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Reliability and Cost based Redundancy Design for Modular Multilevel Converter

Pengfei Tu, *Student Member, IEEE*, Shunfeng Yang, *Student Member, IEEE*, and Peng Wang, *Fellow, IEEE*

Abstract—The Modular Multilevel Converter (MMC) is very attractive in High Voltage DC (HVDC) transmission system due to its high modularity and scalability. It's also a promising candidate for medium voltage applications. MMC has many power devices which lead to a relatively low reliability based only on a direct failure rate calculation. The reliability of MMC can be improved by redundant designs. Lots of redundant designs and strategies have been proposed in recent years while their reliability improvements are hardly quantified in existing literature. In practice, reliability improvement with constraint costs is a challenge. In view of these, this paper proposed a reliability and cost assessment scheme for MMC redundant designs and strategies. Reliability and cost are quantified for comparison purpose. A medium voltage application is used to demonstrate the reliability and cost assessment scheme. The reliability analysis is based on combinatorial model and Poisson process model. The cost analysis focuses on capital cost and power loss cost. The proposed reliability and cost analysis scheme provides a guideline for MMC redundant design and redundant strategy selection.

Index Terms—Cost Model, Fault Tolerant Control, Modular Multilevel Converter, Redundant Design, Redundant strategy, Reliability Model.

I. INTRODUCTION

THE Modular Multilevel Converter (MMC) has been paid tremendous research attention over the last decade. MMC features low Total Harmonic Distortion (THD), high modularity and high scalability [1-3]. It was proposed for High Voltage DC transmission (HVDC) station applications by Marquardt [1] and first used commercially in the Trans Bay Cable project in San Francisco [3]. In the early state of MMC, research focus is mainly on HVDC application. Recently, medium voltage applications such as Solid State Transformer (SST), Medium Voltage Drives are also proposed by

researchers [4-6]. Fig. 1 (a) is the schematic of a three phase MMC. The MMC consists of a number of independent converter submodules (denoted as SM in Fig. 1(a)). The number of series connected submodules can be scaled depending on voltage level. A widely used half bridge submodule is shown in the Fig. 1(b). It contains two semiconductor switches connected in series across a capacitor. Depending on which switch is turned on, the capacitor is either bypassed or inserted into the main circuit. Each submodule can generate a voltage of 0 or independently. Each phase leg can synthesize a stepped voltage waveform to approximate a sine-wave by inserting a suitable number of capacitors. The faulty submodule can be isolated with the additional bypass switch and fuse.

Fig. 1. (a) schematic of a three phase MMC (b) half bridge Submodule

Despite the merits of MMC, the traditional two level converters are still dominant in aforementioned applications. One of the reasons is the reliability concerns for MMC due to large numbers of devices used even in medium voltage applications [7], [8]. To make MMC more reliable in practical applications, many fault tolerant methods are proposed to improve MMC reliability [8-13]. These methods can be

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Pengfei Tu and Shunfeng Yang are with the Rolls-Royce@NTU Corporate Lab, Nanyang Technological University, Singapore (e-mail: PTU002@ntu.edu.sg, SYANG012@e.ntu.edu.sg).

Peng Wang is with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore (e-mail: EPWANG@ntu.edu.sg).

roughly classified as degraded operation and quasi-normal operation according to post-fault operation performance [14].

Fault tolerant strategies relying on the inherent redundancy in MMC usually leads to a degraded performance of post-fault operation. The degraded operation with modified modulation strategies has been studied in [15], [16]. The faulty converter cells are isolated from the system, and redundant switching states are used to generate a neutral voltage shift to maintain a balanced line-to-line AC output voltage. In comparison to normal operation, the magnitude of output voltage decreases and harmonic distortion increases.

Due to limitations of degraded operation, redundant designs are proposed to achieve normal post fault operation [17-20]. Thanks to the high modularity of MMC, it is easy to implement redundant designs, which include cell overrating [17] and backup cells [8], [10], [18-20]. In [21], redundant designs are compared by their operation properties such as control complexity, capacitor voltage balancing, power losses and dynamical behavior. The reliability improvement effectiveness of redundant designs and redundant strategies are not discussed yet. Additionally, to improve converter reliability with a constraint cost is a challenge. In view of these, this paper proposed a reliability and cost assessment scheme for MMC redundant designs and redundant strategies. Quantitative reliability and cost assessment help to identify cost-effective redundant designs. It can also provide a guideline on how to select redundancy strategies, such as active mode and standby mode which are distinguished by whether redundant cell shares the load in normal condition.

In this paper, reliability models for MMC with redundant designs are proposed. The reliability improvements of different redundant designs are quantified. With the reliability analysis, the redundant designs with lowest cost while meet reliability requirements is identified. The following part of this paper is organized to demonstrate the application of reliability and cost assessment scheme. In section II, basic reliability indices and reliability modeling process of MMC redundancy are introduced. The reliability and cost models of MMC are discussed in section III. In section IV, reliability and cost of reliability analysis are conducted to demonstrate the usage of the model with a case study. The last section draws the conclusion of this paper.

II. BASICS OF RELIABILITY MODELING

A. Reliability basics and indices

Reliability is defined as the probability of a device working for a time interval under a specified operating condition [22]. The reliability function, $R(t)$, is defined as

$$R(t) = 1 - F(t) = \frac{N(t)}{N(0)} \quad (1)$$

Where $N(t)$ the number of surviving devices at a time t , $N(0)$ is the number of devices at an initial time, $F(t)$ is the unreliability function or failure function. The reliability function $R(t)$ is the probability of a device survive over an interval $[0, t]$ with $R(0) = 1$, $R(\infty) = 0$.

Failure rate function, $\lambda(t)$, a.k.a hazard rate, is the rate at which failures occur in a certain time interval for items that are working at the start of the interval [22].

$$\lambda(t) = \lim_{\Delta t \rightarrow 0} \frac{N(t) - N(t + \Delta t)}{N(t)\Delta t} = \frac{f(t)}{R(t)} \quad (2)$$

Where $f(t)$ is the failure density function. It is the failure probability density function (pdf) of random variable t .

$$f(t) = \lim_{\Delta t \rightarrow 0} \frac{N(t) - N(t + \Delta t)}{N(0)\Delta t} = \frac{dF(t)}{dt} \quad (3)$$

The failure rate is a relative rate of failure which is often used in practice. Fig. 2 shows the classical bathtub failure rate curve. The device failure rate is usually characterized by an constant value in useful life period. The constant failure rate is used in converter design and comparison. Preventative maintenance and replacement schedules are considered in wear-out phase [7], [14].

Fig. 2. Typical failure rate curve-bathtub curve.

Mean time to failure (MTTF) is the mean or expected value of lifetime t . Based on the probability theory.

$$MTTF = \int_0^{\infty} t f(t) dt = \int_0^{\infty} R(t) dt \quad (4)$$

Another similar reliability index, percentiles of a lifetime, B , is defined as the time at which percent of devices fails [23].

$$F(B_{\alpha}) = \frac{\alpha}{100} \quad (5)$$

It should be noticed that, in converter design phase, the constant failure rate is usually used for system reliability prediction. Under this condition, the reliability indexes can be analytically expressed.

$$R(t) = e^{-\lambda t} \quad (6)$$

$$MTTF = \frac{1}{\lambda} \quad (7)$$

$$B_{\alpha} = \frac{1}{\lambda} \ln\left(\frac{100}{100 - \alpha}\right) \quad (8)$$

B. Reliability modeling of MMC with redundancy

In Fig. 3, the MMC is subdivided into three hierarchical levels such that the reliability function of each level is more easily obtained. In each hierarchal level, the reliability block diagram (RBD) is used to represent the reliability relationship of MMC components. In the first level, each arm is regarded as one lumped reliability block for MMC reliability evaluation. All six arms and auxiliary device are required in good state for

the MMC normal operation. Hence, they are connected in series from reliability point of view.

Fig. 3. Hierarchical reliability modeling of MMC.

To calculate MMC reliability, each arm reliability in first level are to determine. The second hierarchical level shows the reliability modeling of one arm. For MMC designs with redundant submodules, the k -out-of- n : G system can be used to represent each arm in reliability modelling. An n -component system that works if and only if at least k components in the system are in a good state is called a k -out-of- n : G system [24]. When k is less than n , the system has an inherent redundancy with $(n-k)$ spare parts. In Fig. 3, the SM_1 to SM_k are the k basic submodules required for a conventional MMC design. There are n submodules in each arm with m spare parts as redundant cells, where $m=n-k$.

There are usually two operation modes for the redundant cells, active mode and standby mode. The two operation modes are shown in Fig. 3 with RBD. In active mode, all n submodules (including k basic submodules and m spare parts) are sharing the load in MMC normal operation. When submodule fault occurs, the faulty submodule will be bypassed from the arm. In standby mode, the m spare parts are isolated by additional switches in normal operation. When fault occurs in SM_1 to SM_k , the standby submodules SS_1 to SS_m will be employed after faulty submodule's dismissal.

Each submodule reliability evaluation is accomplished in the third hierarchical level in which reliability blocks are basic physical components. The failure rate of physical components in one submodule are application dependent. Therefore, the determination of failure rate is discussed in detail in next section. It should be noticed that, the device failure rate is usually characterized as a constant value in their useful life period. In converter design phase, this constant failure rate assumption is used for reliability evaluation in this paper.

A submodule failure rate is denoted as λ and its reliability function is $R(t) = e^{-\lambda t}$. When an arm works in active mode, the arm reliability is a summation of the probability of more than k submodules inside a set of n are in good condition.

$$R_{arm}(t) = \sum_{k=0}^n C_n^k R(t)^k F(t)^{n-k} \quad (9)$$

The MTTF of one arm can be calculated by its definition in (4), the result is.

$$MTTF = \sum_{k=0}^n \frac{1}{k\lambda} \quad (10).$$

When an arm operates in standby mode, it can be modeled as a homogeneous Poisson process with a constant rate λ_s , where λ_s is the arm failure rate. The homogeneous Poisson process fully characterizes a counting process $\{N(t), t \geq 0\}$ with constant rate, where $N(t)$ denotes a total number of occurrences of the event up to and include time t [25]. The probability of the submodule failure number equals to k follows a Poisson distribution, $N \sim \text{Pois}(\lambda_s)$.

$$P[N(t) = k] = \frac{(\lambda_s t)^k}{k!} e^{-\lambda_s t} \quad (11)$$

Therefore, the arm reliability function $R_s(t)$ can be calculated as,

$$R_s(t) = P[N(t) \leq (n-k)] = \sum_{k=0}^{n-k} \frac{(\lambda_s t)^k}{k!} e^{-\lambda_s t} \quad (12)$$

The corresponding MTTF of an arm operating in standby mode is

$$MTTF_s = \frac{n-k+1}{\lambda_s} \quad (13)$$

The detailed proof of (10) and (13) are described in the appendix section.

After reliability function of each arm is obtained, the MMC reliability can be easily calculated with the RBD network modeling technique.

It should be mentioned that the reliability modeling methods are based on a traditional statistical method due to its wide acceptance by industry and academia over last decades. There are also emerging reliability modeling methods proposed by researchers based on physics of reliability (PoF) [26], which could be used for redundancy design schemes for MMC.

III. RELIABILITY AND COST MODEL OF MMC WITH REDUNDANT CELLS

A. Reliability and cost analysis procedures

The reliability analysis procedures are from the 3rd level (Submodule) to the 1st level (MMC).

Step 1: Determine failure rate of critical components.

Step 2: Modify the failure rate with real stresses calculated.

Step 3: Formulate the submodule failure rate functions

The critical components in submodule reliability evaluation are IGBT and capacitor. The real devices stresses are calculated according to operation condition.

Step 4: Calculate arm reliability with k -out-of- n : G system

The reliability function of an MMC thus can be easily analyzed with RBD technique. To identify the cost-effectiveness of different redundant designs, the cost model of a submodule is needed. The remaining steps are the cost analysis of MMC.

Step 5: Establish cost model for components in a submodule

Step 6: Analyze cost of different redundant designs

Step 7: Select the best application dependent design.

The implementation of these procedures will be discussed in detail in following sections.

B. Parameter design of an MMC

A medium voltage MMC is used as an example to demonstrate the reliability and cost modeling method. A brief parameter designs are listed in Table I.

TABLE I
PARAMETER DESIGN OF A MMC AND SUBMODULE

MMC		Submodule	
cell number per arm	10	Cap. voltage	1000V
DC voltage	10kV	voltage ripple	100Vpp
line voltage RMS	6kV	cell current (rms)	176A
active power	3MW	cell current (peak)	304A
arm inductance	1mH	cell capacitance	3.4mF
ac frequency	50 Hz	switching frequency	2100 Hz

C. Submodule Failure rate calculation considering stress changing in post-fault operation

Base on the model discussed in section II, the MMC failure rates are the key parameters for converter reliability calculation. As failure occurrences of submodules are independent, the converter failure rate is the summation of failure rates of operating submodules. In a submodule, the main and most vulnerable components are semiconductor switches (IGBT/MOSFET) and capacitors. The driver PCB board, auxiliary power supply and bypass switch and fuse can be also modeled for reliability analysis. This paper aims to provide a reliability and cost analysis framework. Although the auxiliary devices are also very important for reliability analysis, a simplified constant failure rate will be used to represent all other components' failure rate.

There are many IGBT candidates that satisfy the given specifications. The 1700V IGBT is selected for its low loss due to a mature technology. The IGBT chip and package are different although the voltage and current rating are the same. For 1700V voltage rating, candidates from different suppliers have similar performance, while FF450R17IE4 is relatively superior to the other candidates due to its lower loss, better thermal dissipation [27]. The base failure rate for this IGBT module is 100 FIT [28]. FIT is failure in time which is an alternative unit for failure rate. 1 FIT is 1 failure in 10^9 hours.

The capacitor bank of 3.4 mF can be designed by using three Aluminum Electrolytic capacitor or film capacitor. For an electrolytic capacitor, the capacitance can be very high while the voltage rating is usually less than 500V. Series connected of the capacitors can be adopted within the capacitor bank, this leads to at least 3 series capacitors in each leg. Another concern of using electrolytic capacitor is its relatively short lifetime when compared with film capacitor [29-31]. From a reliability point of view, the AVX film capacitor with 1850V and the 3.56mF module is selected. The base failure rate is 100FIT [32].

The failure rate first depends on the technological complexity of the devices and, obviously, on the voltage and thermal operating ratio. These constraints and ratio are included in the λ formulation through acceleration factors [33], [34]. For an IGBT failure rate calculation:

$$\lambda = \lambda_b \pi_T \pi_S \pi_A \pi_R \pi_E \quad (14)$$

Where λ is the device equivalent failure rate, λ_b is the

component base failure rate, π_T is the temperature factor, π_S is the electric stress factor, π_A is the application factor, π_R is the power rating factor, P_r is rated power and environmental factor, π_E is the environmental factor.

$$\pi_T = e^{-2114(\frac{1}{T_j+273} - \frac{1}{298})} \quad (15)$$

$$\pi_S = 0.045e^{3.1V_s} \quad (16)$$

$$\pi_A = \begin{cases} 0.7 & \text{Switching} \\ 1.5 & \text{Linear application} \end{cases} \quad (17)$$

$$\pi_R = P_r^{0.37} \quad (18)$$

$$\pi_E = \begin{cases} 1.0 & G_B : \text{Ground Benign} \\ 10 & G_F : \text{Ground Fixed} \\ 20 & G_M : \text{Ground Mobile} \\ 7.0 & N_S : \text{Naval Sheltered} \\ 15 & N_U : \text{Naval Unsheltered} \end{cases} \quad (19)$$

For capacitors:

$$\lambda = \lambda_b \pi_T \pi_C \pi_V \pi_{SR} \pi_E \quad (20)$$

Where λ is the device equivalent failure rate, λ_b is the component base failure rate π_T is the temperature factor, π_C is the capacitance factor, π_V is the voltage stress factor, π_{SR} is the series resistance factor, π_E is the environment factor

$$\pi_T = e^{-4062(\frac{1}{T_j+273} - \frac{1}{298})} \quad (21)$$

$$\pi_C = C^{0.23} \quad (22)$$

$$\pi_V = (\frac{S}{0.6})^5 + 1 \quad (23)$$

$$\pi_{SR} = \begin{cases} 0.66 & 0.8 < CR \\ 1.0 & 0.6 < CR \leq 0.8 \\ 1.3 & 0.4 < CR \leq 0.6 \\ 2.0 & 0.2 < CR \leq 0.4 \\ 2.7 & 0.1 < CR \leq 0.2 \\ 3.3 & 0 < CR \leq 0.1 \end{cases} \quad (24)$$

Where S is the ratio of operating peak voltage to rated voltage C is the capacitance in μF , CR is the ratio of effective resistance to peak voltage.

D. MMC reliability modeling by k-out-of-n: G system methods with submodule as the basic component

When designing redundant cells in an MMC, the system reliability can be assessed with the k -out-of- n : G system methods. In MMC reliability evaluation, the basic component of the MMC is a submodule with failure rate functions obtained in previous steps. Therefore, the failure rate λ in (9) represents a submodule failure rate. When the MMC operates in standby mode, the MMC reliability should be calculated either by (12). As mentioned in section II, the failure rate λ_s represents the MMC system failure rate which is the summation of all active

submodules' failure rate.

It should be noticed that when in active mode, the voltage stress of each cell will be less than those in standby mode. This effect is included in the submodule reliability formulation. Due to the symmetry of the 3 phase 3MW MMC, the reliability study can start from one arm. Each arm is an independent *k-out-of-n*: G system. In this case study, *k* is 10 while *n* is no less than 10. For the MMC with 6 arms, without considering of degraded operation, the system reliability model is a 6-arm series-connected reliability block diagram (RBD)

E. Cost analysis of the MMC

The MMC cost includes initial cost and operational cost [35]. The initial cost mainly consists of the component cost. In this paper, the objective is to assess the cost caused by additional redundant cells. Hence the power loss cost will be selected as the main part of the operational cost for comparison purpose.

The MMC initial cost can be represented by a summation of submodule cost and auxiliary system costs, such as cooling system cost and housing cost. To simplify the cost analysis, the auxiliary cost is assumed 10% of the submodules cost. The submodule cost model is derived based on the IGBT and capacitor cost from manufacturers' viewpoint. There are some non-physical cost factors such as minimum ordering quantity (MOQ), location. To give a general and insightful model, the physical cost factors are mainly considered which can be directly used for converter dimension process [36], [37].

Generally, the cost structure of semiconductors derives from a complex mix of sophisticated manufacturing processing steps and high R&D efforts, whereas the (unprocessed) raw materials take only a negligible share of the total cost [35]. From an engineering point of view, the two most important features of a semiconductor are its chip size and the package. Together they largely define the electrical and thermal behavior of the device. Therefore, the following IGBT cost model in [35] is used:

$$\Sigma_{SC} = \sum_n \sigma_{chip} A_{chip} + \Sigma_{pack} \quad (25)$$

Where σ_{chip} is the specific price per chip area depending on chip technology and A_{chip} is the chip area. Σ_{pack} is the package price. The Si IGBT, diode chip specific price, and package price are 7.5\$/cm², 5.1\$/cm² and 17.2\$/unit respectively [35,36]. The gate driver cost is referred to online distributors. The chip area is determined by the system current rating, 450A in this case study, and chip current density of a Si IGBT [38]. A 75A/cm² chip current density value is used [38]. In general, there are two types of capacitors mostly used in high power application, one is the electrolytic capacitor (E-Cap) and the other is film capacitor. The aluminum electrolytic capacitor (Al-Cap) has a low price due to a mature technology. Its prices are proportional to the energy stored,

$$\Sigma_{ECap} = b_e V_r + c_e C_r V_r^2 \quad (26)$$

Where V_r and C_r are rated capacitor voltage and capacitance. A typical value for b_e and c_e are 1.6×10^{-3} \$/V and 2.8×10^{-5} \$/mF V². While the film capacitors have a much higher lifetime with a relatively high cost [29-31]. Its prices are mainly dominated by its capacitance and insulation,

$$\Sigma_{film} = a_f + b_f V_r + c_f C_r \quad (27)$$

The coefficients are -1.2\$, 0.06\$/V and 2.7\$/mF [36].

The power loss is mainly determined by the semiconductor conduction loss. For the power loss cost calculation, the MMC steady state loss model in [39], [40]. The loss energy price can be selected according to different applications.

IV. RELIABILITY AND COST-OF-RELIABILITY ANALYSIS FOR REDUNDANT DESIGNS

The reliability and cost are assessed for the 3MW MMC. For simplification of expression, the designs of MMC are denoted by a 3-tuple with each number representing basic cells, active reserve cells and standby cells respectively.

A. Reliability improvement of redundant designs

The MMC presented in section III are selected as a reliability case study. The MMC designs require 10 basic cells in each arm. To quantify the effectiveness of redundant designs, reliability evaluation results of original design and two redundant designs are plotted in Fig. 4.

Fig. 4. Reliability comparison of MMC with and without redundancy.

With one redundant cell used, the reliability of MMC is improved significantly over a timespan of 40 years. To verify the theoretical reliability prediction results, the Monte Carlo simulation which mimic the operations of complex systems by random sampling is used as a crosscheck. The scatter plots are a 100 test results of Monte Carlo simulation and the line graphs are obtained by analytical model. Usually, 10000 tests are used for verification purpose [41]. The comparison of analytical results with 10000 test results are plotted in Fig. 5. The analytical reliability prediction results match well with the Monte Carlo analysis in the two tests.

The additional redundant cell can operate under active mode or standby mode. With the reliability function obtained, the reliability indices, MTTF and B10 lifetime can be calculated correspondingly. Table II shows the reliability indexes of the three basic MMC designs.

The redundant designs with only one more cell in each arm improve the system reliability significantly while the cost is negligible. From manufacturer point of view, the B10 lifetime should reach the 20-30 years requirement. This means at year 20 or 30, the MMC reliability should be higher than 0.9. Table II shows that the B10 life requirement is not achieved by the three designs. More redundant cells are needed.

Fig. 5. Reliability verification of the by a 10000 test of Monte Carlo analysis.

TABLE II
RELIABILITY INDEX FOR TYPICAL REDUNDANCY DESIGNS

Designs	MTTF	B10 life
$(10,0,0)$	6.3420	0.6682
$(10,0,1)$	23.9389	7.5835
$(10,1,0)$	28.4547	9.0115

B. Reliability improvement performance comparison of different redundant designs

The one cell redundant designs improve the MMC reliability significantly. However, the reliability requirement is not met with the designs. To achieve reliability requirement, more redundant cells are needed. Reliability functions of different active redundant designs are shown in Fig. 6 and reliability functions of different standby designs are shown in Fig. 7.

When there are few redundant cells, with the increase of the redundant cells, the reliability of the MMC increase significantly. However, there is a saturation effect of the reliability improvement. The reliability improvement of the MMC is negligible when more than 4 redundant cells are added. But the cost still increases if more redundant cell used. To illustrate this saturation effect, the reliability of the MMC at year 20 and 30 with different redundant cell numbers are shown in Fig. 8.

Fig. 6. Reliability of different redundant designs in active mode.

Fig. 7. Reliability of different redundant designs in standby mode.

Fig. 8. MMC reliability with different redundant designs.

With redundant cells increase from 0 to 3, the MMC reliability starts increasing dramatically. But the reliability improvement is negligible with more cells added.

For the case study, to achieve a 20 year B10 lifetime requirement, 2 redundant cells are needed for both active mode and standby mode. If a 30 year B10 lifetime is required, then at least 3 redundant cells are needed. Within the timespan of B10, a 10% return rate of product is expected. Therefore, manufactures would select the warranty time based on this B10 lifetime index.

In summary, with these reliability analysis of redundancy, the minimum redundant cells for different reliability requirements can be identified without considering cost issues.

C. Cost of Reliability comparison for different designs

The more redundant cells, the higher the reliability but the cost will also increase. Another concern is the different redundancy modes have different power loss. Therefore, a cost-effective redundancy design which ensure reliability requirements is yet to be identified.

Fig. 9. Redundant cells impact on MMC initial capital cost

To show the influence of redundant cells cost on MMC cost, the absolute cost value and its percentage change over redundancy are plotted.

Fig. 9 shows the estimated MMC initial cost over the redundant cell number and its percentage change over redundancy. The initial cost change percentage is proportional to the redundant cell number. And when redundant cell number equals to the original design, the MMC initial cost is almost double. It indicates that the redundant cells have a high impact on MMC capital cost. Since different redundancy modes utilize the same number of redundant cells, the operation modes have no impact on MMC capital cost.

Although the initial cost is the same, the operational cost especially the power loss costs are different. A simplified power loss cost for 20 years 30% duty operation is shown in Fig. 10. The power loss cost is the product between the electricity cost and the energy dissipated by IGBT. It can be seen that with the increasing number of redundant cells, the power loss cost increase with active mode while keep unchanged with standby mode. In active mode, the redundant cells added are sharing the load in normal operation. Additional conduction loss of redundant cells is induced. While in standby mode, the number of submodules in normal operation is constant as redundant cells are isolated from the system. This strategy does not include any additional cell in normal operation, hence the additional power loss cost is zero. The unchanged power loss cost of standby mode is an attractive

feature. The cost advantage of standby mode will be more significant with more redundant cells used.

It should be noticed that, the power loss cost is also affected by the load duty. In this case study, a relative light load duty is used. For different applications, this load duty or even load mission profiles can be used as the basis for power loss cost calculation.

Fig. 10. Redundant cells impact on MMC power loss cost.

Fig. 11. Redundant cells impact on MMC total cost

The MMC system total cost and cost change percentage on redundancy are shown in Fig. 11. As the power loss cost are slightly higher than the component cost, the MMC system cost

on redundancy tends to be affected mainly by the power loss cost. The cost change percentage on redundancy suggested that the additional cost caused by redundancy is less than 40% of original design even when the redundant cell number equal to the basic cell number. If the standby mode of redundancy is adopted, the incremental cost is less than 10% to ensure the reliability requirement of a 30 year B10 lifetime.

D. Selection of application dependent redundant designs

As MMC users may have different main considerations, the suitable redundant designs are application dependent. Two applications are discussed for the case study to demonstrate the flexibility of the redundant designs selection.

For a noncritical application such as marine propulsion, economy is the main consideration. If less than 10% additional MMC system cost is the cost constraint, 2 redundant cell design is the only choice with active mode operation to meet the reliability (20 year B10 lifetime) and cost requirements. While up to 4 redundant cells can be used in standby mode. More redundant cells mean higher reliability but lower return rate. Therefore, the standby mode with 4 redundant cells is the best choice in such application.

However, standby mode operation has a potential power interrupt issue during fault. The seamless fault transition [42] may be required by users for some critical applications such as solid state transform in power distribution system. In this application, the 2 redundant cells with active mode operation is a best choice since reliability requirement is met with lowest cost.

For applications with no special requirements, the Cost of Reliability (CoR) index is proposed for cost effectiveness comparison. The Cost of Reliability (CoR) describes the additional cost per reliability percentage increment.

$$CoR(i) = \frac{Ct(i) - Ct}{(R_{20}(i) - R_{20}) / R_{20}} \quad (28)$$

Where $Ct(i)$ is the total cost of a redundant design with i additional redundant cells, Ct is the total cost of original design without additional cells, $R_{20}(i)$ is the reliability of i th design at year 20 and R_{20} is the original converter's reliability at year 20.

Fig. 12. Cost of Reliability over redundant designs and redundant strategies.

The CoR for different designs are plotted in Fig.12. For 2 redundant cells operated in active mode or 3 redundant cells operated in standby mode, the average cost for each reliability percentage increment is around 1000\$. Hence, these two designs are comparable in cost effectiveness. With this index, the two comparable redundant designs with different operation modes can be identified in Fig.12 with a horizontal line. In this case study, as the reliability requirement is satisfied with 2 redundant cells in both operation modes according to Fig. 8 (a), the standby operation mode is always preferable due to the low cost.

V. CONCLUSION

The reliability of MMC can be improved by redundant design and successive fault tolerant operation. Lots of redundant designs and fault tolerant control algorithms have been proposed while their reliability improvements are hardly quantified. In view of these, this paper proposed a reliability assessment scheme for MMC with redundant designs. A 3MW MMC case study is conducted to demonstrate the reliability and cost analysis. With the quantitative reliability analysis result, the redundant designs which meet the reliability requirement can be identified. In addition, the cost analysis assesses the redundancy cost impact on MMC system cost to give the affordable choice for manufactures. A cost of reliability concept is proposed to describe the cost-effectiveness of redundant designs and redundant strategies. With the cost of reliability analysis, the cost effectiveness can be compared for different redundancy designs. The proposed reliability and cost assessment scheme provide a guideline for MMC redundant design and redundant cell operation strategy selection.

APPENDIX

The Appendix provides the proof of the key equations for reliability analysis.

Proof of equation (10):

$$MTTF = \int_0^{\infty} \sum_k C_n^k R(t)^k F(t)^{n-k} dt \quad (A1)$$

Exchanging calculation sequence of integral and summation:

$$MTTF = \sum_k C_n^k \int_0^{\infty} R(t)^k F(t)^{n-k} dt \quad (A2)$$

Calculating $\int_0^{\infty} R(t)^k F(t)^{n-k} dt$ with integration by parts method:

$$\begin{aligned} \int_0^{\infty} R(t)^k F(t)^{n-k} dt &= \frac{n-k}{k} \int_0^{\infty} R(t)^{k+1} F(t)^{n-k-1} dt \\ &= \dots = \frac{(n-k)!}{(n-1)!/(k-1)!} \int_0^{\infty} R(t)^n dt \end{aligned} \quad (A3)$$

Substituting A3 into A2 gives:

$$MTTF = \sum_k \frac{1}{k\lambda} \quad (A4)$$

Proof of equation (13):

$$MTTF_s = \int_0^{\infty} \sum_k \frac{(\lambda_s t)^k}{k!} e^{-\lambda_s t} dt \quad (A5)$$

Exchanging calculation sequence of integral and summation:

$$MTTF_s = \sum_0^{n-k} \int_0^{\infty} \frac{(\lambda_s t)^k}{k!} e^{-\lambda_s t} dt \quad (A6)$$

Calculating $\int_0^{\infty} \frac{(\lambda_s t)^k}{k!} e^{-\lambda_s t} dt$ with the Laplace Transform characteristics:

$$\int_0^{\infty} t^k e^{-\lambda_s t} dt = \frac{k!}{(\lambda_s)^{k+1}} \quad (A7)$$

Substituting A7 into A6 gives:

$$MTTF_s = \sum_0^{n-k} \frac{1}{\lambda_s} = \frac{n-k+1}{\lambda_s} \quad (A8)$$

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Pengfei Tu (S'14) received the B.Eng. degree in electrical engineering from Wuhan University, Wuhan, China, in 2013 and the M.Sc. degree in power engineering from Nanyang Technological University, Singapore, in 2014. He is currently working toward the Ph.D. degree in electrical engineering at the same university. His current research interests include reliability of multilevel converters and model predictive control.

Shunfeng Yang (S'15) received the B.Eng. and M.Sc. degrees in Electrical Engineering from Southwest Jiaotong University, Chengdu, China, in 2007 and 2010, respectively. Since 2014, he has been with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, working towards the Ph.D. degree in power engineering. His research interests include power electronics, multi-level converters and converter control techniques.

Peng Wang (M:00- SM:11- F:17) received his B.Sc. degree from Xian Jiaotong University, China, in 1978, the M. Sc. degree from Taiyuan University of Technology, China, in 1987, and the M. Sc. and Ph.D. degrees from the University of Saskatchewan, Canada, in 1995 and 1998 respectively. Currently, he is a professor of Nanyang Technological University, Singapore.