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# Lifetime estimation of IGBT modules for MMC-HVDC application

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ABSTRACT

Modular multilevel converters (MMCs) usually work in harsh operating environments due to their compact layouts and adverse mission profiles, which accelerate the thermomechanical fatigue process in insulated-gate bipolar transistor modules (IGBTs). Accurate lifetime estimation is desired to conduct reliability prediction and develop maintenance policies. This paper presents an analytical approach to estimating the lifetimes of IGBTs for MMC-HVDC application based on the thermal cycles, which are influenced by the transmission power profile and ambient temperature profile. The structure and operating principle of MMCs are studied to develop an analytical model for computing the IGBT power loss. A thermal equivalent network in the form of a Foster model is adopted to link the power losses and junction temperature. Next, an *RC* equivalent circuit analytical method for characterizing the fundamental-frequency thermal cycles, developed using electrothermal analogy theory, is proposed. The rainflow counting algorithm is applied to extract the low-frequency thermal cycles from the annual junction temperature data computed at every minute. The Bayerer model is employed to predict the IGBTs lifetime. Finally, the lifetime distribution, mission profiles and comparison of different IGBTs are analyzed via case studies.

## 1. Introduction

With the rapid development of power electronics technologies, voltage-source-converter-based high-voltage direct current (VSC-HVDC) systems have been increasingly applied in wind power, photovoltaic power, distributed generation, and smart grid technology [1,2]. Due to a series of unique merits, such as low power losses, low harmonic distortion, and extensible modular structures, modular multilevel converter (MMC) technology has recently received attention regarding its use in VSC-HVDC applications [3,4]. However, MMCs for DC-link are subjected to an adverse mission profile that involves varying power flow and a harsh operating environment. Moreover, MMC-HVDC system has more submodules and a more compact layout, which cause more serious thermal stress. Consequently, MMCs are prone to failure, making them vulnerable components of MMC-HVDC systems. Therefore, a reliability study of MMCs is essential to ensure safe power grid operation [5,6].

The existing options for improving the reliability of the MMC system are as follows: a) select low on-voltage IGBT modules; b) reduce the amplitude of the load (if probable); c) improve the cooling system; d) increase submodule redundancy; and e) reduce the switching frequency. As a key component of MMC, IGBT module is studied here from the perspective of lifetime. Lifetime estimation is a significant part of the MMC reliability analysis, regarding not only operations and maintenance but also efficiency and replacement costs. However, few research studies have focused on lifetime estimation of the MMC, particularly the MMC-HVDC for DC-link. Thus, this work is of great importance regarding this issue.

The MMC contains six arms, each of which consists of N submodules (SMs) in series. The half-bridge structure SM, which is the SM most widely employed in MMCs, is composed of two insulated-gate bipolar transistor modules (IGBTs), a capacitor, a bypass switch and other components. When subjected to high losses and thermal stress, the IGBT module, composed of IGBT chips and diode chips, is likely to fail and is thus a notable fragile component in power electronic converter systems [7]. Previous studies have shown that the two main failure mechanisms of IGBTs are bond-wire liftoff and die-attach solder fatigue, both of which are caused by thermal expansion in the pronounced temperature gradients [8,9]. This thermal stress causes IGBT failure, especially at the joints between different materials, as their coefficients of thermal expansion (CTEs) are mismatched. The lifetime models reflecting the aging failure mechanisms can be divided into two classes: 1) analytical modeling methods based on accelerated experimental and statistical analysis [10,11] and 2) physical modeling approaches based on finite-element (FE) analysis [12]. The latter type of method requires a long simulation time and is not suitable for 8760 hourly analysis.

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The analytical lifetime models use the number of thermal cycles to failure ($N_f$) to quantify the lifetime of semiconductor devices. The main factors affecting $N_f$ are the average junction temperature, frequency and amplitude of the thermal cycle. Thermal cycles can be decomposed into low-frequency thermal cycles and fundamental-frequency thermal cycles [13]. The former are caused by a large variation in ambient temperature and power flow (such as in the MMC deployed in a photovoltaic system, a wind power system, or a DC-link power converter system), while the latter occur due to the discontinuous current of semiconductor devices for the requirements of voltage conversion. A numerical iteration method is applied to estimate the fundamental-frequency thermal cycles [13], which exhibit a constant behaviour during the sampling time interval. The low-frequency thermal cycle is extracted from the junction temperature sequence using the rainflow algorithm [14].

Thermal equivalent networks are frequently used in electrothermal modeling for junction temperature estimation. Currently, the method for estimating the junction temperature primarily involves the use of simulation software [15–17]. The accuracy of this method can be high, but the results are strongly dependent on the software used. In [18], an iterative junction temperature calculation method was proposed. However, this method requires a long time when used for multiple mission profile analyses.

The power losses ($P_{loss}$) produced by chips increase the thermal stress in the IGBT module; in turn, the change in thermal stress affects the loss characteristics of the chips. Due to the interactive relationship between junction temperature ($T_j$) and $P_{loss}$, they must be iteratively calculatied when estimating $T_j$. The methods for calculating the power losses of semiconductor devices in an MMC are divided into two categories: 1) system simulation methods [19] and 2) calculations based on test data or system main parameters [20,21]. The use of a detailed physical model to calculate the losses of semiconductor devices is not desirable [22], whereas the use of the static characteristics and dynamic characteristics from a datasheet to calculate power losses is quite common in the industry [23].

The contributions of this paper to the evaluation of the IGBT lifetimes are listed below:

1) The influence of the fundamental-frequency thermal cycle on the lifetime is considered, and the analytic formula is deduced according to the *RC* equivalent circuit. The fundamental-frequency thermal cycles are shown to have an effect on the lifetime, particularly on the rectifier side of the MMC, which consumes a large fraction of the lifetime.
2) The lifetimes of IGBTs under different ambient temperature profiles, which vary with the latitudes of the MMCs applied, are quantified. In addition, combined with ambient temperature, a junction temperature feedback is introduced to revise the power losses of devices. Considering the effect of ambient temperature on power losses, the lifetime estimation becomes more in line with the specific location at which an MMC is utilized.
3) Differences between the lifetimes of an IGBT and a diode, both on the rectifier side and on the inverter side, are analyzed, and suggestions for improving the reliability are proposed. Finally, by comparing two types of IGBTs, the key parameters related to lifetime are derived and analyzed; these parameters are recommended to take into account when IGBTs are selected.
4) The remainder of this paper is organized as follows. Section 2 formulates a framework for MMC lifetime estimation. Section 3 presents the lifetime estimation process in detail. Case studies in Section 4 provide an analysis of the lifetimes for different profiles and IGBTs. Conclusions are presented in Section 5.

## 2. Framework

A schematic of the proposed framework for the lifetime estimation of an MMC is shown in Fig. 1. The MMC model is used to determine the average and root mean square (RMS) values of the current across the semiconductor devices under the power transmission profile. According to the MMC operating principle, the average and RMS values of IGBTs are calculated via an analytic method. This method is suitable for the calculation of current under different control strategies, such as SPWM and NLC, making the analysis of the power losses of IGBTs more convenient.

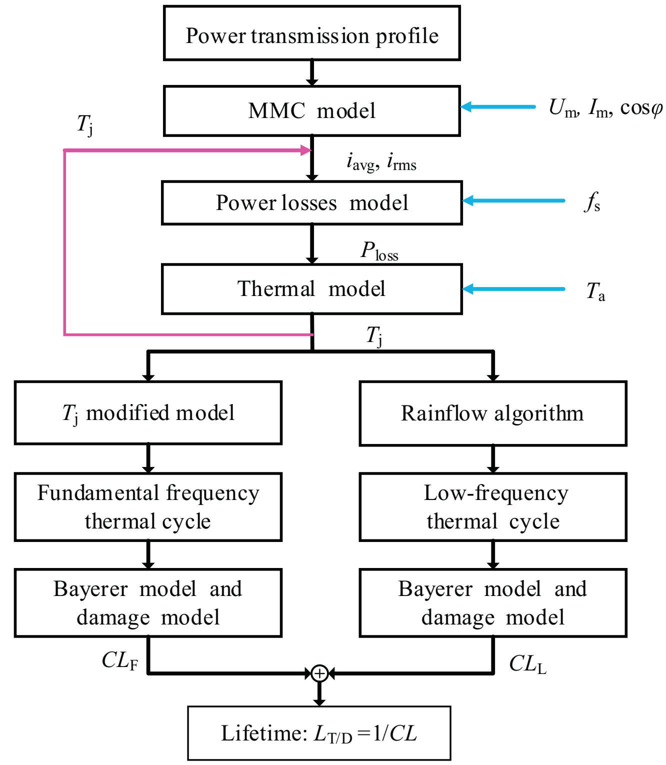


**Fig. 1.** Flowchart.

Next, a power loss model is applied to estimate the power losses of the semiconductor devices. These parameters are then used in the thermal model to calculate the junction temperature. Accounting for the fact that the power losses depend on the junction temperature, $T_j$ loop feedback is introduced to improve the accuracy of the junction temperature calculation.

The core of the framework is to extract thermal cycles from a long time $T_j$ profile. The thermal cycles are divided into fundamental-frequency thermal cycles and low-frequency thermal cycles. The junction temperature data sequence and ambient temperature data sequence have the same length. In this paper, the sampling rate is 1 point/min, that is, approximately 0.5 million sampling points per year for both sequences. The low-frequency thermal cycles are extracted from this disordered junction temperature data sequence. Moreover, during this sampling time interval (1 min), the IGBTs undergo 3000 fundamental frequency thermal cycles when the frequency of the AC side of the MMC is 50 Hz. Because the power flow and ambient temperature remain the same during the sampling interval, the 3000 fundamental frequency thermal cycles behave the same characteristics. Therefore, these 3000 fundamental frequency cycles can be analytically obtained directly. Both of those cycles consume the lifetime. The fundamental-frequency thermal cycles and the low-frequency thermal cycles are estimated using the analytic formula proposed in this paper and the rainflow algorithm, respectively. In addition, the Bayerer model is used to calculate $N_f$, and then the damage model is used to determine the consumed lifetime of all cycles throughout one year. Finally, the lifetime of the IGBT module is estimated.