Reliability Modeling and Evaluation of MMCs Under Different Redundancy Schemes

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***Abstract*—Due to the demand for high reliability, modular multilevel converters (MMCs) are designed with redundant submodules. Redundant submodules can be integrated into the converter by employing different redundancy schemes: the conventional active scheme, the load-sharing active scheme, and the passive scheme. Different schemes have different impacts on the improvement of converter reliability. The contributions of this paper include that an analytical method is proposed to evaluate the reliability of MMCs under different redundancy schemes and the factors' influence on the converter reliability is analyzed to determine the proper redundancy scheme. Reliability models of MMCs under different redundancy schemes are built using Markov chains and the iteration method. Based on the proposed models, the effects of redundant schemes are evaluated in terms of the converter reliability. A case study is conducted to validate the feasibility and robustness of proposed models and to specify the conditions in the favor of each redundancy scheme. The benefits of sharing redundancy among arms are also explored from the reliability point of view. If insulated-gate bipolar transistors (IGBTs) and capacitors are dominant components in a submodule in terms of failure rates, the load-sharing active scheme performs better; otherwise, setting the redundant submodules in an idle state is more effective. It is also found that the number of required redundant submodules is greatly reduced by sharing redundancy among arms.**

***Index Terms*—Load-sharing redundancy, modular multilevel converter, passive redundancy, redundancy scheme, reliability assessment.**

I. Introduction

MODULAR multilevel converter (MMC) shows attractive features in operational power losses, industrial scalability and failure management under severe fault conditions [1], [2], and has emerged as a promising solution in High Voltage Direct Current (HVDC) applications. Different topologies of sub-modules (SMs) have been proposed, including half-bridge SMs, full-bridge SMs and double clamped SMs. Among them, the half-bridge based arrangement is the favoured one because of its simplicity in structure and control [3].

Research on MMCs mainly falls in the area of converter topology design [4], control [5], fault detection [6] and applications [7], [8]. Reliability is also a key feature to be considered in system planning, design and operation. Increased efforts have been made on the reliability of converters for HVDC applications. Published research can be divided into three categories: component-level research, converter-level research and system-level research.

At the component level, reliability of semiconductors and capacitors used in power converters was analysed on the basis of the end-of-life tests [9] and the probabilistic modelling of component lifetime [10]. At the converter level, the reliability of MMCs based on the analysis of the modular topology is evaluated in [11]–[14]. With the consideration of converter topologies, [11] proposed a reliability evaluation method for general converters on the basis of the multi-state computation, and applied the k-out-of-n model to illustrate the reliability of a multilevel converter with redundancy. [12] carried out the determination of the redundancy rate of SMs in MMCs based on the reliability analysis. With both reliability and dc fault ride-through capability taken into account, [13] proposed an approach to obtain the optimal redundancy configuration for hybrid MMCs. In [14], authors compared the reliability of two types of half-bridge MMCs and evaluated the influence of SM arrangements on converter reliability. At the system-level, [15] evaluated the reliability of MMC-based HVDC transmission system using analytical methods. There are few publications on the reliability analysis of MMCs with the comparison of different redundancy schemes.

MMCs are designed with redundancy to avoid unnecessary shut-down upon the failure of a single component. Redundant SMs are integrated each arm to extend the operation time of the arms. Traditionally, redundant SMs are integrated to share the arm voltage [16], operating in the same way as other SMs. Redundant SMs can also operate as idle components, which don't participate in switching until a fault occurs at an operating SM [4], [17]. These two redundancy schemes are denoted as the active scheme and the passive scheme in this paper.

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In the active scheme, the failure rate of operating SMs could be reduced by applying lower voltage or slightly lower switching frequency on each SM. Simple operation could be achieved as redundant SMs are operating in the same way as other SMs. But operating SMs have higher probability of a failure due to triggering errors than those in idle states. In the passive scheme, the idle state contributes to extending the lifetime of redundant SMs, but each SM in operation suffers higher operating stresses. The switching in of a redundant SM is more complicated than that in the active scheme. MMCs with the two redundancy schemes differ in life spans and reliability. This paper also proposes a new redundancy option: passive redundant SMs being shared among arms. Although the complexity of the control strategy and the circuit is increased, the number of redundant SMs can be reduced.

In terms of the methods for analysing redundancy systems, published researches have focused on deducing closed-form expressions for the system reliability [18]–[20], and have successfully applied the methods to the reliability analysis of small-scale systems. However, the accuracy of results calculated by those expressions are affected by round-off errors, and the results tend to be unstable especially for large-scale systems. MMCs in the HVDC applications are usually comprised of hundreds of SMs. Thus, existing methods can not be applied to the redundancy analysis of MMCs.

To evaluate the effects of different redundant schemes on the converter reliability, detailed mathematical models suitable for the redundancy analysis of large scale systems are proposed, which is the main contribution of this paper. With the consideration of the operating conditions of SMs under different redundancy schemes, the reliability of MMCs is modelled explicitly using Markov chains and the iteration method. The proposed models are compared with existing methods, and their feasibility and robustness are evaluated. Based on the proposed models, MMCs under different redundancy schemes are compared with respect to reliability. Sensitivity analysis of component failure rates is presented to specify conditions that are in favour of each redundancy scheme. Reliability benefits of sharing redundancy among arms are also explored.

II. Redundancy Schemes of MMCs

The configuration of a three-phase MMC is shown in Fig. 1. Each phase unit consists of two arms: the upper and lower arms. Each arm is comprised of a number of series-connected SMs and one inductor. Typically, a half-bridge arrangement of power electronic devices, a capacitor, a thyristor, a bypass switch, power supply system and the sub-module control system constitute a SM, as depicted in Fig. 2. The sub-module control system includes drive circuits, fibre-optic communication system, and sub-module controller.

During the operation of a MMC, the desired sinusoidal voltage at the ac terminal is achieved by adjusting the voltage ratio of two arms in each phase unit. To allow the output ac voltage with maximum amplitude, the sum of SM voltages in each arm should not be smaller than the dc-bus voltage [2]. Thus, the minimum number of SMs in each arm is given as:

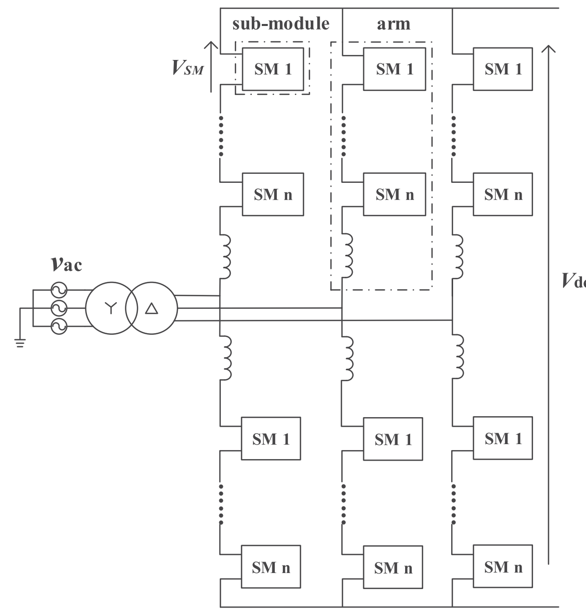

Fig. 1. Configuration of a three-phase MMC.

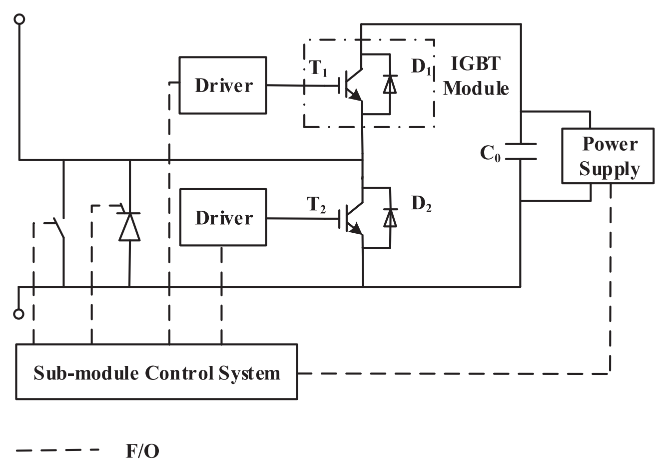

Fig. 2. Configuration of a half-bridge SM.

$$k = \left\lfloor \frac{V_{dc}}{V_M} \right\rfloor \quad (1)$$

where V_{dc} is the dc-bus voltage of the MMC; V_M is the nominal SM voltage.

Upon the failure of one SM, the remaining SMs cannot generate the required dc voltage if there is no redundant SM in an arm. The arm needs to be repaired. To avoid the converter being shut down as a result of the failure of single component, sufficient redundant SMs are integrated. When a SM fails during the operation, the faulty SM is bypassed by a high-speed switch, and the converter will continue to operate. In the next scheduled shut-down for maintenance, the faulty SM will be replaced. Two redundancy schemes can be applied to improve the converter reliability, differing in the operation of redundant SMs.

1) *Active Scheme:* redundant SMs operate "actively". Essentially, no difference exists between the redundant SMs and other SMs. The arm continues to operate upon SM failures as long as the number of healthy SMs is larger than k. SM operation modes can further be categorized into two modes, which are named as **conventional mode** and **load-sharing mode**, respectively, in this paper. Given that n SMs are assembled in an arm, of which $n - k$ are redundant. In the conventional mode, the number of "on-state" SMs in a phase unit is always equal to k [21], [22], which means the number of "on-state" SMs in each arm during a fundamental period ranges from 0 to k. The reference voltage of each SM remains unchanged, and the output levels of the arm voltage is not influenced by a SM failure [22]. The inclusion of redundant SMs thus results in an increase of the number of SMs that deliver zero voltage. In the load-sharing mode, n SMs in a phase unit are chosen to share the dc-bus voltage [22]. Each operating SM is normally subjected to a voltage that is lower than the nominal value. Upon failure of a SM, the faulty SM is bypassed, and other SMs are assigned a slightly higher voltage than the original value. The arm continues to operate after the short transient for setting down at higher voltage for each SM [22]. Unlike the conventional mode, each SM in the load-sharing mode is subjected to a slightly lower voltage, but a greater average switching frequency.
2) *Passive Scheme:* redundant SMs are bypassed when installed, and one of them will be switched into operation whenever one of the operating SMs fails [4], [17]. When the number of failed SMs is larger than the number of initial redundant SMs, the converter needs to be shut down. Compared with the active scheme, redundant SMs in the passive scheme have less possibility to suffer damaging caused by operational disturbances, power failure or triggering errors. Thus, their failure rate is much lower. However, operating SMs endure slightly higher voltage than those in the load-sharing mode or greater average switching frequency than those in the conventional mode, which means they have a higher risk to fail. There exists a balance in terms of the overall reliability. One technical contribution of this paper is to answer this question and compare the reliability of different schemes.

Furthermore, sufficient redundant SMs are normally installed in each arm to ensure the reliability of MMCs. Redundant SMs in some arms might be unused until the annual maintenance, while other arms might fail as a result of losing all redundant SMs. The passive scheme provides the possibility of two or more arms sharing redundant SMs. If redundant SMs are shared among two or more arms, the performance of converters can be improved in terms of reliability or the requirement of redundant SMs. A possible circuit configuration for sharing redundant SMs between two arms in a phase leg is shown in Fig. 3(a). Corresponding switching strategies are similar to that for online tap change transformers. Shown in Fig. 3(a), S represents a switch, which could be a power electronic switch or a mechanical switch, depending on applications.

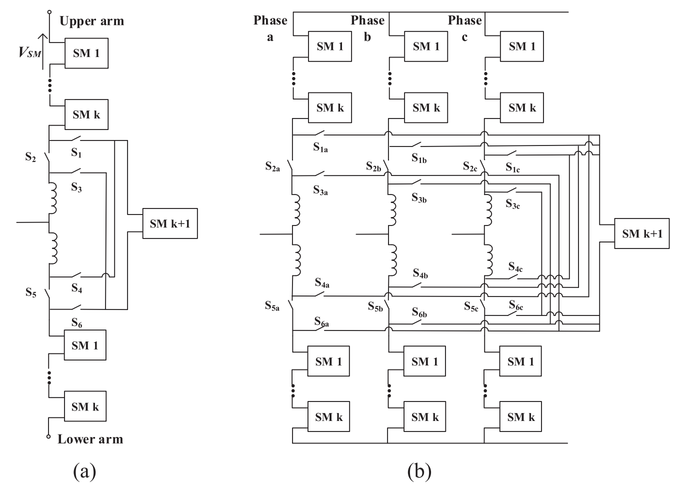

Fig. 3. Circuit configurations for the proposed redundancy schemes: (a) sharing redundancy between two arms in a phase; (b) sharing redundancy among six arms.

When all SMs are in healthy state, S_2 and S_5 are switched on, and S_1, S_3, S_4, S_6 are switched off. If a SM failure occurs in the upper arm, the redundant SM is included in the upper arm with S_1, S_3 and S_5 switched on and others switched off. If a faulty SM detected in the lower arm, S_2, S_4 and S_6 are switched on, and others are switched off.

Similarly, a general configuration for sharing redundant SMs among all arms in a converter is proposed, shown in Fig. 3(b). This configuration increases the control complexity. However, as the switching circuit does not need to work all the time, the increase of the control complexity should not reduce the reliability too much.

For the cases the cost and size of MMCs are the main concern, the sharing redundancy could have higher possibility for industrial applications. Also, between the two configurations in Fig. 3, the sharing redundancy between arms in the same phase leg is more possible to be used in industry as it does not increase the circuit complexity too much. Note that this could trigger new circuit design and patents which are worthy of further investigation, this paper only analyses the reliability benefits and presents a potential trend of research topic.

III. Reliability Models of MMCs Considering Redundancy Schemes

On the basis of the analysis of converter structure, the reliability model of MMCs is established in this section. The converter model is divided into three levels: submodule level, arm level and converter level, as shown in Fig. 4. In this paper, investigations focus on the reliability modelling of an arm under different redundancy schemes. To illustrate the impact of redundancy schemes on individual SM in an arm, the detailed model of SMs is established with the consideration of operation conditions. The reliability of arms with different redundancy schemes is derived using Markov chains and the iteration method. By including the reliability model of arms into the structural modelling procedure that we proposed in [14], the reliability model of the converter is then established.

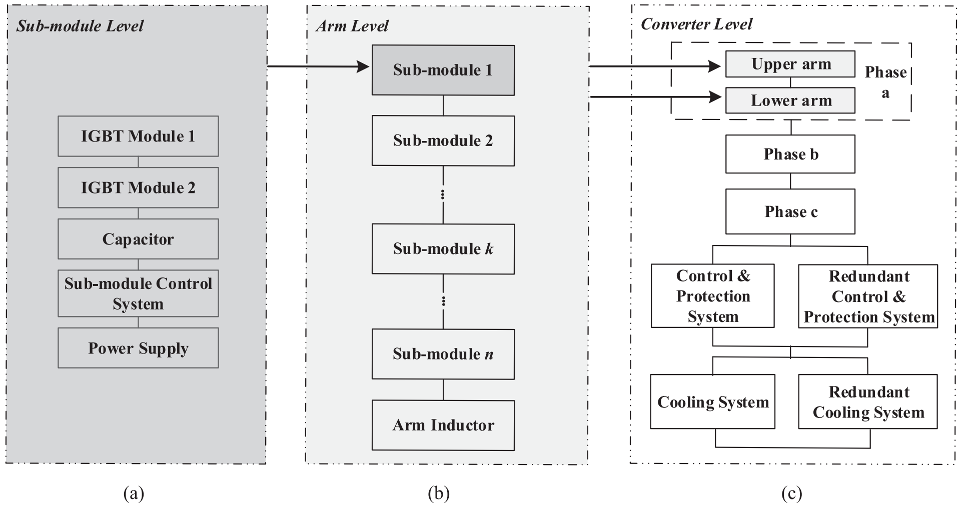

Fig. 4. Reliability block diagram of MMCs: (a) sub-module level model; (b) arm level model; (c) converter level model.

A. Sub-Module Level Reliability Models

Based on the topology of a SM in Fig. 2, the reliability diagram for the half-bridge SM is obtained, which is depicted in Fig. 4(a). Note that the thyristor is fired during DC-side faults, and it does not affect the reliability of a sub-module under normal operating conditions. The bypass switch, which is utilized when a faulty sub-module is detected and needs to be shorted out, is highly reliable [16]. Thus, thyristors and bypass switches are not included in the calculation of the reliability of sub-modules.

1) Reliability of SMs Regardless of Operation Conditions: Assuming that devices in a SM have constant failure rates, their reliability functions are then given as [14]:

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

where λ is the failure rate of devices.

The SM can operate normally only if all components are working properly, and its reliability is given as:

$$R_s(t) = R_{iu}(t) \times R_{il}(t) \times R_{cap}(t) \times R_{sc}(t) \times R_{ps}(t) \tag{3}$$

where $R_{iu}(t)$, $R_{il}(t)$, $R_{cap}(t)$, $R_{sc}(t)$ and $R_{ps}(t)$ are reliability functions of the upper insulated-gate bipolar transistor (IGBT) module, the lower IGBT module, the capacitor, the SM control system and the power supply, respectively.

Regardless of operation conditions, the failure rate of a SM is then obtained by:

$$\lambda_s = \frac{1}{R_s(t)} \times \frac{d[1 - R_s(t)]}{dt} = \lambda_{iu} + \lambda_{il} + \lambda_{cap} + \lambda_{sc} + \lambda_{ps} \tag{4}$$

where λ_{iu}, λ_{il}, λ_{cap}, λ_{sc} and λ_{ps} are failure rates of the upper IGBT module, the lower IGBT module, the capacitor, the SM control system and the power supply.

2) Reliability of SMs Under Different Operation Conditions: SMs in the conventional mode operate with a relatively lower switching frequency than SMs in the load-sharing mode. The switching frequency of MMCs in HVDC applications, however, can be around 100 Hz. In this case, differences in the switching frequency have little influence on the failure rate of electronic equipment [23]. SMs in the conventional mode endure the nominal voltage, and their failure rates are obtained by (4).

If the load-sharing mode is applied to SMs, all SMs share the dc voltage, and each of them is subjected to a lower voltage than the nominal value. Voltage stress has influence on the reliability of IGBT modules [23], [24] and capacitors [9], [25]. Their failure rates are exponentially proportional to the voltage stress [9], [23], and are represented as:

$$\lambda_{*-p} = \lambda_{*-b} \times {v_s}^{\eta} \tag{5}$$

where λ_{*-b} is the base failure rate of capacitors or IGBT modules; v_s is the ratio of the applied voltage to the nominal voltage; η is the voltage stress factor, which varies with component types [9], [23].

In the load-sharing mode, the failure rate of a SM upon j SMs failure is then calculated by:

$$\lambda_{sj} = \lambda_{iu-pj} + \lambda_{il-pj} + \lambda_{cap-pj} + \lambda_{sc} + \lambda_{ps} \tag{6}$$

where λ_{iu-pj}, λ_{il-pj} and λ_{cap-pj} are failure rates of the upper IGBT module, the lower IGBT module and the capacitor upon j SMs failure, shown in (5); λ_{sc} and λ_{ps} are failure rates of the SM control system and the power supply.

Under the passive redundancy scheme, redundant SMs are in the idle state until needed. Note that the redundant SMs are bypassed, the failure rate λ_{sd} should be much less than that of operating SMs λ_s, which is presented as:

$$\lambda_{sd} = \alpha\lambda_s \tag{7}$$

where α is a small decrease factor.

B. Arm Level Reliability Models

As shown in Fig. 1, each arm is comprised of a series stack of SMs and an inductor. Considering that arm inductors have high reliability and this work focuses on the analysis of redundancy schemes of SMs, the inductor is not considered during the reliability modelling of an arm. The reliability block diagram for an arm is presented in Fig. 4(b).

In each arm, redundant SMs can be integrated under either the active scheme or the passive scheme. [13], [14] calculated the reliability of MMCs using the well-known k-out-of-n method, which can only represent the system under the conventional redundancy scheme. For the load-sharing mode and the passive scheme, existing publications modelled the lifetime of redundancy systems based on the characteristics of exponential distributions, and deduced the closed-form expressions for the reliability of small systems [18]–[20]. Due to the round-off errors, those expressions fail to calculate the reliability of large-scale systems, e.g. MMCs for HVDC applications. With the aid of Markov chains and the iteration method, the reliability of arms under different redundancy schemes are modelled in this paper.

1) Reliability Model of Arms Under Active Redundancy Schemes: In the active redundancy scheme, the arm will operate if the number of healthy SMs is not less than k. The system behaviour can be modelled by a Markov chain shown in Fig. 5. State 0 is the initial state where all SMs are working properly. State $(n-k+1)$ is the failed state, and the arm fails to generate the required dc voltage. State j $(j = 1, \ldots, n-k)$ represents the system state when j SMs have failed and remaining $n-j$ SMs are functioning. Based on the Markov transition diagram, a set of differential equations is obtained:

$$
\begin{aligned}
\frac{dP_0(t)}{dt} &= -n\lambda_{s0} P_0(t) \\
&\vdots \\
\frac{dP_j(t)}{dt} &= (n-j+1)\lambda_{s,j-1} P_{j-1}(t) \\
&\quad - (n-j)\lambda_{sj} P_j(t) \\
&\vdots \\
\frac{dP_{n-k+1}(t)}{dt} &= k\lambda_{s,n-k} P_{n-k}(t)
\end{aligned} \tag{8}
$$

where $P_j(t)$ is the probability of the arm in state j; λ_{sj} is the failure rate of SMs upon j SMs failure (in (6)); k is the minimum number of SMs in an arm (in (1)); n is the number of assembled SMs in an arm.

By taking Laplace transforms of (8) and inverse Laplace transforms, the differential equations are solved as follows:

$$
\begin{aligned}
P_0(t) &= e^{-n\lambda_{s0} t} \\
&\vdots \\
P_j(t) &= \int_0^t (n-j+1)\lambda_{s,j-1} e^{-(n-j)\lambda_{sj}\tau} P_{j-1}(t-\tau) d\tau \\
&\vdots \\
P_{n-k+1}(t) &= \int_0^t k\lambda_{s,n-k} P_{n-k}(\tau) d\tau
\end{aligned} \tag{9}
$$

Probabilities of the arm in all states can be solved iteratively. The reliability function of the arm is calculated as the sum of

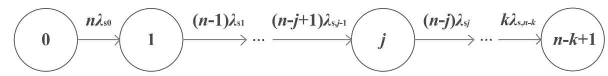

Fig. 5. Markov chain for an arm with active redundancy scheme.

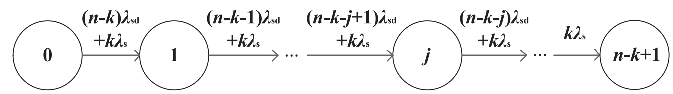

Fig. 6. Markov chain for a arm with passive redundancy scheme.

the probabilities of all success states (state 0$\sim$ $n-k$):

$$
R_a(t) = \sum_{j=0}^{n-k} P_j(t) \tag{10}
$$

The mean time to failure (MTTF) of the arm is given by:

$$
MTTF_a = \int_0^{+\infty} R_a(t)dt = \sum_{j=0}^{n-k} \frac{1}{(n-j)\lambda_{sj}} \tag{11}
$$

where λ_{sj} is the failure rate of SMs upon j SMs failure, and is calculated by (6).

Note that the conventional mode is a special case of active schemes. When SMs in the arm operate in the conventional mode, each SM is subjected to the nominal voltage, which means $\lambda_{sj} = \lambda_{s0}$. Thus, (9)$\sim$(11) can be simplified to the same expressions as for the well-known k-out-of-n model [19], as shown in (12)$\sim$(13).

$$
R_a(t) = \sum_{j=k}^{n} C_n^j (e^{-\lambda_{s0} t})^j (1-e^{-\lambda_{s0} t})^{n-j} \tag{12}
$$

$$
MTTF_a = \sum_{j=0}^{n-k} \frac{1}{(n-j)\lambda_{s0}} \tag{13}
$$

where λ_{s0} is the failure rate of SMs in the conventional mode.

2) Reliability Model of Arms Under the Passive Redundancy Scheme: In the passive redundancy scheme, redundant SMs in the arm will be switched to operate in sequence until the last one fails. The system behaviour can be modelled by a Markov chain shown in Fig. 6, where state 0 is the initial state and state $(n-k+1)$ is the failed state. State j $(j = 1, \ldots, n-k)$ represents the system state when j SMs have failed and remaining $n-j$ SMs are functioning.

Similar to the modelling procedure for arms under the active scheme, state probabilities of the arm under the passive scheme can be derived on the basis of the Markov transition diagram and Laplace transforms:

$$P_0^*(t) = e^{-[(n-k)\lambda_{sd} + k\lambda_s]t}$$
$$\vdots$$
$$P_j^*(t) = [(n-k-j+1)\lambda_{sd} + k\lambda_s] \times \int_0^t e^{-[(n-k-j)\lambda_{sd} + k\lambda_s]\tau} P_{j-1}^*(t-\tau) d\tau$$
$$\vdots$$
$$P_{n-k+1}^*(t) = \int_0^t k\lambda_s P_{n-k}^*(\tau) d\tau \quad (14)$$

where $P_j^*(t)$ is the probability of the arm being in state j when passive redundancy scheme is applied; λ_s is the failure rate of operating SMs (in (4)); λ_{sd} is the failure rate of redundant SMs (in (7)); k is the minimum number of SMs in each arm; n is the number of assembled SMs in each arm.

For the arm with the passive scheme, its reliability function and MTTF can be obtained as follows:

$$R_a^*(t) = \sum_{j=0}^{n-k} P_j^*(t) \quad (15)$$

$$MTTF_a^* = \int_0^{+\infty} R_a^*(t) dt = \sum_{j=0}^{n-k} \frac{1}{[(n-k-j)\lambda_{sd} + k\lambda_s]} \quad (16)$$

The proposed model can be extended to present the reliability of arms with different types of passive redundancy schemes. If the redundant SMs are shared between two arms in a phase leg, the two arms are considered as a sub-system. The reliability of the sub-system is calculated by substituting the minimum number of SMs and the number of redundant SMs in each phase leg to (14)∼(15). If all arms in the whole converter share redundancy, six arms are regarded as a sub-system, and its reliability is calculated by substituting the minimum number of SMs and the number of redundant SMs in the whole converter to (14)∼(15).

C. Converter Level Reliability Models

Fig. 4(c) shows the reliability block of the whole system. Besides the arms, the cooling system and the control and protection system are also critical facilities for the reliable operation of MMCs. The cooling system and the control and protection system are assumed to have constant failure rates, and their reliability functions are calculated by substituting the corresponding failure rate to (2). Taking the cooling system, the control and protection system into account, the reliability function of the three-phase converter is calculated by:

$$R_c(t) = [R_a(t)]^6 \times R_{cp}(t) \times R_{cl}(t) \quad (17)$$

where $R_a(t)$ is the reliability function of an arm, which is given in (10) for active schemes or (15) for passive schemes; $R_{cp}(t)$ and $R_{cl}(t)$ are the reliability functions of the control and protection system and the cooling system.

In practical projects, additional hot-standby control and protection system and cooling system are required to provide reliable auxiliary service for converter operation. When hot-standby auxiliary systems are assembled, the converter reliability in (17) is modified as:

$$R_c(t) = [R_a(t)]^6 \times [1 - (1 - R_{cp}(t))^2] \times [1 - (1 - R_{cl}(t))^2] \quad (18)$$

D. Model Extension

Reliability of electronic components is affected by the environment conditions, such as humidity, temperature[26]–[28]. For MMCs in specific applications, the use conditions also influence the reliability of electronic components, such as the solar irradiance for PV-inverters [27], [28]. The environment and use conditions can be represented by the mission profile. Thus, it is valuable to take the mission profile into account in the reliability modeling of MMCs. [26]–[28] conducted the lifetime prediction of MMCs with the consideration of mission profiles. The environment conditions are first related with the power loss of devices, and the electro-thermal model and lifetime model are established to predict the converter reliability using the obtained data of power losses. However, the converter reliability is represented by the expected lifetime of components and converters. Future work is required to relate the mission profile to the failure rate of components.

Moreover, the loading of SMs and IGBT switches could be different dependent on the position [29], [30], which would have impact on their failure rates. Some work has explored the loading of SMs and IGBT switches in MMCs [29], [30]. The overall loading distribution of SMs among an arm is very similar [29]. But the IGBT switches within a SM have different loading distributions depending on their positions, and the lower IGBT switch is more stressed than the upper one [29], [30]. To take the differences in the loading distributions into account during the reliability analysis of MMCs, the relation of the failure rate of components to the loading distributions is required to be explored first. The failure rate of components on different position is then calculated according to corresponding loading distributions, and the reliability of SMs is obtained by substituting the failure rates of IGBT switches into (3). Hence, the loading of components is considered in the reliability analysis of MMCs.

IV. Validation and Application of Models

In this section, the proposed reliability models are first validated through the comparison with existing methods in terms of the reliability analysis of both small systems and large systems. Effects of different redundancy schemes on the reliability of MMCs are then evaluated by applying the proposed models. Conditions for each redundancy scheme are specified, and the effectiveness of sharing redundancy among arms is assessed. Each SM in a MMC contains two IGBT modules of 3.3 kV, and the sub-module nominal voltage was set as 1.6 kV. Voltage stress factors for IGBT modules and capacitors were assumed as 2.43 [23] and 7.5 [31] respectively. Converter parameters used in this paper are summarized in Table I. Component failure rates were assumed based on statistical data [12], [32] and

TABLE I
CONVERTER PARAMETERS FOR CASE STUDY

Symbol	Quantity	Value
V_D	withstanding voltage of IGBT modules (kV)	3.3
V_M	nominal voltage of SMs (kV)	1.6
η_i	voltage stress factor for IGBT modules	2.43
η_{cap}	voltage stress factor for capacitors	7.5
λ_i	failure rate of IGBT modules (occ\ year)	0.0008
λ_{cap}	failure rate of capacitors (occ\ year)	0.001752
λ_{sc}	failure rate of SM control system (occ\ year)	0.00318
λ_{ps}	failure rate of power supply (occ\ year)	0.03504
λ_{cp}	failure rate of control and protection system (occ\ year)	0.03
λ_{cl}	failure rate of cooling system (occ\ year)	0.04

TABLE II
RELIABILITY OF ARMS IN LOAD-SHARING MODE

t (year)		0	0.01	1	2
Small system	Proposed model	1.000000	0.999991	0.929968	0.786429
	Expressions in [20]	1.000000	0.999991	0.929968	0.786429
Large system	Proposed model	1.000000	1.000000	0.996577	0.437831
	Expressions in [20]	– 8.96E+22	1.41E+21	– 8.16E+17	– 5.67E+13

TABLE III
RELIABILITY OF ARMS UNDER THE PASSIVE SCHEME ($\alpha = 0.2$)

t (year)		0	0.01	1	2
Small system	Proposed model	1.000000	0.999991	0.932623	0.793343
	Expressions in [18], [19]	1.000000	0.999991	0.932623	0.793343
Large system	Proposed model	1.000000	1.000000	0.997169	0.468517
	Expressions in [18], [19]	2.22E+51	2.35E+51	5.74E+47	3.06E+43

information from State Grid Corporation of China. The reliability functions of each component is obtained by substituting the corresponding failure rate to (2). Calculations were conducted using MATLAB R2015a.

A. Validation of Proposed Models

The proposed models are compared with existing methods in [18]–[20] to validate its accuracy and feasibility for both small-scale systems and large-scale systems. In a small-scale MMC, each arm consists of 11 SMs, and one of them is redundant. A converter with 270 SMs (including 20 redundant SMs) in each arm is considered as the large-scale system. The proposed model for MMCs in load-sharing mode is compared with the method presented in [20], and numerical results are shown in Table II. With respect to the MMCs under the passive redundancy scheme, the results obtained by the proposed model are compared with those calculated by the expressions in [18], [19] and listed in Table III. The elapsed CPU time for the calculation of system reliability using existing expressions is around 0.001 s. As the proposed method includes integrations and iterations, the computational complexity increases. Using the proposed method to calculate the reliability of redundant systems in the load-sharing mode, the elapsed CPU time to perform the calculation for the small system is 1.05 s, while that for the large system is 53.40 s. For the systems under the passive scheme, the elapsed CPU time is 1.11 s for the small system and 55.03 s for the large system. Considering that the reliability analysis is off-line calculations, the computational time is acceptable.

TABLE IV
MTTF OF ARMS UNDER DIFFERENT REDUNDANCY SCHEMES

Redundancy scheme	$MTTF_{st}$ (year)
Active scheme, conventional mode	1.9439
Active scheme, load-sharing mode	1.9705
Passive scheme	2.0198

Shown from the numerical results, existing methods are applied successfully to small-scale systems. However, for the large-scale systems, the results obtained using the existing expressions are not stable, and exceed the reasonable range for system reliability, i.e. [0, 1]. Existing expressions are derived based on the characteristics of exponential distributions and their relation to gamma distributions. For MMCs with high level, the value $(n - k)$ is relatively large and the failure rate of SMs is small. The existing expressions include subtractions of two nearly equal numbers and divisions of a large number by a very small one, and the results are prone to numerical round-off errors. Thus, the results calculated by the existing expressions tend to be unstable for a large system. By using the iteration method to solve the probability of the system in each state, the proposed models avoid the subtractions and divisions which are easily affected by round-off errors. The results calculated by the proposed models are stable for both small systems and large systems. The proposed models are suitable for the redundancy analysis of MMCs for HVDC applications.

B. Reliability Comparison of MMCs Under Different Redundancy Schemes

Redundancy schemes are compared in terms of their influence on the reliability of both arms and converters. The nominal dc voltage of the converter is assumed as $\pm$ 200 kV. According to (1), the minimum requirement of SMs is 250 for each arm.

With 20 redundant SMs installed in each arm, the number of SMs in a converter is $270 \times 6 = 1620$. Under the passive scheme, redundant SMs are set in the idle state until needed, and the decrease factor α of redundant SMs was assumed to be 0.01. For the active scheme, two operation modes of SMs, the conventional mode and the load-sharing mode, were considered. According to the reliability evaluation method presented in Section III, MTTFs of arms and reliability functions of MMCs under different redundancy schemes were calculated, and presented in Table IV and Fig. 7 respectively. In Fig. 7, the X-axis is time t, while Y-axis is the reliability of MMCs, which is the probability of MMCs operating without failure to time t.

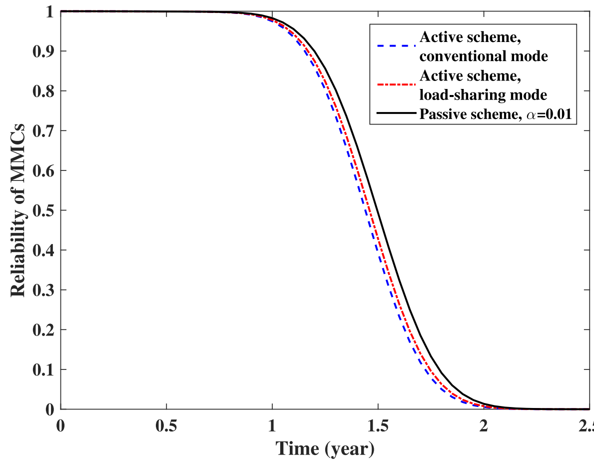

Fig. 7. Reliability of MMCs under different redundancy schemes.

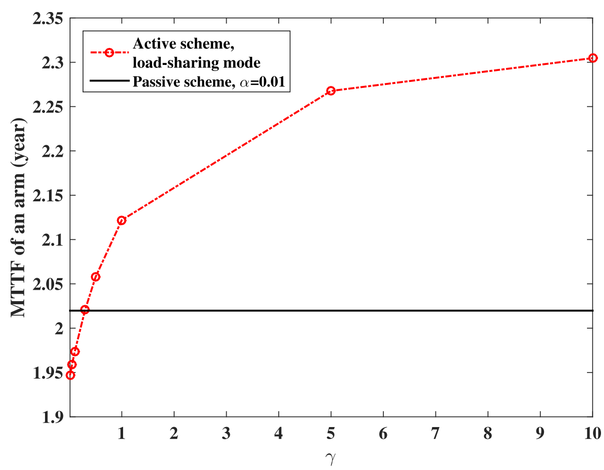

Fig. 8. Comparison of MTTFs of an arm under different redundancy schemes with failure rate ratio γ varying from 0.01 to 10.

As shown in Table IV, the arm with the passive redundancy scheme performs better than that with active schemes in terms of reliability. This is mainly because of that redundant SMs in the passive scheme have much smaller probability to fail when they are in the idle state. Arms with the passive scheme then have a longer operation time. Moreover, the MTTF of an arm in load-sharing mode is slightly larger than that in the conventional mode. In an arm with the conventional mode, k SMs share the voltage stress along a phase unit at time t. If the load-sharing mode is applied, all SMs except for faulty ones are used for making the output voltage waveform. Each of them is subjected to a voltage slightly lower than the nominal value, which results in slightly lower failure risk of SMs.

The reliability of the converter under the passive scheme is higher than that under active redundancy schemes, as depicted in Fig. 7. For the MMC with the passive redundancy scheme, its probability to operate without failure to one year is 95.37%. And for MMCs with conventional active scheme and load-sharing active scheme, the probability is 94.60% and 94.91% respectively. After the first year, the differences of redundancy schemes in the influence on the converter reliability become larger.

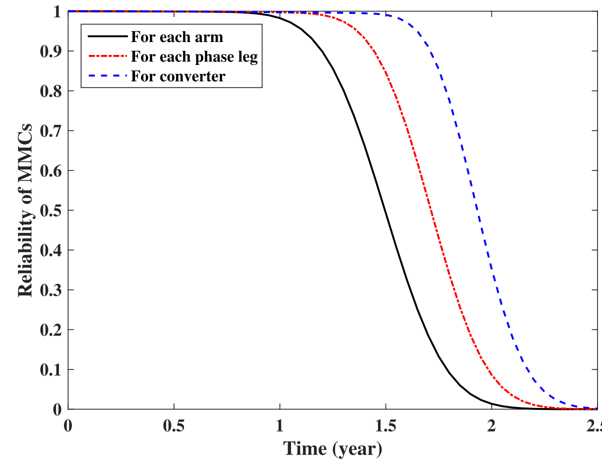

Fig. 9. Reliability comparison of MMCs with different types of passive redundancy schemes.

TABLE V
DESIGN COMPARISON OF MMCS WITH DIFFERENT PASSIVE REDUNDANCY TYPES - TO MEET RELIABILITY $\geq$ 0.98 IN THE FIRST YEAR

Redundancy types	For each arm	For each phase	For the whole converter
No. of redundant SMs	120	99	80
No. of SMs	1620	1599	1580
No. of IGBTs	3240	3198	3160
$R_c(t=1)$	0.9828	0.9833	0.9843

C. Sensitivity Analysis of Component Failure Rates

According to the parameters in Table I, power supply and SM control system are the dominant components within a SM in terms of failure rates. If a SM is in the load-sharing mode, the main benefits are the reduced voltage stress on only IGBTs and the capacitor, which has limited contribution to the improvement of the reliability of the whole SM. It is important to investigate the converter reliability with different failure rates where IGBTs and capacitors become the dominant components. Thus, it is meaningful to specify the conditions in favour of each redundancy scheme. Let γ be the ratio of the failure rates of IGBT modules and capacitors to those of the SM control system and the power supply, $\gamma = (2\lambda_i + \lambda_{cap})/(\lambda_{sc} + \lambda_{ps})$. The sum of failure rates of all components within a SM remains constant as 0.042 occ/year, and γ varies from 0.01 to 10. The decrease factor for passive redundant SMs is set as 0.01. The load-sharing mode is compared with the passive scheme in terms of the MTTF of arms, and the results are shown in Fig. 8.

With γ varying, the MTTF of the arm under the passive redundancy scheme remains constant at 2.0198 years. However, the MTTF of the arm in the load-sharing mode varies according to the failure rate ratio γ. Shown in Fig. 8, the critical point is $\gamma = 0.3$, which means the proportion of the IGBT and capacitor failures to the SM failures is 23%. When γ is greater than 0.3, the MTTF of the arm in load-sharing mode is larger than that under the passive scheme. If the failure of IGBTs and capacitors contributes more to the failure of SMs, sharing voltage leads to greater improvement of system reliability. Based on current statistic data, the failure rates of IGBTs and capacitors are much smaller than those of power supply and SM control system ($\gamma = 0.088$). In this case, the passive scheme performs better than active schemes. However, if the failure rates of power supply and SM control system can be reduced, the load-sharing mode will show advantages over the passive scheme in terms of system reliability.

D. Reliability Analysis of Different Types of Passive Schemes

In the passive scheme, each arm is equipped with redundant SMs separately [4], [17]. As long as any one arm is running out of redundancy, the converter has to be shut down, but at the same time there are still some redundant sub-modules not in operation in other arms. This enables a possibility for redundant SMs shared among two or more arms. The reliability of the converter can be improved with the same total number of redundant SMs, or the number of redundant SMs can be reduced with the same reliability objective. Three types of passive scheme for a MMC are considered: redundancy for each arm, for each phase leg and for the whole converter.

Use the previous case as an example. The number of redundant SMs was set as 120. If the passive redundancy scheme is applied separately in each arm, 20 redundant SMs are integrated into each arm. If the redundancy is for phase legs, 40 redundant SMs are installed in each phase and shared by two arms. 120 redundant SMs are shared among six arms if the redundancy is for the whole converter. Based on the modelling procedure in Section III, the reliability of converters is calculated and shown in Fig. 9. X-axis is time t, and Y-axis is the probability of MMCs operating without failure to time t. If redundant SMs are installed within each arm, the MMC has a probability of around 98% surviving to one year. For the same probability, the operation time can be extended to 1.25 years if redundant SMs are shared between two arms in a phase leg. If redundancy is shared among all arms in a converter, the operation time is further extended to 1.55 years, which is almost 7 months more than that with redundancy installed separately in each arm.

For a given reliability objective, different types of passive schemes are compared with respect to the number of required redundant SMs. Considering that the maintenance for MMCs is performed annually, the probability of MMCs surviving to one year is concerned. In the previous case, a MMC with 20 redundant SMs integrated into each arm has a probability of around 98% surviving to one year, which is chosen as the reliability objective. To meet the same reliability target, the number of redundant SMs for other two types of schemes is calculated and shown in Table V. If redundancy is shared between two arms in the same phase leg or among all arms in a converter, the number of required redundant SMs is reduced to 99 and 80 respectively. A reduction of 33.33% in terms of the number of redundant SMs is a great advantage of sharing redundancy among arms, although proper design and control of redundant SMs are needed for achieving the reliability benefit.

V. Conclusion

With the consideration of different redundancy schemes, detailed reliability models of MMCs for HVDC applications have been presented in this paper. Two redundancy schemes, differing in the operation of sub-modules, were considered: the active scheme (in the conventional mode or the load-sharing mode) and the passive scheme. The reliability of an arm was modelled for each redundancy scheme. Combined the reliability of arms with those of other components, the reliability of the MMC was derived and expressed as a function of time. The robustness of the proposed models was validated. Case studies were conducted to compare the effects of different redundancy schemes on the improvement of system reliability, and to evaluate the advantages of sharing redundancy among arms. The following conclusions are drawn.

With the aid of Markov chains and the iteration method, the proposed reliability models for redundancy systems under active and passive schemes have the advantages over existing methods in terms of accuracy and robustness. For both small scale systems and large scale systems, numerical results calculated by the proposed models are stable and accurate. The proposed method is suitable for the redundancy analysis of MMCs with high level.

If sub-module control system and power supply dominate the overall reliability of sub-modules, converters under the passive scheme are more reliable as sub-modules in the idle state suffer less risk to fail. If IGBT and capacitor failures account for more than 23% of the sub-module failures, the reduction of voltage stress provides great improvement of sub-module reliability, and MMCs under the load-sharing scheme are more reliable.

The passive scheme has great potential in improving the system reliability if redundancy can be shared among arms. For a given reliability target, if passive redundancy SMs are shared between two arms in a phase leg or among all arms in a converter, the number of redundant SMs is reduced by 17.5% and 33.33% respectively.

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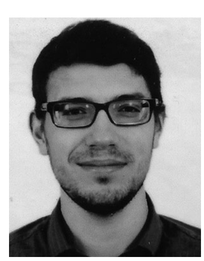

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