules for the comparison of the reliability of MMCs. Statistical data about the reliability of different IGBT modules used in HVDC system is not available as most of MMC-based HVDC projects were put into operation recently. To investigate the impact of IGBT modules' lifetime on the voltage capability of MMCs, a sensitivity analysis was conducted. In the MMC_{ID} and the $\text{MMC}_{SV_{\text{RNV}}}$, the failure rate

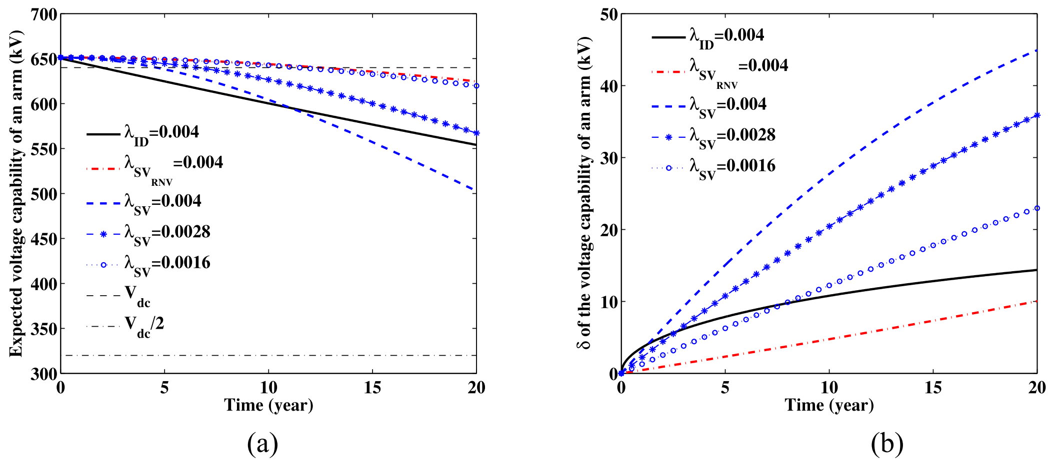


Fig. 8. (a) Expected voltage capability of an arm and (b) the corresponding standard deviation $\left(\lambda_{\mathrm{ID}} = \lambda_{SV_{\mathrm{RNV}}} = 0.004; \lambda_{\mathrm{SV}} = 0.004, 0.0028, 0.0016\right)$.

of IGBT module λ_d was set to 0.004. In the $\mathrm{MMC_{SV}}$ operating in the normal mode, several values for λ_d were chosen, from 0.004 to 0.0016. The MTTF and failure rate of MMCs are calculated using (19) and (20) respectively. Basic parameters of converters are shown in Table III, and failure rates of MMCs over time are plotted in Fig. 7. As the failure rate of IGBT modules decreases, the reliability of the $\mathrm{MMC_{SV}}$ is improved. If the failure rate of IGBT modules decreases by 30%, the MTTF of the $\mathrm{MMC_{SV}}$ increases to approximately 3 years. When the failure rate of IGBT modules is further reduced to 0.0016 occ/year, the failure rate of the $\mathrm{MMC_{SV}}$ goes close to that of the $\mathrm{MMC}_{SV_{\mathrm{RNV}}}$ in the first five years, and increases more slowly afterwards.

Based on the modelling procedure in Section III, the expected voltage capability of an arm in the variants and the corresponding standard deviation are evaluated and shown in Fig. 8(a) and (b) respectively. If the failure rate of IGBT modules decreases, the descent rate of the expected voltage capability of the $\mathrm{MMC_{SV}}$ decreases. The profile of standard deviation over time is also improved. When the failure rate of IGBT modules in $\mathrm{MMC_{SV}}$ is less than 70% of that in $\mathrm{MMC_{ID}}$ ($\lambda_{\mathrm{SV}} = 0.0028$), the $\mathrm{MMC_{SV}}$ has a better expected voltage capability in the first 20 years. If the failure rate is reduced to 0.0016, the voltage capability of the $\mathrm{MMC_{SV}}$ will be improved approximately match that of the $\mathrm{MMC_{SV}}$ operating in the **RNV** mode with the original λ_d.

C. Design Comparison of MMCs

Based on the reliability models and the voltage capability calculation procedure described in Section III, reliability-oriented design of MMCs is conducted in this subsection. The design objective chosen is that probability of a converter operating without failure should be not less than 0.998 in the first three years. The basic parameters, i.e., number of SMs and IGBT modules, in each variant are determined to meet this objective. The SM capacitor for each variant is kept to the value given in Table II. Comparison of the resultant MMCs in terms of component number and redundancy schemes are shown in Table IV.

TABLE IV
DESIGN COMPARISON OF MMCS

	$\mathrm{MMC_{ID}}$	$\mathrm{MMC_{SV}}$	$\mathrm{MMC_{SV_{RNV}}}$
Levels	271	41	38
No. of SMs in each arm	270	40	37
No. of IGBTs in each SM	2	16	16
No. of IGBTs in each arm	540	640	592
Voltage capability at $t = 0$ (kV)	680.4	704	651.2
Energy Storage at $t = 0$ (kJ/MVA)	31.37	32.33	30
Redundant SMs per Arm	16	3	0
Redundant IGBTs per SM	0	2	2
MTTF (year)	5.80	7.77	9.07

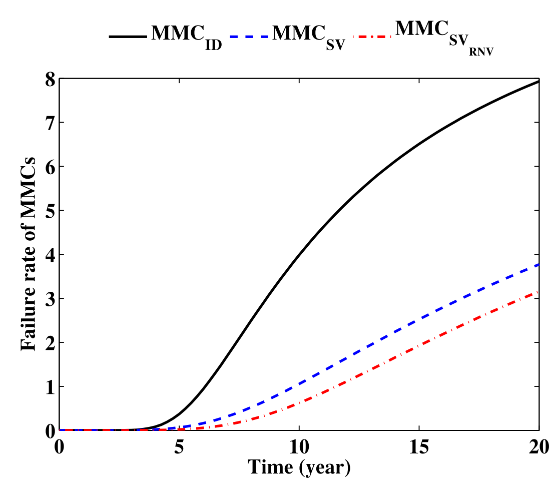


Fig. 9. Failure rate of MMCs—Design to meet Reliability ≥ 0.998 in the first three years.

In the case of $\mathrm{MMC_{ID}}$, 16 redundant SMs (6.3%) were found to be required to meet the reliability target. 270 SMs are installed in each arm in the $\mathrm{MMC_{ID}}$, and 16 among them are redundant.

The minimum number of SMs in each arm of the $\mathrm{MMC_{SV}}$ is 37 to generate a dc voltage of ± 320 kV. To meet the reliability objective, 3 more SMs are required in each arm of the $\mathrm{MMC_{SV}}$ in the normal mode, whilst no redundant SMs are needed for

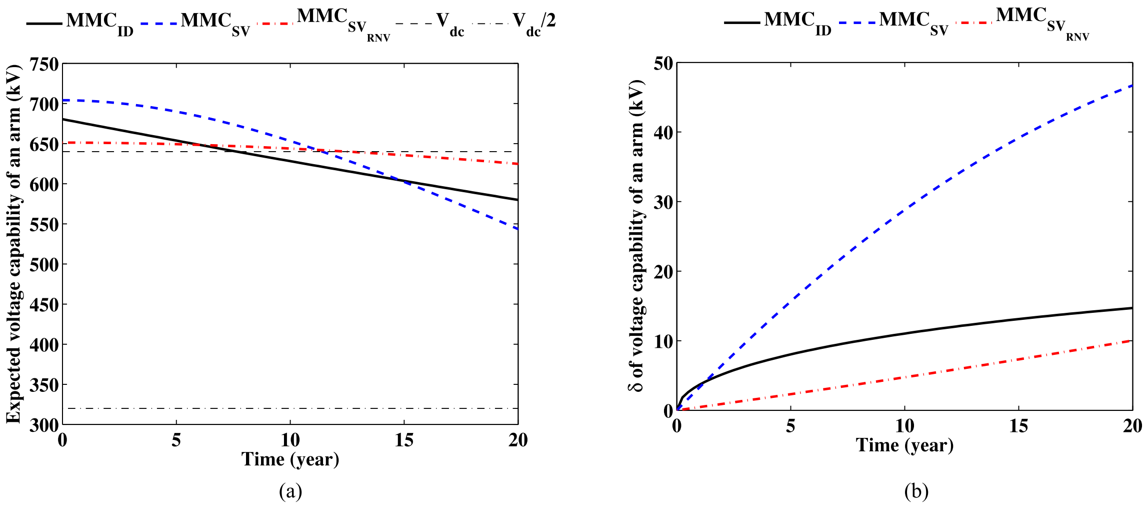


Fig. 10. (a) Expected voltage capability of an arm and (b) the corresponding standard deviation—Design to meet Reliability≥ 0.998 in the first three years.

a converter operating in the **RNV** mode. The initial expected voltage capability in the three variants are 680.4 kV, 704 kV and 651.2 kV respectively. The utilisation of SMs in the $\mathrm{MMC}_{\mathrm{SV}_{\mathrm{RNV}}}$ is better than that in the $\mathrm{MMC}_{\mathrm{ID}}$. The overall energy storage value in the $\mathrm{MMC}_{\mathrm{SV}_{\mathrm{RNV}}}$ is also lower than the other two variants as no additional SMs are required.

The power-losses within MMC are dominated by the conduction losses within the semi-conductor devices [30]. The number of IGBTs within the arm can therefore be used as a measure of the expected relative efficiency of each converter. The $\mathrm{MMC}_{\mathrm{SV}_{\mathrm{RNV}}}$ has been found to require a lower number of redundant SMs to achieve the same reliability as the $\mathrm{MMC}_{\mathrm{ID}}$ gets. The total number of IGBT devices within the converter is significant because of the redundant IGBT modules within the SM. In the example case given the $\mathrm{MMC}_{\mathrm{SV}_{\mathrm{RNV}}}$ has approximately 9.6% more IGBTs. This indicates that if IGBTs with similar characteristics are used the $\mathrm{MMC}_{\mathrm{ID}}$ may be expected to be more efficient, compared to the $\mathrm{MMC}_{\mathrm{SV}_{\mathrm{RNV}}}$. As noted in Section II, the $\mathrm{MMC}_{\mathrm{SV}}$ requires the use of press-pack devices which have higher performance than the HiPak modules typically used in $\mathrm{MMC}_{\mathrm{SV}}$. This may reduce the loss penalty imposed by including redundant IGBTs within each SM.

In terms of reliability, the MTTF and failure rate of MMCs are calculated based upon the procedure in Section III and shown in Table IV and Fig. 9. To meet the reliability target, more redundant IGBT modules have been added in both the $\mathrm{MMC}_{\mathrm{ID}}$ and the $\mathrm{MMC}_{\mathrm{SV}}$. Compared to the results in Table II, the redundancy rate of IGBT modules in the $\mathrm{MMC}_{\mathrm{ID}}$ is increased from 1.6% to 6.3%, and the MTTF increases from 1.25 years to 5.80 years. The MTTF of the $\mathrm{MMC}_{\mathrm{SV}}$ is improved from 2.04 years to 7.77 years. Failure rates of all variants are close to 0 in the first five years. After that, the failure rate of the $\mathrm{MMC}_{\mathrm{SV}}$ goes more slowly over time than the $\mathrm{MMC}_{\mathrm{ID}}$ because higher redundant rate of IGBT modules is applied.

The expected arm voltages of all variants and the corresponding standard deviation are calculated using (24)–(27) and plotted in Fig. 10(a) and (b) respectively. Due to the required installation of redundant SMs, the $\mathrm{MMC}_{\mathrm{ID}}$ and the $\mathrm{MMC}_{\mathrm{SV}}$ have a larger initial voltage capability than the $\mathrm{MMC}_{\mathrm{SV}_{\mathrm{RNV}}}$. As the expected number of failure of the IGBT modules increases over time, the expected voltage capability of the $\mathrm{MMC}_{\mathrm{SV}}$ in the normal mode decreases significantly. The expected voltage capability of an arm in the $\mathrm{MMC}_{\mathrm{SV}_{\mathrm{RNV}}}$ decreases relatively slowly. The $\mathrm{MMC}_{\mathrm{SV}_{\mathrm{RNV}}}$ also has the smallest standard deviation.

In the $\mathrm{MMC}_{\mathrm{SV}}$ operating in the normal mode, an expected voltage greater than the nominal dc voltage lasts available for almost 4.6 years if no redundant SMs are installed, shown in Fig. 6(a). With the installation of redundant SMs and also with the **RNV** operation mode, the probability of an arm being able to generate the nominal dc voltage increases. The expected voltage is greater than the dc nominal voltage for more than 11 years with 4 redundant SMs installed in each arm and nearly 12.5 years with the application of the **RNV** mode. The improvement of the converter's voltage capability by applying the **RNV** operation mode is seen to be greater than by installing redundant SMs.

V. Conclusion

In this paper, a detailed model of the reliability of the MMCs used for HVDC transmission has been presented. Two variants of the half-bridge submodule were considered: one with single IGBT and one with valves of several series-connected IGBTs. An additional operating mode of the series-valve topology was considered in which operation with reduced nominal voltage (RNV) is used after more than one IGBT failure per submodule. For each topology and mode, the reliability of the MMC was expressed analytically in terms of reliability of the IGBT modules and expressions found of the expected available arm voltage as function of time. The converter as a whole is deemed to have failed if any one of the six arms has an available voltage of less than the DC voltage required. A case study design was used to compare the converter topologies. The following conclusions are drawn.

The decrease in available arm voltage with time is initially slower with the series valve submodule than the individual device submodule. The former has a higher available voltage for the first few years but then the decrease rate accelerates and in future years the individual device fares better.

The RNV mode of operation applied to the series valve submodule is very effective in preventing the expected available arm voltage from decreasing quickly with time and greatly reduces the need to install redundant submodules. In effect it makes better use of redundancy within the submodules.

Comparing the three approaches for the same converter reliability target, the individual device submodule leads to the lowest number of IGBTs overall and by extension will have the lowest conduction power loss. The series valve submodule operated with RNV is placed second on this basis but has the additional advantage of using less capacitance.

Acknowledgment

Information on the data that support the results presented in this paper, including how to access them, can be found in the Cardiff University data catalog at http://dx.doi.org/10.17035/d.2016.0009095138.

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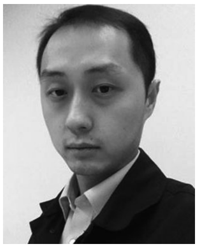

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