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THERMAL ANALYSIS OF WATER COOLED POWER CONVERTERS USED BY WIND TURBINE

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Abstract. *Wind energy is one of the most promising renewable sources to generate electricity worldwide and its market share has been growing continuously. In this scenario, the installation of wind turbines with increasing capacities also increases the heat losses, affecting directly the performance of the power converters. The purpose of this work is to investigate the heat losses and the temperature distribution of IGBT modules applied in a water-cooled power converter of 5 MW wind turbine. A time-dependent physical model considering a mixed equivalent thermal circuit is proposed. Real devices data is taken into account as input variable. The results indicated a junction temperature far from the maximum temperature of semiconductor devices, confirming the suitability of the suggested cooling method, even for a low flow rate.*

Keywords: *Heat sink, IGBT module, Power losses, Junction temperature, Wind turbine*

1. INTRODUCTION

For the last decade, the wind power is leading the renewable energy generation and has good perspectives to expand its facilities. Large capacity offshore wind farms are being promoted worldwide, and in these installations, wind turbines above 6 MW power capacity have become a trend. "Larger turbines reduce the power generation cost and increase the total power generation capacity of the site" (Furuse et al., 2016).

According to Sheng et al. (2015), about 5% of the power generated by wind turbines is lost through waste heat and the main heat-generating components are gear box, power converter and generator. The heat produced by different components of wind turbine rises significantly with the increase of the unit capacity of these plants. In MW offshore wind turbines, direct-driven system is considered a promising alternative. Therefore, in these projects, power converters and generators are the components that have the most significant losses. In the literature, many papers handle about cooling systems for wind turbine generators, for example Furuse et al. (2016), Alexandrova et al. (2014) and Stautner et al. (2013), but there is a lack of works dealing with thermal generation and control of the power converter.

Semiconductor devices such as the insulated gate bipolar transistor (IGBT) module are key components at electrical and thermal design of power converters. In general, the module is consisted of the IGBT and diode chips, the NTC (negative temperature coefficient) thermistor, the direct copper bonded (DCB) substrate, the solder, the base plate and the heat sink (air- or water-cooled), as shown in Figure 1.

The performance of the IGBT module is affected by its operating temperature (so called junction temperature), thus, the module should work at lower temperatures to maintain the fast switching speed and good reliability. Several works related to thermal generation in semiconductors, especially in IGBT modules, can be found in the literature. Ma et al. (2015) developed a complete loss and thermal model to estimate the junction temperature behavior of a popular two-level voltage source converter (2L-VSC) used in wind power applications. That work takes into account not only the electrical loading but also the device rating as input variables. The proposed model is well agreed by experimental tests and FEM simulations.

This work aims to study the thermal losses and the temperature distribution of IGBT modules used in a DC-AC power converter (inverter) of a 5 MW wind turbine. In this approach, a time-dependent physical model is performed to describe the junction temperature behavior. In addition, this model takes into account real device data of manufacturer's datasheets to perform the calculation. This work was motivated aiming to meet the demand of a project proposed by Petrobras S.A., recently contracted with UFSC.

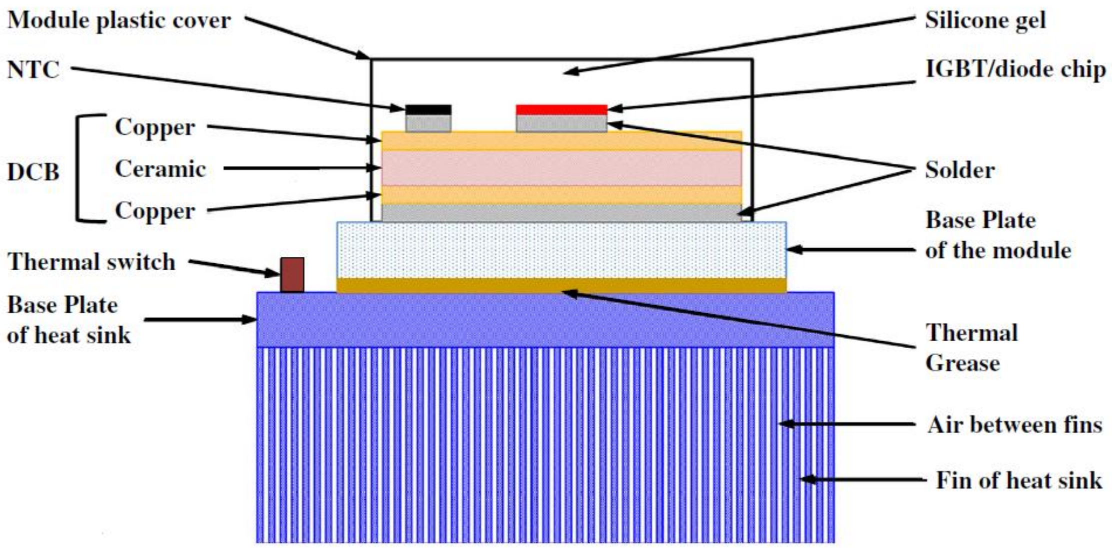

Figure 1. Cross-sectional view of the packaging associated to IGBT module (Han and Jeong, 2016)

2. METHODOLOGY

The calculations were performed considering a case study investigated by Roshanfekr et al. (2014). This work presents the efficiency evaluation of a 5 MW wind turbine powered by two different permanent magnet synchronous generators (PMSG) with medium and low rated voltage (4.8 and 1.3 kV). For each generator, three DC-link voltage are considered. The chosen case study has a 4.8 kV (5 MW/6.2 MVA) machine and DC-link voltage of 8.4 kV with switching frequency of 2 kHz. The wind turbine works at rated power.

The methodology for investigation of thermal behavior in IGBT modules is divided in two topics: the power loss estimation and the thermal model.

2.1 Power losses

The power loss for the semiconductor devices is composed of two parts: conduction loss and switching loss. The conduction heat losses occur when a semiconductor is conducting current, as consequence of Joule effect in the device. Switching heat losses occur each time the switch turns ON-OFF and vice versa.

Preliminary calculations of electric parameters of the converter were performed and the results are found in Appendix. After estimating the voltage and current behavior, a steady-state analysis of the thermal losses was considered. The time-dependent losses was estimated using the duty ratio for transistors and diodes employed in the inverter. A graph showing the duty ratio in function of the time for these devices is just reported by Ma et al. (2015).

The conduction losses on IGBT and diode are here calculated as

$$P_{\text{condT}} = V_{\text{CE0}} \cdot \left(\frac{1}{2\pi} + \frac{M \cos\varphi}{8} \right) \hat{I} + R_{CE} \cdot \left(\left(\sqrt{\frac{1}{8} + \frac{M \cos\varphi}{3\pi}} \right) \hat{I} \right)^2 \tag{1}$$

$$P_{\text{condD}} = V_{F0} \cdot \left(\frac{1}{2\pi} - \frac{M \cos\varphi}{8} \right) \hat{I} + R_{F} \cdot \left(\left(\sqrt{\frac{1}{8} - \frac{M \cos\varphi}{3\pi}} \right) \hat{I} \right)^2 \tag{2}$$

where $V_{\text{CE0/F0}}$ is the voltage drop of transistor/diode when conducting, $R_{\text{CE/F}}$ is the semiconductor resistive value, $\hat{I}$ is the peak value of output current , M is the modulation index and cosφ is the power factor.

The switching losses in IGBT module are calculated by

$$P_{SW} = f_s \cdot \left(E_{sw\_on} + E_{sw\_off}\right) \cdot \left(\frac{1}{\pi}\right) \cdot \left(\frac{\hat{I}}{n_p \hat{I}_{ref}}\right) \cdot \left(\frac{V_{dc}}{n_s V_{ref}}\right)^{1.35} \tag{3}$$

$$P_{rr} = f_s \cdot E_{rr} \cdot \left(\frac{\sqrt{2}}{\pi}\right) \cdot \left(\frac{\hat{I}}{n_p \hat{I}_{ref} \sqrt{2}}\right)^{0.6} \cdot \left(\frac{V_{dc}}{n_s V_{ref}}\right)^{0.6} \tag{4}$$

where E_{sw_on}, E_{sw_off} and E_{rr} are the average switching energies of transistor (on and off) and diode, respectively, f_s is the switching frequency of converter, V_{dc} is the DC-link voltage, V_{ref} and I_{ref} are the reference values of voltage and current from IGBT module, n_p and n_s are the numbers of modules in parallel and in series, respectively.

The voltage drop, the resistive values and the switching energies were acquired from the 1.7 kV 2400 A IGBT module datasheet (ABB HiPak, 2014), as previously considered by Roshanfekr et al. (2014).

2.2 Thermal model

In order to estimate the junction temperature in power semiconductor devices, equivalent thermal circuits are considered. These circuits aim to obtain the equivalent thermal resistance R_{th}, in case of stationary analysis (Fig. 3a), or the equivalent thermal impedance Z_{th}, in case of transient analysis (Fig. 3b). Approaches using thermal resistance models are simplier and take average values as input data considering steady-state conditions. In these cases, only average temperatures are found.

For problems with time-dependent boundary conditions, thermal impedance models should be taken into account. In this way, a time-based solution can be obtained, as shown in Fig. 2.

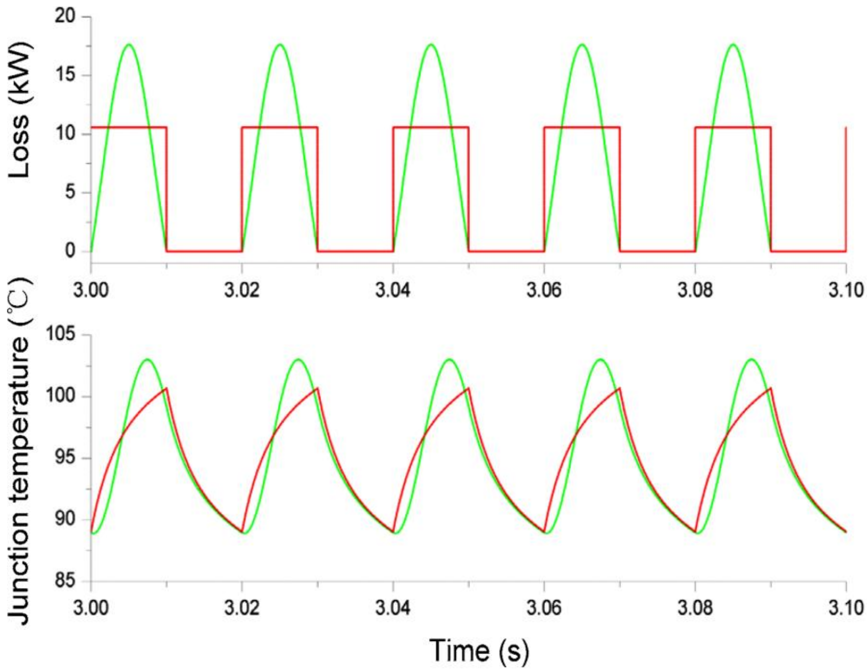

Figure 2. Approaches for heat losses and corresponding junction temperature: (a) actual - green lines; (b) approximate - red lines (Ma et al., 2015).

Normally, the thermal impedance of semiconductors devices is modeled by sets of RC lumps, which are composed of a thermal resistance R_{th} and a thermal capacitance C_{th} in parallel. The junction to case thermal impedance $Z_{th(j-c)}$ is calculated using information available in devices' datasheets. The modeling of the others thermal impedances involves many uncertainties, relatively complicated to predict them.

These impedances own greater thermal capacitance when compared to the junction to case. Therefore, the temperature fluctuation in these parts are less significant than the first one. In this work, a mixed equivalent thermal circuit is proposed as shown in Fig. 3(c). Due to these uncertainties and the high capacitances, equivalent resistances can be used.

To estimate the time-dependent junction temperature, the thermal model considers a simple approach of transient conduction, termed the lumped capacitance method, as described by Bergman et al. (2014). The junction temperature in function of the time is calculated as

$$\frac{T_j(t)-T_c}{T_i-T_c}=\mathbf{exp}\left(-\frac{t}{\tau}\right)+\frac{\dot{E}_g\cdot R_{j-c}}{T_i-T_c}\left[1-\mathbf{exp}\left(-\frac{t}{\tau}\right)\right] \tag{5}$$

where T_c is the case temperature, T_i is the initial temperature (in calculations, the initial temperature is equal to the temperature of the previous iteration), τ is the time constant of the RC lump equal to the resistance times the capacitance and E_g is the volumetric heat generation.

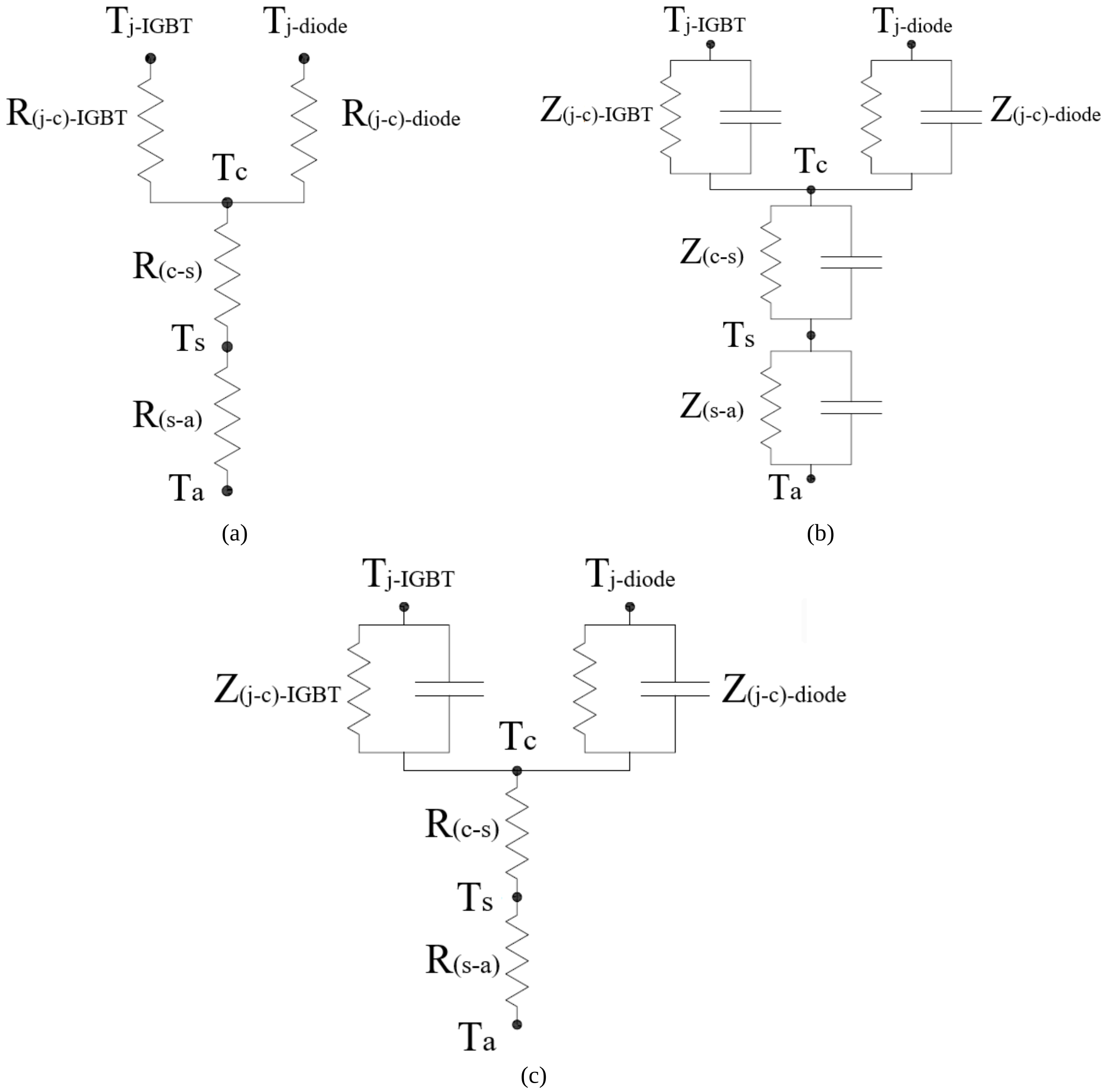

Figure 3. Equivalent thermal circuit approaches. (a) Model of resistances; (b) Model of impedances; (c) Mixed thermal circuit

The resistances and time constants proposed by Eq. (5) are informed in the device datasheet (ABB HiPak, 2014) as a summation of 4 analytical functions as it follows

$$Z_{\text{th(j-c)}}(t) = \sum_{i=1}^{4} R_{\text{i}}(1 - e^{-t/\tau_i}) \tag{6}$$

In this work, it was considered average values for thermal resistance and time constant. These values were obtained through the simple approach

$$R_{th}(1 - e^{-t/\tau}) = \sum_{i=1}^{4} R_{\text{i}}(1 - e^{-t/\tau_i}) \tag{7}$$

So, when the time approaches infinity,

$$R_{th} = \sum_{i=1}^{4} R_{\text{i}} \tag{8}$$

The time constant considered the simplification

$$\mathbf{exp}(\tau) = \sum_{i=1}^{4} \mathbf{exp}(\tau_i) \tag{9}$$

The case to sink resistance $R_{\text{th(c-s)}}$ was calculated considering data provided by GE Advanced Materials (2005). This resistance is calculated as it follows

$$R_{th(c-s)} = \frac{L}{kA} \tag{10}$$

where L is the thickness of thermal grease, k is its thermal conductivity and A is the IGBT module base area. For the heat dissipation, a water cooled heat sink was considered. The model KW 188 Style 5 from DAU GmbH & Co (2011) was chosen. Thermal information, such as the thermal resistance per water flow is available in catalog.

3. RESULTS AND DISCUSSIONS

The results section of this work considers 2 different analyzes: (i) a simplified stationary analysis that considers an equivalent circuit of thermal resistances and losses in steady-state and (ii) a time-dependent analysis that considers the proposal of the mixed thermal circuit and time-dependent losses.

3.1 Steady-state analysis

This preliminary analysis has considered the thermal losses calculated by Eqs. (1) – (4) individually in each chip (transistor and diode). The results of thermal losses is shown in Tab. 1.

Table 1. Thermal losses for 5 MW wind turbine converter (60 IGBT modules)

Thermal losses	**[W]**
Conduction losses – IGBT	436.0
Conduction losses – Diode	79.25
Switching losses – IGBT	431.7
Switching losses – Diode	307.8
Conduction losses – Converter	30916
Switching losses – Converter	44367
Total losses	75283

The Tab. 2 shows the results of the preliminary analysis, based in the first configuration shown in Fig 3(a), considering an equivalent thermal resistance model. The $T_{\text{j,equivalent}}$ was calculated considering a parallel equivalent resistance $R_{\text{th(j-c)}}$. The cooling fluid temperature is 40 ºC.

According to the results of steady-state analysis, the employed cooling method is suitable to the IGBT module working in the suggested boundary conditions, even considering a low flow rate. The highest junction temperature for 5 l/min (found in IGBT) is about 65 ºC, significantly far from the maximum operating temperature for the device (125 ºC).

Table 2. Preliminary temperature distribution for case study considering several fluid flow in the heat sink

Flow [l/min]	T_s [ºC]	T_c [ºC]	**$T_{j,IGBT}$ [ºC]**	**$T_{j,Diode}$ [ºC]**	$T_{j,equivalent}$ [ºC]
5	53.30	58.92	**64.99**	**63.56**	64.46
10	50.67	56.28	**62.35**	**60.92**	61.83
15	49.41	55.03	**61.10**	**59.67**	60.57
20	48.53	54.15	**60.22**	**58.79**	59.69
25	47.90	53.52	**59.59**	**58.16**	59.07

In this case, the junction temperatures of the IGBT and the diode were very close and the equivalent temperature represents well the behavior of both chips. This is because the ratio between the thermal losses from IGBT and diode is very close to the ratio between the resistances of these devices. However, this phenomenon does not occur in all converter scenarios. Therefore, it is important to perform the thermal calculations for the IGBT and the diode separately.

3.2 Time-dependent temperature estimation

The results of the time-dependent simulation for IGBT and Diode junction temperatures are shown in Figs. 4 and 5. In this simulation, a cooling fluid flow rate equal to 5 l / min was considered, as according to the steady-state analysis, a low flow rate is already sufficient to cool the components. The cooling fluid temperature is 40 ºC. The initial transient behavior was disregarded, as the simplifications of the proposed model do not present good assumptions to perform the system simulation at the moment of the converter starting.

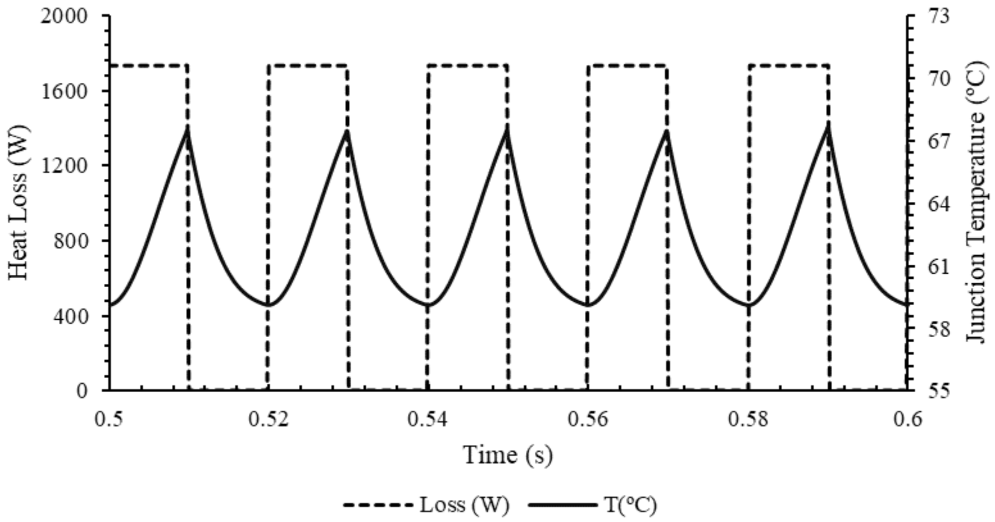

Figure 4. Time-dependent heat losses and junction temperature of IGBT.

According to the simulations, the peak value of the IGBT junction temperature is equal to 67.7 ºC, while the minimum value is 59.1 ºC. Thus, the junction temperature fluctuation is 8.6 ºC and occurs in a period of 20 milliseconds. For the diode, the maximum temperature is equal to 65.5 ºC and its minimum value is 59.1 ºC. The junction temperature fluctuation is, in this case, equal to 6.4 ºC.

The differences between the junction temperatures predicted by the steady-state analysis and the maximum temperatures of the time-dependent model are very small. For the IGBT, this difference was about 2.7 ºC, while for the diode it was around 2 ºC. This shows that the simplified stationary analysis already has a good accuracy in estimating the junction temperature in the converters addressed in this study.

Both analyzes showed junction temperatures very far from the maximum operating temperature of the semiconductors employed in IGBT modules. Therefore, the models consider that the proposed cooling system is sufficient to remove the thermal power generated by the converters in the case study. However, the time-dependent analysis showed a significant junction temperature fluctuation for a short period, which can cause long-term problems by thermal fatigue in the modules. Analysis of cyclical stresses due to temperature is recommended.

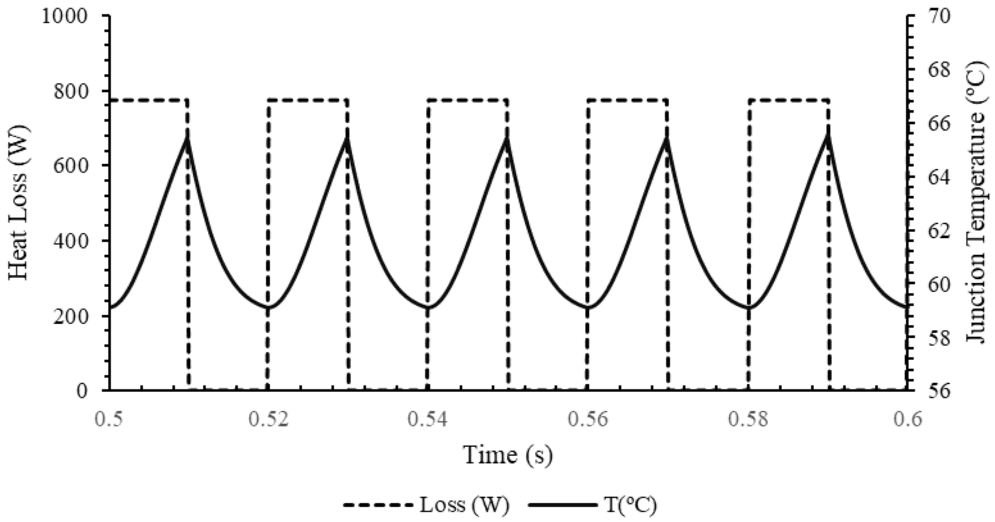

Figure 5. Time-dependent heat losses and junction temperature of diode.

4. CONCLUSIONS

Power converters are key-components in wind energy conversion systems. The thermal management of the semiconductor devices is a critical design topic and it is closely related to the cost, efficiency and reliability of these systems. The main parameter of the thermal control in converters is the junction temperature. In this paper, the thermal behavior of a two-level back-to-back converter of a 5 MW wind turbine is investigated.

Initially, a simplified stationary analysis was performed. Then, a mixed thermal circuit is proposed, in order to predict the junction temperature of IGBTs and diodes. This model combines a thermal circuit of resistances and impedances. The losses were calculated considering steady-state equations and then, the duty cycle was considered to obtain the time-dependent heat generation. The lumped capacitance method was used to solve the problem of time-based temperature estimation. This work took into account real devices data to perform the simulations, such as, datasheets of IGBT modules, thermal grease and heat sinks.

The results showed a low junction temperature for IGBT and diode, even working with low cooling flow rate. The difference between the average temperatures of stationary analysis and the peak value of the proposed method was very close. However, the time-dependent analysis results showed a considerable junction temperature fluctuation, which can prejudice the long-term equipment reliability.

For further works, the authors recommend the simulation of thermal fatigue to indicate how the junction temperature fluctuation can compromise the working of these devices. Numerical simulations and experimental tests are suggested to validate the results of the analytical simulations.

5. ACKNOWLEDGMENTS

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7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

APPENDIX

Table A1. Calculated electric parameters of the converter

Parameter	**Value**
Power factor	0.80943
RMS line voltage - Generator	4800 V
RMS current - Generator	743 A
RMS current - IGBT	476 A
Average current – IGBT	266 A
Voltage drop - IGBT	1.12 V
Resistance - IGBT	0.606 mΩ
RMS current - Diode	222 A
Average current – Diode	68 A
Voltage drop - Diode	0.94 V
Resistance - IGBT	0.313 mΩ
Modules in parallel	1
Modules in series	10

Table A2. Thermal parameters of the simulation

Parameter	**Value**
Resistance junction to case - IGBT	7.001 K/kW
Time constant - IGBT	202.9 ms
Resistance junction to case - Diode	12.065 K/kW
Time constant - IGBT	210 ms
Resistance case to sink	4.475 K/kW
Resistance sink to ambient – 5 l/min	10.6 K/kW
Resistance sink to ambient – 10 l/min	8.5 K/kW
Resistance sink to ambient – 15 l/min	7.5 K/kW
Resistance sink to ambient – 20 l/min	6.8 K/kW
Resistance sink to ambient – 25 l/min	6.3 K/kW