European Association for the
Development of Renewable Energies, Environment
and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality
(ICREPQ'12)
Santiago de Compostela (Spain), 28th to 30th March, 2012

Insulated Gate Bipolar Transistor Failure Analysis in Overvoltage Condition

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Abstract. This paper presents the Insulated Gate Bipolar Transistor (IGBT) device failure analysis in overvoltage condition, which is a normal phenomenon occurring in a poor power quality utility system. In most of the IGBT gate drive design, conventionally it embeds the overvoltage protection circuit, however, the problem of short-circuit would still happen. Therefore, a detailed study had been carried out, where the overvoltage condition is being simulated to a boost Power Factor Correction (PFC) circuit implementing the IGBT as a switching device. A set of equations is derived for calculating the maximum junction temperature of an IGBT using the device switching characteristics during overvoltage condition. This approach can be used to determine the heat generation of IGBT device as well as identifying the root-cause of the short-circuit failure of hard switching design scheme during overvoltage condition.

Key words

Insulated Gate Bipolar Transistor, Switching Losses, Junction Temperature, Boost Power Factor Correction

1. Introduction

In the days of rapid technological progression, both the electric utilities and end users of electric power are becoming increasingly concerned about the quality of electric power. Poor power quality may cause electrical appliances malfunction or fuses to trip [1]. One of the most common power quality events occur in daily basis is the overvoltage condition, which may happen due to the supply transformer tap settings are set incorrectly and loads have been reduced. Over-voltage conditions can create high current draw and cause unnecessary tripping of downstream circuit breakers, as well as overheating and putting stress on equipment. Hence, this may cause failure to the power electronics device, which is a common device in household appliances [2]. The use of the IGBT, which is a relatively new power semi-conductor device, has increased in these few years. IGBT is a device whose performance is a combination between a MOSFET and a BJT was developed due to a need to combine the desirable characteristics of the bipolar junction transistor (BJT) and the MOSFET. Therefore, if the IGBT is applied in the hard switching application such as motor drives or boost power factor correction (PFC), the switching waveform must ensure that the IGBT's loci of operation does not exceed its' safe operating area, (SOA). One of the drawback of the IGBT power device is its turn-OFF switching characteristics, although it is similar to normal MOSFET switching characteristic, but it has the tail current. The tail current is caused by the recombination of the minority carrier (hole), which is injected into the N- drift región; one of the switching characteristic of BJT in IGBT [3]. The tail current is the root-cause of the IGBT short-circuit failure, which is neglected in many circuit applications. Thus, it is necessary to have a reliable method of determining the expected power losses and also the total heat generation caused by the tail current in the device for different applications.

2. Effect of IGBT Turn-OFF and Switching Losses

Fig. 1 shows the basic structure of an IGBT. During the turn-OFF process, the gate must be shorted to the emitter or a negative bias must be applied to the gate.

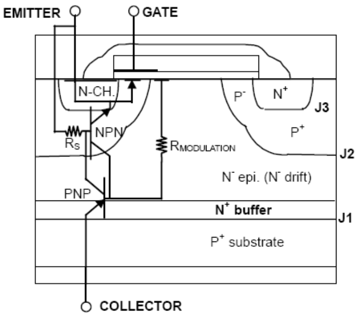
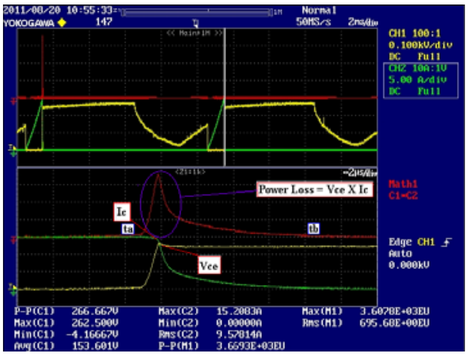


Fig. 1. Basic Structure of an IGBT

When the gate voltage falls below the threshold voltage, the inversion layer will not be maintained, and the supply of electrons into the N- drift region is blocked, at the point where the turn-off process begins. However, the turn-off will not be quickly completed due to the high concentration minority carrier injected into the N- drift region during forward conduction. First, the collector current rapidly decreases due to the termination of the electron current through the channel, and then the collector current gradually reduces, as the minority carrier density decays due to recombination [4]. Fig. 2 shows the IGBT turn-OFF switching losses.



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P-P(C1)   266.667V    Max(C2)   15.2083A     Max(M1)   3.6078E+03EU
Max(C1)   262.500V    Min(C2)   0.00000A     Rms(M1)   695.68E+00EU
Min(C1)  -4.16667V    Rms(C2)   9.57814A
Avg(C1)   153.601V    P-P(M1)   3.6693E+03EU
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Fig.2. IGBT Turn-OFF Switching Losses

Switching Losses is the power dissipated during the turn-on and turn-off switchings of transistors. Conduction losses (or ON state drop) are the losses that occur while the transistor is on and conducting current. The most accurate method of determining switching losses is to plot the I_c and V_{ce} waveforms during the switching transitions. The area under the power waveform is the switching energy expressed in watt-seconds [7].

$$P_{off} = \int_{ta}^{tb} I_c(t) \times V_{CE}(t) d \tag{1}$$

A.IGBT Failure Mechanism and SOA

IGBT in switching applications received high electrical and thermal stress under short-circuit or turn-off switching of clamped inductive load; for instance the boost PFC circuit, which include an inductor connected in series to the collector's terminal of the IGBT. If there is a large power loss within the device due to electrical stress, much heat is generated to the limitations in packaging and due to semiconductor's thermal parameters. It would lead to thermal breakdown if this continues. As a reference for the design, the IGBT performances are based on the maximum allowable junction temperature and also the safe operating area, SOA [4]. The SOA depicts the safe operating area for short duration simultaneous application of high current and voltage at the time of turn-ON and turn-OFF of the IGBT. IGBT's turn-off at clamped inductive load determines reverse bias SOA.

B. Effect of Temperature and Overvoltage in IGBT Switching

As it has been stated earlier, typical IGBT gate drive design embeds the overvoltage protection. Whenever the operating voltage exceeded a certain value, it will cut off the switching process. By the time the IGBT turns off rapidly, energy that has been stored in the inductor is dissipated in the switching device. Because of this, there is voltage overshoot in either side of the device. The size of this transient voltage is directly related to the size of the stray inductance and the falling rate of the turn-off current. In conjunction with that, the IGBT switches the largest amount of energy in a short time, and it is possible for a large current to be injected to lead to the destruction of the device. The moment when the power device turns off to protect the IGBT during short circuit is the most dangerous and important period. At this time, the rate of change of the current could be higher than the normal operating current value, typically two to three times of the rated current value. Inserting the snubber circuit design as a protection circuit to protect normal switching may lead to design constraint, for example inserting higher gate resistance, R_g causes the delay in gate voltage switching. Apart from the overvoltage switching condition, the high temperature causes the minority carrier lifetime in the drift region increases. This will lead to the delay of recombination process (tail current) of the minority carrier, but it also increases the PNP transistor gain. So the portion of the initial abrupt fall in the overall collector current reduces. As such, the tail current fall time is lengthened, and turn-off time increases with an increase in temperature. The results are shown in Table I and Table II in the experimental and data analysis section [4].

C.Previous Research

The International Conference paper written by A.D. Rajapakse, A.M. Gole, P. L. Wilson, Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB, Canada, [5], explained about the method for simulating switching and conduction losses of an Insulated Gate Bipolar Transistor (IGBT) device in an electromagnetic transient program (EMTP) without recourse to an unreasonably small timestep. A set of equations is derived for calculating switching losses of an IGBT using the device switching characteristics approximated with piece-wise linear functions. These loss equations are integrated to a power electronic switch model of an emtp-type program and used for the simulation of losses in the device. This approach can be used to determine the heat generation of IGBT devices in a large class of Voltage Sourced Converter (VSC) systems [5].

3. Experimental Analysis

This project is implemented to identify the main cause of the IGBT failure in the boost PFC circuit application, which is the most severe switching condition due to the clamped inductive load, where the current from the boost inductor flows through the IGBT, which is high enough to produce more switching losses. The testing had been carried out at the ambient temperature, T_a of 25℃ and 40℃. The temperature of 25℃ reflects the normal IGBT switching behavior in room temperature condition while the 40℃ reflects the IGBT switching behavior in the actual application. The measurement is mainly focused on the turn-OFF switching of the IGBT due to the design of the switching, where during turn-ON the losses can be neglected. After the experimental works had been carried out, the data are being calculated by using the derived formula. The derivation of the formula is explained in the experimental results and data analysis section.

A.Boost PFC Circuit

The switching boost PFC circuit is used in this study as a typical design example for clamped inductive load. This analysis proceeds by a derivation of numerical algorithm as a loss prediction techniques for IGBT power device switching. The losses are validated by the test data measured from the circuit [6]. In this research study, the equations of calculating the maximum junction temperature, T_j are developed for IGBT turn-off losses. The equations describe IGBT losses as a function of junction temperature,T_j and collector current, I_c as well as collector-emitter voltage, V_{ce}. These equations are applied to determine the total losses in the IGBT in the continuous mode boost PFC circuit as illustrated in Fig. 3.

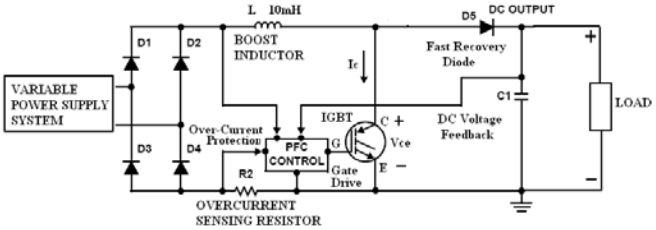

Fig. 3. Typical Design of Boost Power Factor Correction (PFC) Circuit

Fig. 3 illustrates the typical design of boost PFC test circuit used for developing the turn-off losses [6]. The variable power supply system is used to simulate the overvoltage condition, which raises the voltage from 230V AC to 276V AC for the duration of more than one minute. The voltage fluctuation in this range can be classified as the overvoltage condition; one of the power quality events which occur frequently. The energy loss measurements were calculated for a consecutively two similar pulse with the device preheated to the specific junction temperature. Some switching losses formulae are being derived based on a single pulse of the switching, however, due to the consistency and accuracy of the switching losses calculation, two consecutive pulse are more preferred. The energy loss per pulse was recorded as the integral of the total turn-OFF energy pulse including collector current tailing.

B. Experimental Set-up and Measurement

An IGBT punch-through type rated at 600 V, 30 A was used for the experiment. The test circuit as in Fig. 1 was constructed with the parameters, L = 10mH. The on-state current in the device was adjusted by selecting the gate resistance R_g = 47 Ω appropriately. The current and voltage waveforms for IGBT turn-on and turn-off transients were recorded using a high sampling speed oscilloscope. The tests were implemented at the ambient temperature of 25℃ and 40℃, and the overvoltage rises from 230V to 276V randomly for 100 times in order to obtain the trend of the unpredictable measurement results. The switching operation is left to operate for 500 hours, where in between the overvoltage simulation activates randomly for a duration of 2 minutes. The experimental energy losses were obtained by integrating the product of the measured voltage and current during switching.

4. Instrumentations

Instrumentation range and quality is essential for the accuracy and validity of test data, especially for the current measurement. The experimental results need the use of proper current and voltage measurements during the IGBT device switching in different temperature conditions [8]. The measured results from the probes are used to calcúlate the heat generation and total losses, therefore the accuracy of the measurements play an important aspect in this research.

A.Current Measurement

The current measurement of the IGBT device’s collector current, I_c as well as the collector and emitter voltage, V_{ce} during the failure analysis testing, is a very demanding measurement for this testing verification and recurrence checking. The results of evaluation data are retrieved from the Yokogawa 701930 current probe. This device became the main measurement tool in combination with a Yokogawa DS1640L digital oscilloscope which allowed on board mathematics of IGBT collector’s current multiply with collector and emitter voltage, V_{ce} as the turn-off losses.

B. Voltage Measurement

The collector emitter voltage, V_{ce} of the IGBT is captured by using a high voltage differential probe, Yokogawa 701926, connected in parallel at the IGBT collector and emitter gate voltage.

C.IGBT Case Temperature Measurement

The IGBT case temperature T_{case} is an important parameter in determining the maximum junction temperature. The IGBT, already has a heat sink firmly attached. In order to obtain the case temperature, a thermocouple made up of copper and constantan is attached in between the IGBT body and heat sink contact, with ample thermal grease applying on the heat sink. This is followed by the thermocouple connected to a temperature recorder, which captures the reading every one second. The T_{case} of the IGBT is measured at the steady state operating condition, (not in overvoltage condition) at the ambient temperature of 25℃ and 40℃.

5. Experimental Results and Data Analysis

Most of the semiconductor device are very sensitive to heat, especially during the switching processes since there is a large amount of heat generated. Junction temperature T_j is used as an indication of IGBT performance parameter. This section will discuss the method used to calculate the IGBT’s junction temperature. Before the $T_{j\,max}$can be calculated, the case temperature should be measured in order to determine the temperature of the IGBT during normal operating condition. Thus, the maximum junction temperature is equal to the given formula as below;

$$T_{j\,max} = T_{case} + \Delta T_{(j-c)} \qquad (2)$$

Fig. 4 shows the overvoltage condition during the IGBT power device switching, which obviously reveals that the IGBT's collector's current , I_c as high as 23.54 A, is higher than the typical switching value, which is merely 15.45 A.

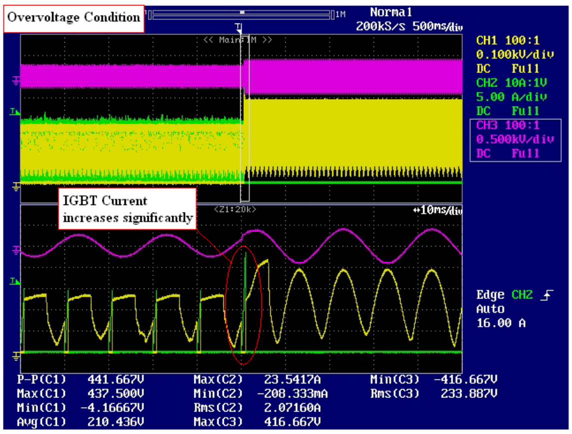

Fig. 4. Overvoltage Condition during IGBT Switching

The overvoltage condition causes a sudden increase in I_c, where it is enough to cause the junction temperature, T_j of the IGBT to increase since the switching losses is increased at the moment. Figure 5. shows the IGBT Turn-OFF switching losses waveform, which is the multiplication of the IGBT collector's current, I_c and IGBT collector-emitter voltage, V_{ce}.

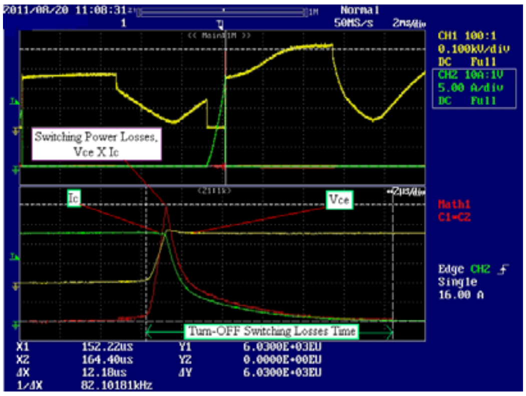

Fig. 5. IGBT Turn-OFF Switching Losses (1000 times zoom in)

The switching power losses provide the details of the total power losses as well as the IGBT Turn-OFF switching time during the overvoltage condition occurs, where these few parameters are needed to calculate the junction-case temperature difference, $\Delta T_{(j-c)}$. The $\Delta T_{(j-c)}$ indicates the total heat generated during the overvoltage condition, hence it may reflect the main cause of the IGBT power device failure root-cause since the maximum junction temperature of the IGBT is approximately 150°C.

A.Formula Derivation

The formula for the calculation of the temperature difference between the junction-case, $\Delta T_{(j-c)}$ of the IGBT can be derived once the Turn-OFF switching losses waveforms obtained from the oscilloscope. The derivation is based on the two consecutively switching losses at the interval time of T. Therefore, the derivation is divided into two formula, which is the $\Delta T_{(j-c)}$ during steady-state operating condition of the IGBT and also $\Delta T_{(j-c)ov}$ which indicate that the $\Delta T_{(j-c)}$ of the IGBT at the time of overvoltage condition occurs, where more heat generated at the particular moment. Hence, it can be stated as;

$$T_{j\,max} = T_{case} + \Delta T_{(j-c)} + \Delta T_{(j-c)ov} \qquad (3)$$

Before the derivation of the formula, the switching power losses that are involved should be clearly identified, as depicted in Fig. 6.

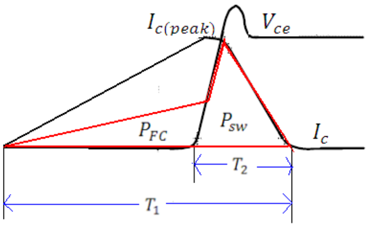

Fig. 6. Types of Power Losses, Forward Conduction and Switching Losses during IGBT turn-OFF

The turn-ON losses are neglected due to the different design applications. Therefore, the P_{FC} indicates the forward conduction losses where this happens during the IGBT in forward conduction mode. This follows by P_{sw} where it involves the tail current and also the collector emitter voltage, during IGBT turn-OFF which is the main switching losses.

B. Condition I. Steady State Operating Condition

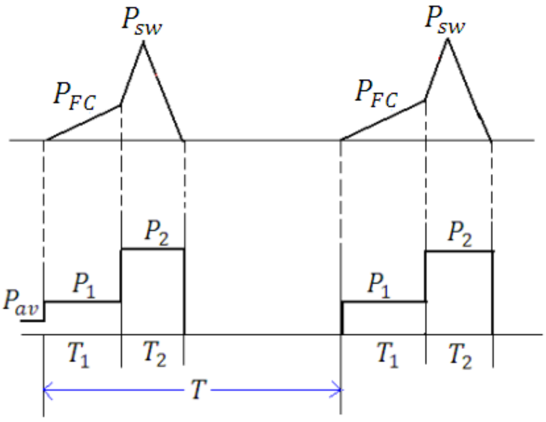

Fig. 7. Two Consecutive Switching Losses Waveforms

Based on the waveforms in Fig. 7, an approximate expression for the turn-off energy and junction-case temperature difference, $\Delta T_{(j-c)}$can be derived as [7];

$$\Delta T_{(j-c)} = P_{av}R_{th\,(j-c)} - P_{av}R_{th}(T+T_1+T_2) + P_1R_{th}(T+T_1+T_2) - P_1R_{th}(T+T_2) + P_2R_{th}(T+T_2) - P_2R_{th}(T) + P_1R_{th}(T_1+T_2) - P_1R_{th}(T_2) + P_2R_{th}(T_2) \qquad (4)$$

where,

$$P_{av} = \frac{1}{T}\int (P_1 + P_2)dt$$

(5)

$$P_1 = \frac{P_{FC}}{\sqrt{2}} \tag{6}$$

and

$$P_2 = \frac{P_{SW}}{\sqrt{2}} \tag{7}$$

where $P_{FC} = I_{c(peak)} \times V_{ce\,(sat)}$ is the forward conduction switching losses of the IGBT. The $I_{c(peak)}$ is measured from the oscilloscope while the $V_{ce(sat)}$ is obtained by referring to the typical output characteristic of the IGBT, which is a standard parameter from the manufacturer's product datasheet. The time T_1 and T_2 reflects the forward conduction time as well as switching losses time. T_1 and T_2 values need to be divided by 1.414 as a result of the root-mean-square value. $R_{th\,(j-c)}$ is the transient thermal resistance (°C$/W$). It acts as the function of duty cycle and pulse length or switching frequency. When the power loss multiplies with the transient thermal impedance, it yields junction temperature rise [7].

C. Condition II. During Overvoltage Condition

Fig. 8 shows the two consecutive switching waveforms during overvoltage condition. In order to obtain the junction-case temperature difference, $\Delta T_{(j-c)ov}$, the $\Delta T_{(j-c)}$ should be included in the formula, so that the $\Delta T_{(j-c)ov}$ is equal to the total sum-up during the steady state switching as well as overvoltage switching, T.

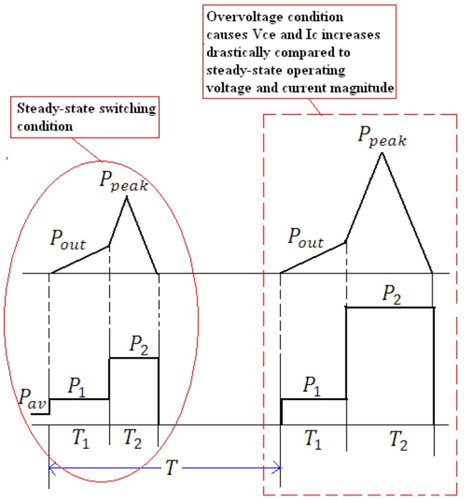

Fig.8. Two Consecutive Switching Waveform during Overvoltage Condition

Therefore, the formula can be derived as;

$$\Delta T_{(j-c)ov} = \Delta T_{(j-c)}(steady\ state\ switching) + P_1 R_{th}(T_1 + T_2) + P_2 R_{th}(T_2) - P_1 R_{th}(T_2) \tag{8}$$

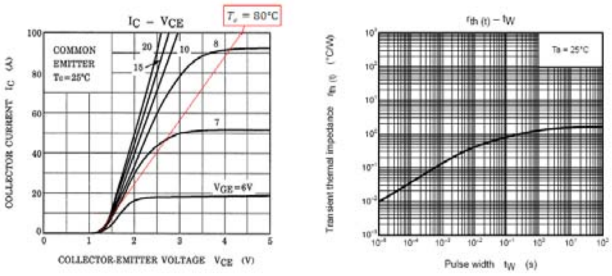

Fig. 9. IGBT Typical Output Characteristic and Transient Thermal Resistance

Fig. 9 shows the IGBT typical output characteristic and Transient Thermal Resistance obtained from the manufacturer's datasheet. The typical output characteristic is used to determine the $V_{ce(sat)}$ of the IGBT in forward conduction mode during the case temperature, $T_c = 80$°C. In this equation P_{av}, P_1, P_2 are main power losses in the Turn-OFF switching, while $R_{th\,(j-c)}$ is the IGBT's power device under chip thermal resistance and can be found in the datasheet, value at 1.67 °C$/W$. $R_{th}(T + T_1 + T_2)$ is the transient thermal resistance at the time of T, T_1 and T_2, which indicates as the pulse width in the graph. The data are calculated based on the waveform measurement.

Table I: Measurements results from T_a =25°C

$I_{c(peak)}$ (A)	T_{sw} (μs)	P_{sw} (W)	$\Delta T_{(j-c)}$ (°C)	$\Delta T_{(j-c)ov}$ (°C)	$T_{j\,max}$ (°C)
25.4167	12	5789	10.69	64.9591	125.7591
27.7523	12	6568	10.69	70.1307	130.9307
25.8337	12	6438	10.69	68.8267	129.6267
26.0417	12	6005	10.69	66.4036	127.2036
25.8331	12	5841	10.69	65.4112	126.2112
25.4167	12	5947	10.69	65.9689	126.7689
26.6667	12	6158	10.69	67.3876	128.1876

Table II: Measurement results from T_a =40°C

$I_{c(peak)}$ (A)	T_{sw} (μs)	P_{sw} (W)	$\Delta T_{(j-c)}$ (°C)	$\Delta T_{(j-c)ov}$ (°C)	$T_{j\,max}$ (°C)
27.9376	15	8337.9	27.396	86.2560	168.8560
26.375	15	7851.4	27.396	82.8318	165.4318
28.7583	15	7763.7	27.396	82.7086	165.3086
28.7516	15	9232.2	27.396	92.3323	**174.9323**
29.1667	15	8983.3	27.396	91.1391	173.7391
26.8751	15	8351.7	27.396	86.1835	168.7835
27.9167	15	8817.4	27.396	89.5746	172.1746

Based on the Table I and Table II, the data show the difference of maximum junction temperature, $T_{j\,max}$ in different ambient temperature during overvoltage condition. The DC voltage bus was kept constant at 300V, and the maximum peak current at turn-off is 29.1667 A. The measurements are taken at two different ambient temperatures which are at 25°C and 40°C. Table I and Table II show the measured current, voltage and maximum junction temperature, $T_{j\,max}$ at 25°C as well as 40°C. From the two tables, it can be observed that the switching transition takes a longer time at 40°C than at 25°C, where T_{sw} increases in T_a = 40°C. The losses increase with higher temperature because of the increase in turn-on transition time. The máximum junction temperature, $T_{j\,max}$ recorded in the testing is 174.93°C, higher than the rated junction temperature rating, 150 °C, which lead to the destruction of the device. As a result, high temperature increases the switching losses significantly and therefore, in the design of IGBT switching module it is imperative to take into consideration of the actual ambient temperature rating as well as the possibility of the overvoltage condition occured. This condition is neglected in some particular designs. Fig. 10 shows the maximum voltage and current across the IGBT during switching, although it does not exceed the RBSOA (in border line margin of safe operating region), it still can cause the IGBT failure.

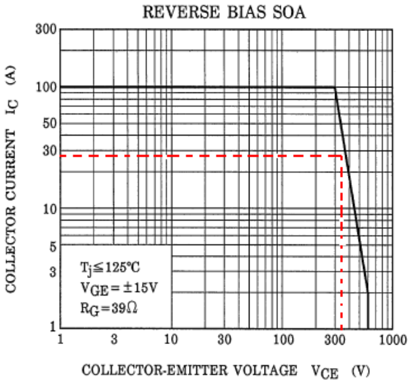

Fig. 10. Reverse-Biased SOA of IGBT in Boost PFC Switching (Red Line Indicates the Safe Operating Región)

After long hours of measurement, the IGBT failure occurs, and the particular device is sent for the de-capsulation process, for the purpose of inspection of the die and the internal interconnection as a part of this failure analysis.

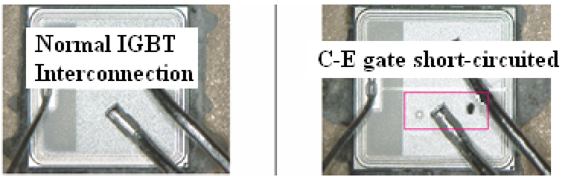

Fig. 11. De-capsulation Photo of the IGBT Switching Power Device

Based on Fig. 11, it is clearly illustrated there are some holes (damages) between the collector and emitter gates. This can be explained that this is caused by the avalanche breakdown, the rapid increase in current at the reverse-bias voltage. The product of the large voltage, V_{ce} and large current, I_c during the turn-OFF switching process in overvoltage condition leads to excessive power dissipation. This caused the destroy of the device. The breakdown is caused by a physical mechanism termed impact ionization [9]. In terms of the physics of semiconductors, it can be explained that if a free electron with sufficient kinetic energy strikes a silicon atom, it can break a covalent bond and release an electron from the bond. If the kinetic energy is gained from an applied electric field, such as reverse voltages applied across a space charged layer, the liberation of the electron from the bond is termed impact ionization. This process is important because the newly liberated electron can gain enough energy from the applied field to break a covalent bond when it strikes a silicon atom, thus liberating an additional electron. This process can cascade (avalanche) very quickly in a chain reaction-like manner, producing a large number of free electrons and thus a large current, and the large power dissipation will quickly destroy the power device [9].

6. Conclusion and Recommendations

This paper has presented a detailed study of the IGBT maximum junction temperature $T_{j\,max}$ formulae derivation as well as the failure analysis during overvoltage conditions. The analyses have shown that the increase in temperature will lengthen the switching transition period, also the effect of the overvoltage during the IGBT switching, generated much more heat than expected, more than the rated junction temperature, 150℃ even though it is still in the safety region of the reverse-biased safe operating area of the device. This has proven that overvoltage causes the IGBT failure. The formula derivation method can be applied in other IGBT switching appliances. However it needs proper derivation consideration such as including the turn-ON losses as well as the diode losses. In order to overcome this problem, it may be suitable to insert the RC snubber circuit into the design. However it must be optimized so that it will not affect the switching characteristic of the IGBT as well as the designed circuit. More work is currently in progress to validate the proposed tool, which will be reported in near future.

Acknowledgements

The authors gratefully acknowledged the financial support by the Ministry of Higher Education (MOHE), Malaysia under FRGS (Vote: 0717) for this research. The authors would also like to thank the staffs in Basic Electrical Machines Laboratory and ORICC, UTHM, for their continous support and valuable contributions towards the success of this research.

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