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Sensitivity Analysis of Switching Electrical Parameters of Semiconductor Devices for Wind Turbine Converters

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Abstract—The failure of power converters is currently the main reason of stopping for wind turbines. The unpredictable nature of wind power flow causes temperature swings to the semiconductor devices, which leads to additional thermal stresses and, eventually, unexpected failures. A suitable way to avoid this is using condition monitoring systems, which detect the degradation of the devices and reduce the stopping time by a planned maintenance. The choice of the most appropriate early failure detector is therefore essential to make sure that the condition monitoring system is accurate and indicates a fault only when this is actually occurring. For this reason, this paper focusses on the sensitivity analysis of switching parameters in response to a variation of the load and the dc-bus voltage, which may introduce uncertainty in the detection of early fault as they have a direct influence on the device temperature. The results of the experimental investigation show a substantial sensitivity of switching parameters to dc-bus voltage variation and a moderate sensitivity to load variation.

Index Terms—Condition monitoring, early failure indicators, thermal sensitive electrical parameters, wind turbines.

I. INTRODUCTION

Wind power generation is nowadays one of the most important renewable power sources. Due to the unpredictable nature of wind, it is essential that wind turbines (WTs) have very high availability to harvest the most of the energy available. Manufacturers are constantly working on the enhancement of WT reliability, as this leads to an increase of longevity and a reduction of failures over the lifetime, increasing the total electrical energy generation. However, unexpected failures require a well-organized maintenance team and, hence, high costs as faults do not normally occur during scheduled maintenance. Condition monitoring (CM) is likely to provide an efficient alternative to traditional maintenance schedule, as they can provide information on the health conditions and, hence, advise the maintenance team to act on time, preventing unplanned halts of WTs [1].

Modern MW-size WTs use full-size power electronic converters (PECs) to supply power to the electricity grid. Statistically, PECs are responsible for the majority of failures of the electrical system of WTs. The converters

IGBTs are the most vulnerable components in a PEC [2]. The early detection of failure mechanisms is therefore essential to prevent major malfunctions of the electrical system. CM systems are used to monitor the temperature variations of IGBTs and, in particular, those of the junction temperature T_j , as it has been recognized that most of the failures can be accounted for thermal stresses [3]. However, due to inaccessibility of the junction, direct measurement of the temperature is difficult. The junction temperature can be instead estimated from the measurements of thermal sensitive electrical parameters (TSEPs) as indicated by Fig. 1.

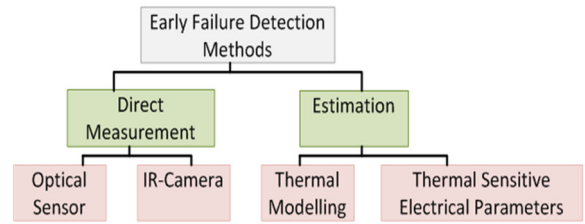


Fig. 1. Different methods of tracking temperature variations.

Both direct measurement and estimation have advantages and disadvantages as summarized in Table I [4]. The methods based on the direct measurement of T_j are rarely used, because they require a modification of the IGBT structure and they are not accurate for tracking fast variations of T_j [5]. Junction temperature estimation via TSEPs is a new and promising approach, but still requires further investigations as it requires fast sampling times and expensive hardware to be satisfactorily accurate.

The methods based on thermal models require a very high computational effort and extra in-situ hardware [6]. The methods based on the monitoring of converter voltage and current are promising for overcoming these technical limitations, but they generate a not negligible number of false alarms. The methods based on TSEPs can follow quick variation of the junction temperature of IGBTs and the parameters are normally externally assessable and easy to measure. However, they are difficult to implement, as the fast switching of devices reduces the accuracy of the

monitoring of the variation of the relevant TSEPs [7].

TABLE I
COMPARISON OF CONVENTIONAL AND NEWLY
DEVELOPED FAILURE INDITACTOR METHODS

Direct Measurement	Estimation	
<ul style="list-style-type: none"> Accurate No integrated circuit However... No fast response Not easy to calibration 	Thermal modeling	TSEPs
	<ul style="list-style-type: none"> Accurate However... Complicated Time-Consuming 	<ul style="list-style-type: none"> Applicable within the operation of system However... Integrated circuit fast sampling time, cost

The research on methods based on TSEPs is mainly focused on the identification of the most appropriate set of parameters used as junction temperature detector in terms of sensitivity, linearity and complexity. The challenging issue of TSEPs originates from the observation that variations of these parameters are affected by different sources or failure mechanisms and, at the same time, also by temperature swings caused by load variation during normal operations of the converter. These conditions normally apply to WT, which operates with constantly variable wind speed, presence of turbulence and variable atmospheric conditions. Thus, accurate CM algorithms for WTs require an in-depth understanding of failure mechanisms of IGBTs and their root causes.

The analysis of the technical literature points out that the most probable failure mechanisms of IGBTs are bond wire lift-off (BWLO) and solder fatigue (SF) [8]. These can be detected with different methods before a complete damage to the component has occurred. Temperature swings are the cause of a not uniform expansion of the different materials of IGBT's and the resulting shear stresses potentially lead to fatigue [9]. The bonded area is where the bond wire foot is connected to the metal chip. The most fragile part of bond wire is its heel and heel cracks due to shear stresses can lead to the disconnection of the wire bonds and the following extension of the crack causes full BWLO. The root causes of wire failures are temperature swings, mean temperature and variation of temperature with the time [4]. On the other hand, a small initial crack in the die-attached solder generated during the manufacturing process can be aggravated by small and short temperature swings leading to full SF. The root causes of solder failures are temperature changes and mean humidity [10].

Previous studies have shown that the on-state collector-emitter voltage $V_{CE,on}$ is a good failure indicator of BWLO [9]. However, this parameter is affected by temperature changes and, hence, it can be caused by both BWLO and SF. Therefore, many algorithms proposed in the literature may lead to an inaccurate indication of the failure

mechanism, especially for the initial steps of progression. Therefore, in order to uncouple the coupled effects of different failure mechanisms, different TSEPs should be examined and applied in a CM system. TSEPs are divided in two different categories, i.e. static TSEPs such as the on-state resistance, R_{on} , the junction to case thermal resistance, $R_{j,c,th}$, the collector current, I_C ; and switching TSEPs such as the threshold gate-emitter voltage, $V_{GE,th}$, turn-on delay time, $t_{d,on}$, turn-on time, t_{on} , turn-off delay time, $t_{d,off}$, and turn-off time, t_{off} .

The variation of external factors, such as the wind speed, contributes to the variation of static TSEPs and, hence, the variation of TSPEs may indicate the likelihood of failure; however it does not indicate necessarily the presence of any degradation on the IGBTs. Therefore static parameters are not recommended to be used alone to estimate the presence of degradation. However, there is still no clear understanding on how switching TSEPs can be combined with the static parameters to enhance the accuracy of CM systems and mitigate the adverse influence of external factors and multi-failure mechanisms. As a first step to achieve this goal, this paper analyses the sensitivity of switching parameters of IGBTs to different levels of the dc-bus voltage and load for healthy devices. These curves will be then used as a baseline to assess the presence of failure mechanisms with the CM system discounting the effect of the load variations. The next step of this study will be to show how switching parameters can be combined with static parameters to improve the accuracy of CM systems of power converters for wind turbines.

II. SENSITIVITY ANALYSIS OF SWITCHING PARAMETERS

The sensitivity switching parameters has been experimentally evaluated using the half-bridge circuit shown in Fig. 2. The experiment has been executed in a fixed ambient temperature. The IGBT module under test is VS-50MT060WHTAPBF, featuring a blocking voltage of 600 V and a collector current of 50 A for a $T_j = 109^\circ\text{C}$, which has been tested in healthy mode.

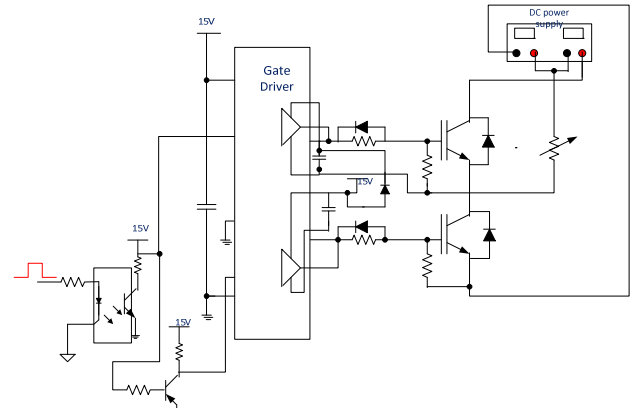


Fig. 2. Schematic of the test-rig.

The tests have been focused on the measurement of the turn-on delay time, turn-on time, turn-off delay time and turn-off time to understand the sensitivity to the variation

of the dc-bus voltage and the collector current. Although the dc-bus voltage is constant at steady-state, there are significant variations every time the wind speed suddenly changes. The collector current instead changes almost continuously, as it is directly related to the power generated by the wind turbine.

The values of the switching parameters can be captured by measuring the instantaneous collector current I_C , the collector-emitter voltage V_{CE} and the gate-emitter voltage V_{GE} and then applying the definition of t_{on} , t_{don} , t_{off} and t_{doff} [10]:

- turn-on delay time: time from 10% of the gate voltage to 10% of collector current;
- turn-on time: time from 10% of the gate voltage to 90% of collector current;
- turn-off delay time: time from 90% of the gate voltage to 10% of the collector voltage;
- turn-off time: time from 90% of the gate voltage to 10% of the collector current.

Fig. 3 and Fig. 4 show an example on how to use the switching waveforms to calculate the switching parameters for a dc-bus voltage of 90 V and a collector current of 10 A.

From a mathematical point of view, the relationship between t_{on} and t_{don} , t_{off} and t_{doff} are described by the

following equations:

$$t_{on} = t_{d,on} + t_r, \quad (1)$$

$$t_{off} = t_{d,off} + t_f, \quad (2)$$

where t_r and t_f are the rise time and falling time, respectively. Additionally, the turn-on time varies linearly with the dc-bus voltage if the temperature is constant, as indicated by the following equation [11]:

$$t_{on} = R_G C_{GC} \left[\frac{V_{dc} - V_F}{V_{GE,on} - V_{miller}(T_j)} \right], \quad (3)$$

where R_G is the gate resistance, C_{GC} is the gate emitter capacitor, V_F is the forward voltage across the diode, $V_{GE,on}$ is the on-state gate-emitter voltage, V_{miller} is the voltage due to the Miller effect, which is temperature dependent. It is necessary to mention that although R_G and $V_{GE,on}$ are constant, C_{GC} and V_{miller} are not constant when V_{dc} is changed, which are mathematically described by following equations[12].

$$V_{miller}(T_j) = V_{th}(T_j) + \frac{I_c}{g_{m,sat}(T_j)}, \quad (4)$$

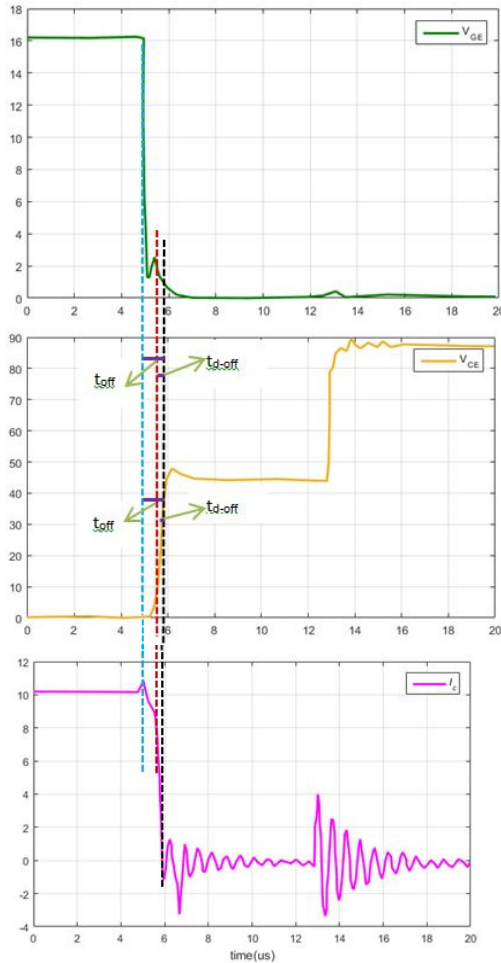


Fig. 3. Turn-off delay time and turn-off time of the IGBT in healthy mode.

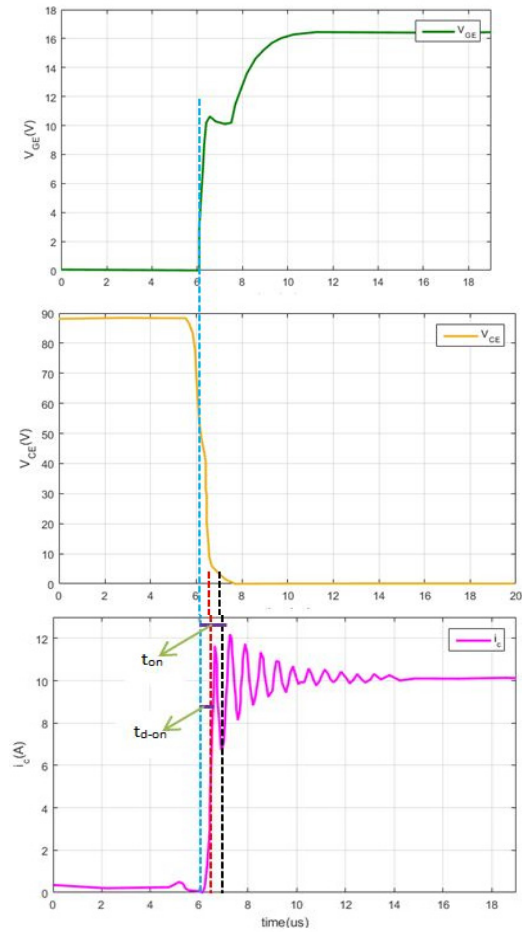


Fig. 4. Turn-on delay time and turn-on time of the IGBT in healthy mode.

$$g_{m,sat}(T_j) = \frac{dI_{C,sat}}{dV_{GE}} = 2K_c[V_{GE} - V_{th}(T_j)], \quad (5)$$

where $g_{m,sat}$ is the trans-conductance for the collector current I_C , V_{th} is the gate bias voltage creating a channel for the current from collector to emitter.

Based on (4), when the dc-bus voltage increases V_{miller} increases and C_{GC} decreases, as indicated by (6) and (7), as suggested in [12]:

$$V_{GE} = \Delta V_{dc} \times \left(1 - e^{-\frac{t}{\tau}}\right), \quad (6)$$

$$\tau = (R_{G,ext} + R_{G,int}) \times C_{GE}$$

$$t_{on} = \tau \log\left(1 - \frac{V_{GE,th}}{\Delta V_{dc}}\right), \quad (7)$$

where $R_{G,int}$ is internal gate resistor, $R_{G,ext}$ is the external gate resistor and C_{GE} is the gate emitter capacitor, which varies with the dc-bus voltage.

When an IGBT is turned on, the gate current charges the gate-emitter capacitor, which is formed by the gate-oxide capacitor and the junction capacitor. The gate-oxide capacitance can be considered constant, as long as gate-emitter voltage and temperature are constant. The junction capacitance is instead affected by the collector-emitter voltage as the depletion region becomes wider with the decrease of the voltage across the IGBT [14]. The expansion of the region causes an increase of this capacitance and, hence, a prolongation of the turn-on time of the IGBT [15]. In other words, the junction capacitance has a negative correlation with the collector-emitter voltage and, hence, an increase of the dc-bus voltage leads

to a decrease of $t_{d,on}$ and t_{on} .

The turn-off time has instead a more significant variation with the load, as shown by the following equation:

$$t_{off} = R_G C_{ISS} \log\left[\frac{I_C}{g_{m,sat}(T_j) - V_{th}(T_j)} + 1\right], \quad (8)$$

where C_{ISS} is the input capacitance, R_G is gate resistance, which are constant. V_{th} is the threshold voltage and $g_{m,sat}$ is trans-conductance, which are both temperature dependent. Eq (6) illustrates that the trend variation of t_{off} to the load variation is not linear and it is relevant to the variation of $g_{m,sat}$ and V_{th} as well.

Both (3) and (8) show that switching parameters have a dependency to T_j variations in healthy mode. However, further investigations are needed to obtain a trend variation of switching parameters in presence of thermal stresses and failure mechanisms, which might be useful to use the switching parameters as TSEPs for failure detection.

Fig. 4a and Fig. 4b show the results of the experiments carried out on the test rig. The curves with variable dc-bus have been evaluated for a constant load resistance of 102 Ω , while the curves with variable load resistance have been evaluated with a constant dc-bus voltage of 50 V.

Fig. 5a illustrates that an increase of the dc-bus voltage causes a reduction of the turn-on time. Fig. 5b shows that the turn-on switching parameters have a negative correlation with the load resistance and, hence, a positive correlation with the collector current I_C .

The correlation between turn-off time, dc-bus voltage and load resistance are shown in Fig. 6a and Fig. 6b, respectively. Fig. 6a reveals that an increase of the dc-bus voltage causes an increase of both turn-off time and

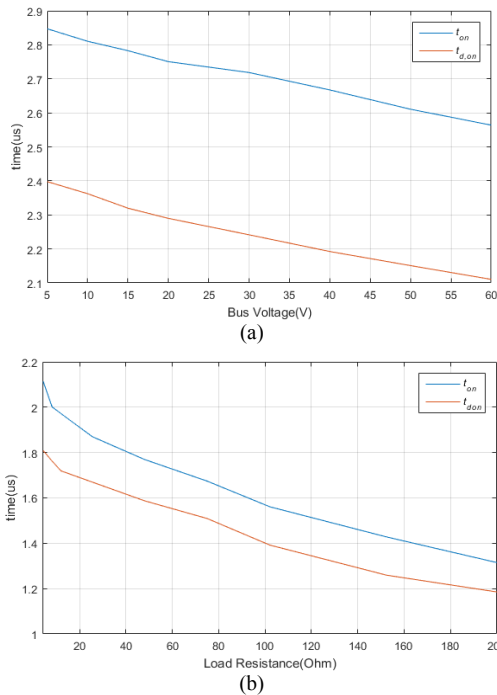


Fig. 5. Variation of IGBT on-time for different dc-bus voltages (a) and loads (b).

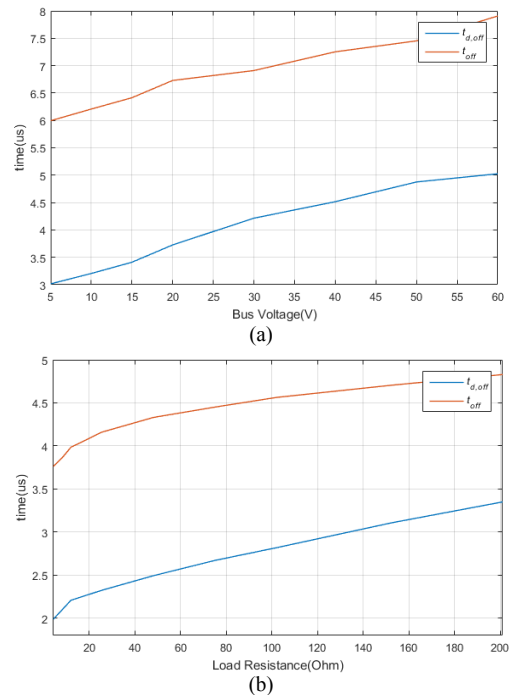


Fig. 6. Variation of IGBT off-time for different dc-bus voltages (a) and loads (b).

turn-off delay time. Fig. 6b shows instead a positive correlation between the load resistance and the turn-off switching characteristics, i.e. a positive correlation with the collector current I_C .

III. SENSITIVITY ANALYSIS

Using the experimental curves of Fig. 5 and Fig. 6, the sensitivity of switching parameters to variation of the dc-bus voltage and the load resistance has been found, as shown in Tab. II and Tab. III, respectively. In particular, these tables show the minimum, average and maximum sensitivity, as the curves are not linear and the sensitivities are not constant. The sensitivities have been calculated as the first derivative of the fitting curves interpolating the data shown in Fig. 5 and Fig. 6.

With reference to Tab. II, it is shown that t_{on} and t_{off} are much more sensitive to variations of the dc-bus voltage than $t_{d,on}$ and $t_{d,off}$ with a factor of 10. However, their sensitivities do not change significantly in the whole range of variation. Additionally, t_{on} is slightly more sensitive than t_{off} in the whole range of variation. Similarly, $t_{d,on}$ is slightly more sensitive than $t_{d,off}$ in the whole range of variation.

With reference to Tab. III, it is shown that t_{off} is the most sensitive to variations of the load with a factor of 2. Also its sensitivity changes substantially in the whole range of variation. The switching times $t_{d,on}$ and $t_{d,off}$ show similar sensitivities for the whole range of variation. Finally, t_{on} is the least sensitive parameter and it has also a change of sensitivity slightly higher than $t_{d,on}$ and $t_{d,off}$.

TABLE II

Sensitivity of switching parameters to the variation of dc-bus voltage

Switching parameter	Minimum Sensitivity [$\mu\text{s/V}$]	Average Sensitivity [$\mu\text{s/V}$]	Maximum Sensitivity [$\mu\text{s/V}$]
t_{on}	0.034	0.039	0.041
$t_{d,on}$	0.005	0.012	0.016
t_{off}	0.031	0.032	0.035
$t_{d,off}$	0.004	0.005	0.006

TABLE III

Sensitivity of switching parameters to the variation of load resistance

Switching parameter	Minimum Sensitivity [$\mu\text{s/Ohm}$]	Average Sensitivity [$\mu\text{s/Ohm}$]	Maximum Sensitivity [$\mu\text{s/Ohm}$]
t_{on}	0.002	0.007	0.012
$t_{d,on}$	0.003	0.019	0.029
t_{off}	0.005	0.018	0.030
$t_{d,off}$	0.002	0.015	0.026

IV. CONCLUSION

Advanced condition monitoring algorithms for the semiconductor devices of power converters for wind turbines require an accurate tracking of the junction temperature, as the operating condition are continually changing due to the variation of the wind speed and the atmospheric conditions. The junction temperature of the IGBTs can be estimated from the measurement of thermal sensitive electrical parameters, which allows to

incorporate the effects of multiple failures discounting the bias due to wind speed variations. Switching parameters are promising to increase the accuracy of junction temperature estimation, but their efficacy has not been completely clarified. This paper contributes to this problem by analysis experimentally the sensitivity of the switching parameters to the variation of the dc-bus voltage and the load. The results reveal a higher sensitivity of the turn-on switching parameters to the dc-bus voltage and a higher sensitivity of the turn-off switching parameters to the load. Therefore, by knowing the variation in healthy mode, it is possible to use these results to remove the bias due to normal operations of IGBTs and use the residual value to evaluate the presence of degradation effects.

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