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Sustainable energy saving: A junction temperature numerical calculation method for power insulated gate bipolar transistor module

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A B S T R A C T

This study is significant to ensure its safe and reliable operation for promoting the sustainable energy saving. The insulated gate bipolar transistor module was widely applied as the core electronic component in energy-saving and new energy industries. A junction temperature numerical calculation method was proposed to calculate the module operating junction temperature that has closed connection with the reliability and lifetime of module accurately in real time. Various parameters were obtained through tests and surfaces that have connected with the degree of the parameters. Junction temperature polynomial fitting equations under each power cycle were established on the above basis. The corresponding polynomial fitting equation was selected according to the aging degree of the module, and the value of junction temperature was obtained by taking the collector current and the saturation voltage. The polynomial fitting algorithm was compared with the junction temperature prediction algorithm based on particle swarm optimization-support vector machine. This study showed that the absolute error of the junction temperature obtained by polynomial fitting equations is mainly concentrated in the temperature and the maximum absolute error is no more than ±5 Celsius degree, and the average relative error of the junction temperature is about 2%. Therefore, polynomial fitting algorithm is more explicit and accurate to calculate the junction temperature of the module. Because the polynomial fitting method simplifies the method of selecting the junction temperature value with the saturation voltage drop as the temperature calibration criterion, and the process of building database between parameters in the whole aging process is omitted, it realizes the on-line measurement of the junction temperature of the module in the aging process, which has remarkable practical value.

1. Introduction

Develop clean energy and improve the efficiency of energy utilization have been drawing more and more attention as a result of the rapid growth in energy consumption, the limited reserves and non-renewable characteristics of fossil fuels, and the environmental pollution brought by the excessive use of fossil energy (Liu et al., 2015; Lalvani et al., 2015). Renewable energy sources like wind and solar power, as a product of the new energy industry, have been widely applied to the field of power generation (Ludin et al., 2014). It is of great significance to solve the energy shortage and reduce environmental pollution (Santoyo-Castelazo and Azapagic, 2014). However, with the development of the new energy power generation to the large scale and industrialization, the increasing installed capacity of power generation systems puts forward higher requirements for the performance of the power converter. Insulated gate bipolar transistor (IGBT) module is the most important part of power inverter device, and its reliability study is of great significance for improving the performance of converter.

The IGBT module is a composite device of metal oxide semiconductor field effect transistor and bipolar junction transistor, which has the advantage of low driving power, high switching speed and low conduction voltage drop (Ji et al., 2013), even so, as the core device of the power converter device, it is usually subject to a great deal of thermal stress and electrical effect, which leads to

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the failure of the IGBT module bonding lead and the aging of the solder layer, and then leads to the devices failure. The junction temperature is an important state parameter that reflects the aging characteristics of the IGBT module, on the one hand, the internal parameters change with junction temperature that resulted in the change of its performance index, and then affects the IGBT module lifetime. The repeated impact thermal stress caused by the junction temperature fluctuation of the module leads to the metal crack on the surface of the device, the internal package chip crack and the bonding wire strength decreases that causes the module reliability to be reduced. Therefore, it is necessary to find a feasible method to measure the junction temperature of the device to ensure the safe and reliable operation of the power converter, which is the key to resolve the energy crisis and promoting the stable economic growth.

The reliability and lifetime of the module are directly related to its operating junction temperature (Astigarraga et al., 2016). Therefore, the study on the method of measuring IGBT junction temperature is crucial to strengthen the health management, optimize the use and prolong the lifetime of the device. At this stage, methods to obtain the junction temperature include sensor method, infrared thermal detection method, thermal network model and thermo-sensitive electric parameters method. The sensor method measures the junction temperature by attaching the temperature sensor to the chip and belongs to the contact measurement (Jiang and Liu, 2017; Ji et al., 2015). The packaged IGBT module layout needs to be changed, resulting in increased stray parameters and poor operability. The principle of infrared thermal detection method is similar to sensor method, which does not need to make contact with the detected object, and the precision of infrared thermal detection method is higher than the thermal sensor, but the infrared thermal image instrument that meets the measurement accuracy requirements is expensive, restricting the use of this kind of method, and the aforementioned two sorts of methods can not satisfy the application requirements of junction temperature measurement in operating condition (Mirone et al., 2016; Bazzo et al., 2012; Wang et al., 2016). In order to overcome the above problems, prior studies proposed that the on-line measurement of junction temperature can be realized by means of combining the electrical loss model and the thermal network model of device to obtain the trend of junction temperature, however, the thermal coupling relationship between the chips is not taken into account, and the accuracy of junction temperature calculation depends on the loss and thermal impedance of device (H. Li et al., 2016). Electrothermal parameters were influenced by the aging process of device.

Consequently, this method has some limitations in measuring junction temperature (Li et al., 2014; Carastro et al., 2012). L. Li et al. (2016) and Lee et al. (2014) analyzed the thermal coupling distribution between the internal chips of the IGBT module through the finite element analysis. A revised model of junction temperature calculation model considering the thermal coupling between the internal chips is established based on the lumped parameter method that improves the accuracy of the junction temperature measurement, but requires complete structural parameters of the device. Numerical iteration method is proposed, according to the theory of the electrothermal analogy (Musallam and Johnson, 2010; Xiong et al., 2015), which is for calculating junction temperature by means of mathematical theory. Compared with the electrothermal coupling model method, numerical iteration method takes account of the coupling relationship between the electrical and thermal, the junction temperature calculation precision is increased, however, under circumstance of requiring high precision of junction temperature calculation, the number of iterations is increased and the calculation is complicated.

At present, thermo-sensitive electric parameters method (Du et al., 2016; Suh et al., 2016) as a promising junction temperature measurement method with high accuracy and conducts online temperature measurements on fully packaged devices. This study is to find the corresponding relation between thermo-sensitive electric parameter and junction temperature that can be regarded as temperature calibration standards to determine the junction temperature value. Common uses of thermo-sensitive electric parameters included saturation voltage drop, collector-to-emitter voltage change rate, the rate of current of collector, turn-on delay time of gate and threshold voltage of gate, however, with the aging of the device, the relationship between thermo-sensitive electric parameters and junction temperature varies, thus affecting the accuracy of junction temperature measurement (Luo et al., 2017).

Hence, in order to operate the real-time online monitoring to the IGBT junction temperature in the aging process, thermo-sensitive electric parameters method is selected to monitor junction temperature variations in the aging process, and the saturation voltage drop is selected as the thermo-sensitive electric parameter to measure the junction temperature. The power cycle aging test platform and the single pulse thermostat test platform are designed and built to monitor the parameters of the IGBT module in the power cycle aging process, and surfaces which have connection with the degree of power cycle aging, saturation voltage drop, collector current and junction temperature were built. Furthermore, the polynomial fitting equation of junction temperature under each degree of power cycle aging is established by the fast searching and fitting of polynomial. The module has been running for a period time, according to the degree of power cycle aging, the corresponding polynomial fitting equation of junction temperature is selected, and the collector current and the saturation voltage drop are taken into the equation to get the corresponding junction temperature.

This study is to evaluate the accuracy of the polynomial fitting equation of junction temperature, the junction temperature polynomial fitting algorithm is compared with the junction temperature prediction algorithm based on particle swarm optimization support vector machine (PSO-SVM) (Liao and Zheng, 2011; Lin et al., 2008). The results show that the fitting equation and the fitting coefficient of the junction temperature polynomial fitting algorithm are easy to obtain, and the method of selecting the junction temperature value with the saturation voltage drop as the temperature calibration criterion is simplified to some degree, which makes the calculation of junction temperature more intuitive and flexible. Compared with the junction temperature prediction algorithm based on particle swarm optimization support vector machine, the maximum absolute error of junction temperature calculated by junction temperature polynomial fitting algorithm is no more than 5 Celsius degree, the maximum relative error is about 5% and the average relative error is about 2%, on the whole, its effect is better than PSO-SVM. Therefore, the junction temperature polynomial fitting algorithm has initially realized the on-line measurement of the junction temperature of the IGBT module in the aging process that chosen to evaluate the reliability and predict the lifetime.

2. Accelerated aging test of IGBT module

2.1. Accelerated aging test principle

The period of IGBT module's failure caused by natural aging is too long to meet the requirements of scientific study. In order to simulate the aging failure of the module in a short period of time and obtain the parameters of the aging process, the accelerated aging test (Rigamonti et al., 2016; Thebaud et al., 2003) is often