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SWITCHING CHARACTERISTICS OF IGBT AS THE INITIAL FAILURE INDICATOR: A CASE STUDY

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Abstract. *The remarkable growth of wind power generations has raised the motivation of further investigations on reliability of wind turbines. Unlike traditional methods based on typical failure risks, an accurate analysis of the reliability requires an in-depth understanding of the wind turbine operations. These have to include unpredictable wind conditions that cause temperature swings and the thermal stresses of electrical and mechanical parts of the nacelle. In particular, power electronic converters have to be specifically investigated, as they are responsible for the majority of failures in wind turbines. This paper focusses on the thermal modeling of the power converter for wind turbines with permanent magnet generators with the purpose of detecting early failure mechanisms of the semiconductor devices. The junction temperature has been estimated from power losses via a simplified thermal modelling of a 2-level converter in order to see the effects of the main semiconductor parameters. The paper also evaluates the effectiveness of using thermal sensitive electrical parameters as early failure indicators.*

1 INTRODUCTION

The number of wind turbines (WTs) has significantly increased over the recent decades [1]. The increased proportion of power generation from WTs has raised the necessity of further studies to enhance their availability and maintain the stability of the power generation. The newly advanced WTs are equipped with power electronics (PEs) components. PE converters provide a flexible interface of WTs to the grid to maximize the energy yield. The power losses of the semiconductor devices cause significant thermal stresses, which is due to conduction and switching [2]. Statistically, the most vulnerable parts are semiconductors, printed circuit boards and capacitors [3]. According to [4], 55% of failures of PEs is due to thermal stresses, 20% to vibrations, 19% to humidity, and 6% for dust. The most popular semiconductor components for WTs are Insulated Gate Bipolar Transistors (IGBTs). This is because they have high efficiency and high nominal current. However, because of their multilayer structures and having different thermal expansion coefficients (TEC) in each layer [5]. Different thermal cycles and TEC result in different failure mechanisms of IGBTs. The thermal losses are generated from silicon chips and then the heat propagates through the different layers and heatsink. It then causes cracks, because of the thermal fatigue continuous and causes expansion and contractions during the operation of the converter. thermal stresses have adversely affected the residual life time and hence, availability of PEs analysis of thermal distribution of IGBT is necessary. It is justified owing to the aim that detection of any resulted degradation before fully failure of the components in advance. Early detection of failure mechanisms leads to further availability of power electronics converter and save the costs originated by maintenance and unplanned halt of WTs. To analyse the thermal stress of IGBTs, the variation of T_j (as the hottest point) should be taken into account. Owing to the fact that the temperature of this spot is not available, estimation is often required [6]. Thermal losses modelling can be applied to estimate this temperature. The most newly developed method to examined thermal distribution of the PEs is that examine the variation of thermal sensitive electrical parameters (TSEPs) of the IGBT as the early failure indicators.

In this paper, the power losses of 2-level inverter have been calculated for the analysis of thermal behavior of IGBTs. Then, the effect of electrical parameter of IGBT (collector-emitter voltage) and thermal resistance of heatsink to ambient is studied as a failure indicator of two common failure mechanisms, i.e, bond wire lift-off and solder fatigue. Finally, the effect of wind speed variation has been studied by switching frequency variation for different load current.

2 POWER ELECTRONICS IN WIND TURBINES

Two-level pulse-width modulated voltage source converters (2L-PWM-VSC) are the most popular PEs converters for WTs.

The active power can only flow from the generator to the grid and, hence, a simple and economical diode rectifier can be used as generator side converter [7], [8]. To analyse the thermal distribution of the 2-L-PWM-VSC, the junction temperature (T_j) has been estimated from the power losses of the converter and a simple thermal model for the sample IGBT FZ300RG12KE3. Since the reliability and the lifetime of IGBTs are directly affected by the variations of the junction temperature, it is necessary to make sure that the maximum T_j is never exceeded.

3 MODELLING OF POWER LOSSES

Different methods have been applied to analyse the variation of T_j [9]: infrared camera [10], thermocouple [11] and using thermal sensitive electrical parameters (TSEPs) [12]. Thermal analysis of IGBT and diodes, considering power losses is another method that can be used to estimate T_j.

Power losses (P_d) are the sum of power conduction losses (P_c) and power switching losses (P_{sw}) as written in (1). Conduction losses depends on three parameters: the current through the device, the voltage across the device and the junction temperature T_j. Conduction losses are the sum of the conduction losses of IGBT and diode, which can be calculated by (2), (3) and (4), respectively[13],[14].

$$P_d = P_c + P_{sw} \tag{1}$$

$$P_c = P_{c-IGBT} + P_{c-D} \tag{2}$$

$$P_{c-IGBT} = \frac{1}{2}\left(V_{CE} \times \frac{I_m}{\pi} + \frac{R_{CE0} \times I_m^2}{4}\right) + M \times pf\left(V_{CE} \times \frac{I_m}{8}\right) + \frac{\left(R_{CE0} \times I_m^2\right)}{3\pi} \tag{3}$$

$$P_{c-D} = \frac{1}{2}\left(V_D \times \frac{I_m}{\pi} + \frac{R_D \times I_m^2}{4}\right) - M \times pf\left(V_D \times \frac{I_m}{8}\right) + \frac{\left(R_D \times I_m^2\right)}{3\pi} \quad (4)$$

Where, for the IGBT module considered in the paper, the collector emitter resistance ($R_{CE,on}$) is 7e-3 Ohm, Voltage collector emitter (V_{CE}) is 0.921057 V, Diode voltage (V_D) is 1.03562V, Diode resistance (R_d) is 7.5e-3 Ohm. As additional hypothesis, the modulation index (M) is considered 1 and the power factor is 0.9.

The switching power losses are caused by the transitions from on-state to off-state and vice versa, as (5) shows. Based on the manufacturer datasheet, the switching energy dissipated depends on the current and the collector-emitter voltage, as (6) and (7) show [15].

$$P_{sw} = f_{sw}\left(E_{sw-IGBT} + E_{sw-D}\right) \quad (5)$$

$$E_{sw-IGBT} = \left(a_0 + a_1\, i_t + a_2 i_t^2\right)\frac{V_{dc}}{V_n} \quad (6)$$

$$E_{sw-D} = \left(b_0 + b_1\, i_t + b_2 i_t^2\right)\frac{V_{dc}}{V_n} \quad (7)$$

where the switching frequency (f_{sw}) is 10 kHz, the power factor (pf) is 0.9, the dc-link voltage (V_{dc}) is 525 V, $E_{sw\text{-}IGBT}$ is the switching energy dissipated on $IGBT_{Esw\text{-}D}$ is switching energy dissipated by diode, a_0, a_1, a_2, b_0, b_1 and b_2 are constant parameters, based on datasheet.

3.1 ESTIMATION OF T_j

Considering equations that mentioned in the previous section, power losses of a 2L-PWM-VSC have been modelled. Power losses modelling and modeling of thermal resistance of IGBT lead to the estimation of T_j (9). The power loss of the module generates heat that spreads through the different layers, from the junction terminal to the ambient. The modelled power losses are used in a simplified thermal model of IGBT to calculate the thermal resistance, Figure.1.

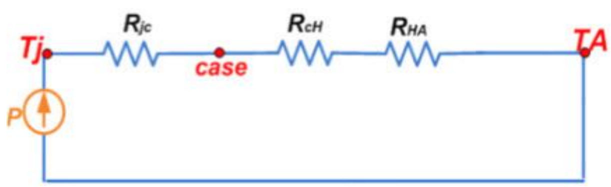

Fig.1. Thermal equivalent circuit of IGBT

Equation (8) is relation between the thermal resistance of the different layers of IGBT, as shown in Figure.1. Based on (9) junction temperature can be estimated.

$$R_{th(j-a)} = R_{th(j-c)} + R_{th(c-s)} + R_{th(s-a)} \quad (8)$$

$$R_{th(j-a)} = \frac{T_j + T_a}{P_d} \quad (9)$$

where, P_d is power losses, T_a is ambient temperature, thermal resistance junction to case $R_{th(j\text{-}c)}$, thermal resistance case to heatsink $R_{th(c\text{-}s)}$, thermal resistance of heatsink to ambient $R_{th\,(s\text{-}a)}$.

4. EARLY FAILURE DETECTION

The accurate estimation of T_j is essential so as to detect the progressive degradation of IGBTs, although it is not readily measurable. Estimation of T_j, however, cannot be a proper detector of failure mechanisms in IGBT, although any failure mechanisms affect the amount of T_j. It is owing to the fact that not only temperature is not fast response phenomenon, but also the value of T_j can be affected by external factor such as wind speed variations in the application of wind turbine. The bond wire lift-off and solder fatigue are the most common degradation of IGBT modules for WT application. These failures affect the thermal distribution of IGBT modules. Bond wire lift-off affects the current distribution through the die of the device. It shows its effect on the collector emitter voltage. It exponentially increases with a variation of T_j [16]. Moreover, the IGBT conduction loss is related to the gate-emitter voltage and the collector current magnitude, which in turn defines the on-state voltage, $V_{CE,on}$. Thus, an increases of $V_{CE,on}$ causes an increase of T_j independently on the load current, as shown in Fig.2. The solder fatigue affects not only the electrical coupling of the die with the contact pad, but also the thermal coupling. Solder fatigue introduces voids between the layers and reduces the effectiveness of the power transfer from the die to the heatsink($R_{,\theta sa}$) [17]. Therefore, it increases the thermal impedance of the IGBT. The effect of the solder fatigue is modelled by changing the thermal impedance, as shown in Fig.3.

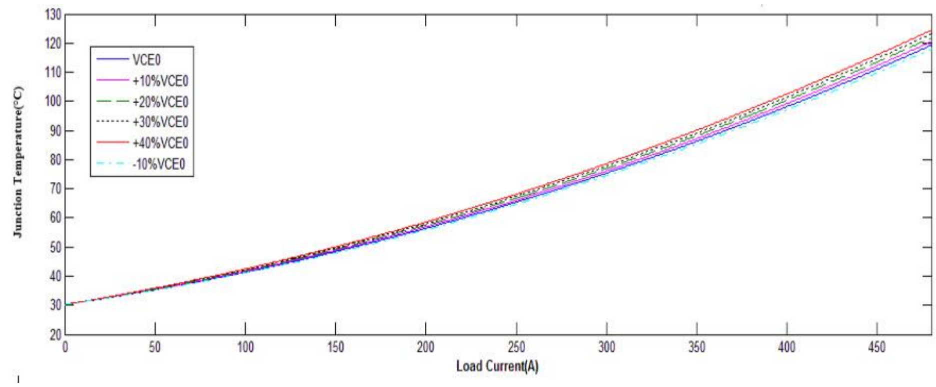

Figure 2. Junction temperature vs load current for different collector emitter voltages

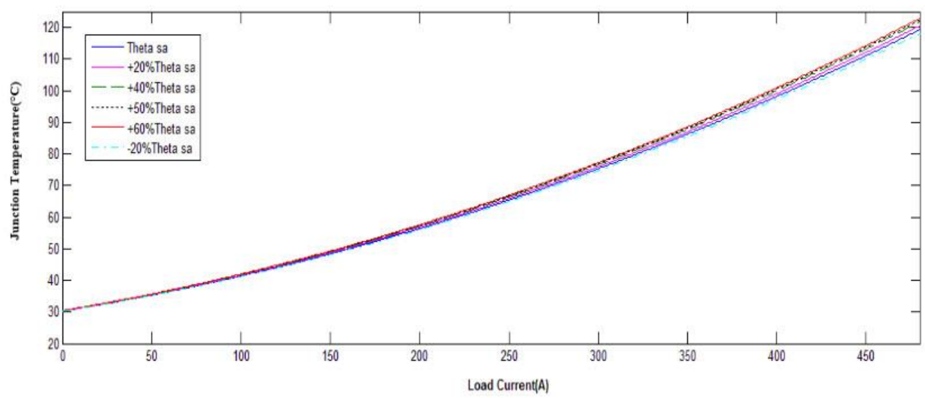

Figure .3. Junction temperature vs load current in different thermal resistance

Negative aspect of estimation of T_j through measurement of TSEPs is the low accuracy of early failure detection in the present of muti-failure. In other words, while different types of failures occurring at the same time can produce the same variation trend on the failure indicators. In order to increase the accuracy of T_j estimation and correlate it with failure mechanism, it is preferable to predict early failure mechanism through monitoring the variation of TSEPs and estimate T_j and then correlate the estimated T_j (TSEPs method) with estimated T_j through power losses modeling.

5 WORK IN PROGRESS

The analysis of previous technical literature on the early fault detection and also residual life time (RLT) estimation have revealed that further investigation is needed to understand the strength and weakness of the proposed CM methods in terms of accuracy, complexity and implemented costs. Furthermore, literature reviews showed that the operation condition of wind turbine has been ignored in previous CMs. Thus, in the case of wind turbines, looking just the variation of the electrical parameters is highly likely leads to inaccurate on-line CMs. Moreover, early failure indicator can be affected by the several different failure mechanisms. To conclude, there is no accurate on-line condition monitoring so far, especially in the applications of WTs and multi-failure situation. Therefore, the effectiveness of the wind speed conditions on the condition monitoring system should be carefully studied. The outcome should be investigated in the CM algorithm and validated within the presence of multi-failure situation.

The idea is to investigate the wind speed variation (laminar flow) in the wind tunnel and study the effect of wind speed variation on the thermal sensitive electrical parameters (TSEPs) of the insulated-gate bipolar transistor (IGBT), junction temperature (T_j) during the operation of wind turbine (WT). The variable wind condition causes the variations of the electrical parameters and also temperature swings of the IGBT's Layer. The effect of these variations on the failure mechanisms of IGBT should be carefully investigated. In order to enhance the accuracy of the condition monitoring (CM), wind condition should be correlated with TSEPs and also failure mechanisms. As a result, the root causes of failure mechanism can be correlated with the wind speed variations. The analysis would lead to the development of the novel CM algorithm of IGBT that can predict the early degradation of IGBTs, within the operation of WTs.

The first step is doing sensitive analysis between wind speed variations and the electrical output parameter of the drive train component as well as the temperature distribution. In other words, the thermal and electrical behaviour of IGBT, generator and DC-Link will be modelled in different wind speed.

To implement the idea above, the micro-wind turbine will be installed inside a wind tunnel and operated at different wind speed (from cut in to cut out wind speed) to monitor and model the temperature and electrical parameters on the different electrical drive train components (generator, inverter and DC-link).

The whole experimental test will be implemented in two main different parts: healthy mode of IGBTs and degraded mode of IGBTs. The initial test rig of one phase of inverter to look at the healthy mode is shown in Fig.4. The experimental test rig consists of one IGBT module with two devices (VS-50MT060WHTAPBF), a gate driver circuit (IR2113), and one Opto-coupler (TLP521-4) to insulate the switching and power parts from the control parts. The DC bus voltage of the test rig is 10 V.

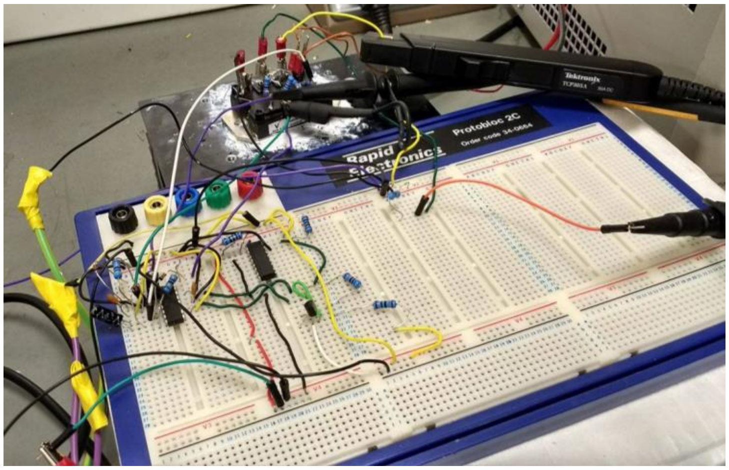

Fig. 4. Test rig to investigate thermal response of IGBTs in health-mode

The test rig allows the measurement of TSEPS and the estimation of the variation of *Tj*. Turn-on delay time, turn-off delay time, on state collector emitter voltage ($V_{CE,on}$) have been chosen as TSEPs for this test rig. Fig. 5 shows the collector-emitter voltage), the gate emitter-voltage and the collector current for a load of 330 Ω. The turn-on delay time is defined as the time during which the gate-emitter voltage rises from 10% to 90% of the nominal value. Turn-off delay time is the time during which the gate-emitter voltage drops below from 90% to 10% of the nominal value. For this test, turn-on and turn-off delay times are 10 ns and 8 ns respectively.

The next will be to add a resistor in series with emitter bond wire to simulate the bond wire lift-off and then compare the turn-on and turn-off delay times with those measured in healthy mode to see whether there is any significant different. This will be repeated for different loads and DC bus voltages.

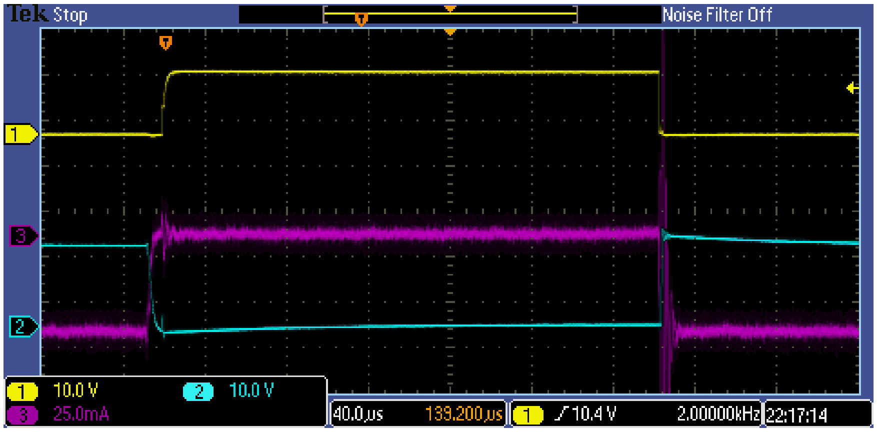

Fig. 5. TSEPs of the subjected IGBT in healthy mode: collector-emitter voltage (blue), gate-emitter voltage (yellow) and collector current (purple)

5.1 HEALTHY MODE OF IGBT

In this step, temperature (T_j, heatsink temperature of IGBT) as well as the electrical parameters of IGBT, DC-Link and PMG have been measured and analysed. Wind turbine will be run in three different range of wind speed, i.e cut in, rated speed and cut-off wind speed. In each rang of wind speed, TSEPs and T_j will be measured as well as voltage and current output of rectifier, current before and after DC-Link.

5.2 UNHEALTHY MODE OF IGBT

The thermal and electrical behaviour of IGBT will be monitored while failure mechanism (solder fatigue) is modelled and imposed on IGBT. The failure will be modelled by changing the heatsink diameter, causes changes in thermal distribution of IGBT. Three different heatsink will be replaced and its effect on TSEPs, T_j and heatsink temperature will be monitored. In this step, temperature (T_j, heatsink temperature of IGBT) as well as electrical parameters of IGBT, DC-Link and PMG have been monitored in cut-in speed, rated and cut out wind speed separately. Wind turbine will be run in three different range of wind speed, i.e cut in, rated speed and cut-off wind speed. In each rang of wind speed, turn-on delay time, turn-off delay time, Tj and $V_{CE,on}$ will be measured as well as voltage and current output of rectifier, current before and after DC-Link.

5.2.1 BOND-WIRE LIFT-OFF (EARLY TO FULLY LIFT-OFF)

The thermal and electrical behaviour of IGBT will be monitored while failure mechanism (bond wire lift-off) is modelled and imposed on IGBT. The failure will be modelled by series specific about of resistance in four different steps, due to test the effect of bond wire lift-off from early to fully lift-off (the subject IGBT includes 4 bond wires for each chip). It causes changes in current distribution emitter (bond wires) of IGBT. Wind turbine will be run in three different ranges of wind speed, i.e cut in, rated speed and cut off wind speed. In each rang of wind speed, turn-on delay time, turn-off delay time, T_j and $V_{CE,on}$ be measured as well as voltage and current output of rectifier, current before and after DC-Link.

5.2.2 SOLDER FATIGUE

Three different heatsink will be replaced and its effect on the chosen TSEPs and T_j and heatsink temperature will be monitored. In this step, temperature (T_j, heatsink temperature of IGBT and PMG' winding) as well as electrical parameters of IGBT, DC-Link and PMG have been monitored in cut-in speed. Wind turbine will be run in three different range of wind speed, i.e cut in, rated speed and cut off wind speed In each rang of wind speed, Turn-on delay time, turn-off delay time, T_j and $V_{CE,on}$ will be measured as well as Voltage and current output of rectifier, Current before and after DC-Link.

5.3 The Last Step

In the last step, the achieved output values in each section have been applied to implement sensitive analysis based on input data. After that, mathematical behaviour of the system over the defined input parameters has been estimated by regression.

As presented in the last steps, wind speed and the variation frequency of wind speed, acceleration of tower are considered as the input parameter. Temperature of stator winding, T_j of IGBT, heatsink temperature of IGBT and TSEPs of IGBT are considered as output parameter. Variation behaviour of output parameters to the variation of input parameters will be determined based on mathematical relation between input and output parameters by applying multiple regression technique. The regression model is (10), using the data analysis. It is assumed that the error u is independent with constant variance.

$$y = \beta_1 + \beta_2 x_2 + \beta_3 x3 + u \tag{10}$$

6 CONCLUSIONS

Insulated gate bipolar transistor modules are widely used in power electronics converters for wind turbines. However, due to the layered structure of these devices, the calculation of reliability is a problematic issue. This is due to the unpredictable operation conditions due to the variation of wind speed, which in turn causes variable power losses. The most vulnerable part of an IGBT is between the semiconductor chip module of silicon and the bond wires made of aluminium resulting in bond wire lift-off and solder fatigue. Each failure mechanism shows its adverse effect on a specific part of the IGBT structure directly based on the root cause of failure. Bond wire lift-off can be detected through the observation of $V_{CE,on}$ variation, while solder fatigue can be detected by monitoring the thermal resistance variation in IGBT. Considering the variation of the wind speed and wind turbulence may have a significant effect on the healthy level of the IGBT. The influences of wind fluctuation and its impact on condition monitoring have received only little attention so far in the technical literature. Therefore, this project will try to fill this gap and integrate the information on wind conditions into the condition monitoring system of the electrical components.

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