Mutual and self-aging effects of power semiconductors on the thermal behaviour of DC-DC boost power converter

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ABSTRACT

A shift from conventional to renewable resources has increased the importance of power exploitation via power converters. In this respect, estimating an accurate useful lifetime of power converters plays a major role for the manufacturers and users. This paper touches the issues related to the self and the mutual degradation effects of the power semiconductors such as IGBT and diode on each other in a conventional DC-DC boost converter. By IGBT and diode aging, junction-case thermal resistance, IGBT collector-emitter voltage and diode forward voltage have been increased leading to thermal operating point changes. These changes have a significant effect on the degradation and the useful lifetime of devices. It is shown that by either IGBT or diode aging due to the thermo-mechanical fatigue, an increase in the IGBT or diode junction temperature has been occurred. The results reveal the importance of mutual- and self-aging effects on the reliability assessment. An experimental validation has been also performed via a prototype setup of 200/400V 3000W DC-DC boost converter.

1. Introduction

Reliability assessment (RA) plays a crucial part in the power converter’s design and hence considerable number of studies have been recently undertaken [1]. Opinions on the useful lifetime evaluation (ULE) are mainly divided into mathematical and physics-of-failure (PoF) based methods [2]. Regarding the limitations of mathematical method [3], PoF has been extensively used in RA [4].

Among all the power components, capacitors and power semiconductors have a significant share in the power converter’s failure due to the dielectric loss and the thermo mechanical fatigue failure mechanism, respectively [5, 6]. Recently, researchers have been motivated to consider the effects of self and mutual degradations in the RA [7]. Since thermal and electrical operating points (TOPs and EOPs) of the power converters are strongly correlated to the status of power components (see Fig. 1), considering the effects of self and mutual degradations in RA of the power converters seems to be necessary. In this figure, the devices of a conventional boost converter are considered. Their related waveforms and temperatures can be estimated by using electrical, loss and thermal models. These models are fed by electrical and thermal parameters and by working conditions of the converter. The waveforms and temperatures can then be used to estimate the aging status of every device. However, the aging of one device will induce a deviation of its electrical and/or thermal parameters. Thus, due to the electrical and thermal coupling in the converter, the deviation of one electrical or one thermal parameter of one device will be able to affect the waveforms and temperatures of the others which, in turn, will impact their own aging status.

Accordingly, consideration of operating point deviations due to the components’ degradation is paramount of importance which on previous studies are still lacking. This paper supports the claim of self and mutual degradations effects on the ULE of power semiconductors (IGBT and diode) in both thermal and electrical environments without going into much details of other components’ degradations. The remainder of paper is organized as follows. Electrical and thermal modeling of the considered DC-DC converter is discussed in Section 2. While Section 3 deals with experimental procedure, Section 4 focuses on the experimental results and their validations by modeling and simulations. Finally, a brief conclusion is drawn in Section 5.

2. Electro-thermal modeling of DC-DC boost converter

A conventional 200/400V and 3000W DC-DC boost converter is considered as a case study (see also Table. 1). For the main switches, 600V-15A IGBT and diode of Infineon, namely IKP15N60T, are selected. With regard to the critical failure mechanism, electrical modeling, power loss calculation and thermal modeling have to be considered and performed. Employing EOP of the power converter, one can
calculate power loss of devices (heat sources). Then it is possible to estimate the junction temperature of power semiconductors by using thermal modeling. Based on the junction temperature and constants of fatigue life time model (Goffin-Manson), ULE of each device can be estimated.

For considering the mutual- and self-degradations effects on the ULE of IGBT and diode following four different cases have been taken into account.

Case I, in this case all the devices including IGBT and diode are new and have their own nominal parameters.

Case II, in this case (aged case) all the devices including IGBT and diode have been degraded and reached to their failure criterion. The failure criterion is defined by 20% increase in both junction-case thermal resistance of IGBT increases by 20\% and its collector-emitter voltage increases by 20\% \cite{8, 9}. Based on this definition of the failure criterion, after complete aging of IGBT and the diode, the junction temperatures of IGBT and the diode have been reached to their maximum allowable temperatures, namely 175 °C.

Case III, in this case IGBT has been electrically and thermally degraded while all other components have remained unchanged. It assumes that junction to case thermal resistance of IGBT increases by 20\% and its collector-emitter voltage increases by 20\% \cite{8, 9}.

Case IV, in this case the diode has been electrically and thermally degraded while all other components have remained unchanged. It assumes that junction to case thermal resistance of diode increases by 20\% and its forward voltage increases by 20\% \cite{8, 9}.

2.1. Electrical modeling

Although, there are numerous methods for electrical modeling of a conventional DC-DC boost converter, a method capable of obtaining precise voltage/current ripples has to be applied due to the necessity of power loss calculation’s accuracy. Therefore, time invariant multi frequency (TIMF) model has been selected \cite{10}. This approach has many advantages including easy construction, capable of considering feedback and accurate ripple estimation.

2.2. Power loss calculation

For obtaining junction temperature of devices, an accurate power loss calculation is needed. In this study standard power loss calculation has been employed based on Infinenon proposal \cite{11}. The power losses include conducting, turn-off and turn-on switching losses. The required parameters for power loss calculation can be easily extracted from IKP15N60T datasheet. The power losses of semiconductors are temperature dependent and therefore the power losses must be estimated by iterative algorithm till they are converged.

2.3. Thermal modeling

Generally, there are two types of thermal modeling including transient and steady state thermal models. Complete steady state thermal modeling has many advantages including its simplicity and its fast response. In addition, the transient thermal modeling is more accurate in estimating of real temperature variations with time at the expense of losing simplicity and fast pace of calculation \cite{12}. However, this accuracy can also be achieved in the complete steady state thermal modeling depending on the dynamic of mission profile (application dependency). Providing that the time response of the considered system is faster than the dynamic of mission profile, the complete steady state modeling seems to be sufficient which is supposed to the case in this study.

Accordingly, a complete steady state thermal model considering the thermal coupling effects will be employed and applied to our problem. Fig. 2 depicts the physical structure of an IGBT and a diode mounted on a common heat sink. Regarding Fig. 2, the dissipation in one device will change the temperature of the other, which induces a thermal coupling in the system. A conventional heat sink, namely trapezoidal plate-fin heat sink, has been designed and used in the forced convection heat transfer conditions. Dimensions of the heat sink and thermal values are listed in Table 2. Based on the power losses (see Section 2.2), the maximum allowable junction temperature (170 °C) and the ambient temperature (40 °C), one can calculate the thermal resistance of the heat sink equaling 1.16 °C/W. For achieving this thermal resistance, forced convection heat transfer coefficient of 47.6 W.m \(^{-2}.K^{-1}\) and air velocity of 8 m/s is required in the channels.

In the complete steady state thermal modeling, a thermal matrix

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>(V_i)</td>
<td>200 V</td>
<td>(V_{ac})</td>
<td>400 V</td>
</tr>
<tr>
<td>(P_a)</td>
<td>3000 W</td>
<td>(R)</td>
<td>53.34 Ohm</td>
</tr>
<tr>
<td>(L)</td>
<td>2.50 mH</td>
<td>(r_t)</td>
<td>0.3 Ohm</td>
</tr>
<tr>
<td>C</td>
<td>47 (\mu)F</td>
<td>(r_c)</td>
<td>0.05 Ohm</td>
</tr>
<tr>
<td>(r_D)</td>
<td>0.04 Ohm @(T_j = 175 °C)</td>
<td>(V_{CE0})</td>
<td>1 V @(T_j = 175 °C)</td>
</tr>
<tr>
<td>(r_D)</td>
<td>0.0726 Ohm @(T_j = 175 °C)</td>
<td>(V_{F0})</td>
<td>0.81 V @(T_j = 175 °C)</td>
</tr>
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Fig. 1. Thermal and electrical reliability correlations in a power converter.

Table 2

<table>
<thead>
<tr>
<th>Working conditions and parameters values.</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>(V_i)</td>
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including self and coupling thermal resistances has to be solved after estimating all of its elements by performing finite element analysis (FEA) via ABAQUS environment.

\[
\begin{bmatrix}
R_{IGBT} & R_{Diode} & R_{IGBT-Diode} & R_{Diode-IGBT}
\end{bmatrix}
+ T_{ref}
\]

For obtaining the thermal resistance matrix elements in Eq. (1), one can use superposition theory [13]. For example, by applying a heat source to IGBT (calculated power loss in different cases) and nothing to the diode, \( R_{IGBT} \) and \( R_{Diode-IGBT} \) can be obtained. It is also true vice versa for calculating \( R_{Diode} \) and \( R_{IGBT-Diode} \). Accordingly, one can easily calculate both self and cross coupling thermal resistances. Since thermal resistances of power semiconductors and heat sink are all temperature-dependent, having an accurate thermal modeling, four set of FEA simulations (case I to case IV) have been performed. General and thermal characteristics of the materials constructing the chips and heat sink are listed in Table 3. Ambient temperature was assumed to be 40 °C and forced convection heat transfer of fins were assumed to be 47.6 W·m\(^{-2}\)·K\(^{-1}\). Other boundary conditions are listed in Table 2.

From these simulations, both self and cross coupling thermal resistances have been derived. The thermal resistances are shown in Fig. 3. By increasing power loss the self-thermal resistances have been increased due to the dependency of the thermal conductivities to temperature.

Junction temperatures of IGBT and diode obtained by coupling the loss and thermal models are listed in Table 4. These values have been also validated by experimental procedure discussed in the following...
3. Experimental procedure

In this section thermal modeling and online temperature measurement of the considered DC-DC boost converter have been expressed. As previously defined, four different cases are considered. For cases II to IV, there is a need to have aged IGBTs and diodes. Therefore by an accelerated thermal cycling, IGBTs and diodes for this test have been prepared. Thermal cycling test was based on JESD22-A105C standard [14] and performed for 3 months and 2500 cycles (−40 °C to 170 °C) in a programmable chamber, namely, WTL 34/70 chamber. After these cycles, both IGBTs and diodes have reached the considered failure criteria both thermally and electrically. While the voltages of new IGBT and new diode at the nominal current are 1.51 V and 1.43 V respectively, IGBT collector-emitter voltage and diode forward voltages reached to 1.81 V and 1.72 V, respectively when they have been aged. Junction-case thermal resistances reached to 1.4 and 2.3 °C/W for IGBT...
and diode respectively (they are 1.15 and 1.9 °C/W as the new devices respectively).

3.1. Junction temperature estimation

Usually, thermo sensitive electrical parameters (TSEPs) have been employed for indirect measurement of junction temperature [15]. In this study, the collector-emitter (forward) voltage of IGBT (diode) under low bias current has been used for indirect junction temperature measurement. For this reason, a constant current of 22.5 mA is injected to the device at the instant of $T_j$ measurement and simultaneously collector-emitter (forward) voltage of IGBT (diode) has been measured by a data acquisition (HBM-Gen$^\text{TM}$). This current source value is selected as a trade-off between the measurement accuracy and the self-heating limitation. Fig. 4 demonstrates collector-emitter (forward) voltage of IGBT (diode) as a function of the temperature with 22.5 mA current injection.

3.2. Thermal characterization

In this section, some experimental tests had been performed for validating the thermal resistance matrix (1) by using indirect junction temperature measurement based on the following equation,

$$R_{th} = \frac{T_j - T_{ref}}{P_{DUT}}$$

where $T_j$ and $T_{ref}$ are junction temperature and reference temperature in terms of °C and $P_{DUT}$ is the power loss of the device under test (DUT) which can be either IGBT or diode power loss.

In this experiment, IGBT and diode mounted on the common heat sink were used to obtain the thermal behaviour of the system as shown in Fig. 2. This test had been done in four different cases as discussed in Section 2 and each case fell into two categories, based on the superposition theory. As shown in Fig. 5a, in each case, a power loss equaling its calculated power loss (Section 2.2) was separately applied to the IGBT or diode and then $T_{j-IGBT}$ and $T_{j-diode}$ were measured based on TSEPs. The period of applying power was selected so that the certain time for thermal transient passed. Since $P_{DUT}, T_{ref}$ and $T_j$ are all determined, one can calculate self and cross coupling resistances (thermal resistance matrix). Fig. 5b demonstrates the circuit schematic and experimental setup for supplying sufficient power to the dies. In $t_{0}$-$t_{meas}$ MOS 1 is OFF while MOS 2 is ON and therefore power current flows through DUT in this period. In the other periods, only MOS 1 is ON and keeps L being charged. Fig. 6 depicts the designed test bench for the thermal characterization of power semiconductors based on the circuit shown in Fig. 5. IGBT and diode have been mounted on the common heat sink as shown in Fig. 2. In case I and based on the simulation, junction temperatures of IGBT and diode have been estimated as

Fig. 7. Collector-Emitter Voltage during measuring period.

Fig. 8. Equipped boost converter, a) schematic, b) switching pattern.

Fig. 9. 200/400 V-3000 W DC-DC boost converter.
142.8 °C and 126 °C, respectively. The fan velocity has been tuned by its feeding voltage adjusting through a DC low voltage power supply. The fan voltage has been adjusted (8.6 V) for achieving 142.8 °C and 126 °C junction temperatures of IGBT and diode respectively and kept fixed during all other cases.

Fig. 7 shows the waveform of $V_{CE}$ in the temperature measurement period. Regarding the impedance change and noises during data acquisition at the beginning of the measuring time and for having an accurate result, an interpolation of $V_{CE}$ was defined as a function of polynomial root square of time [15]. Then an extrapolation has been used to extract the voltage value at $t_{\text{meas}}$. In this case (case II) by using TSEP, one can find that junction temperature of IGBT is 170 °C. Accordingly, thermal resistances of the circuit would be obtained. Maximum error between the experimental and simulation result is limited to the 10%, in case IV. The experiments thoroughly validated the simulation results with the very small errors as shown in Fig. 3 as error bars.

3.3. Online measurement of junction temperature of IGBT and diode in the conventional boost converter

The mutual- and self-degradation effects of power semiconductors on each other’s useful lifetime in a conventional DC-DC boost converter have been studied in this section. Accordingly, a conventional DC-DC boost converter with some auxiliary circuits as shown in Fig. 8a has been designed and experimentally implemented with the specification listed in Table 1. In addition to the main components, two high power MOSFET in series with two power diodes ($S_2$ and $S_3$), two low power switches ($S_a$ and $S_b$), two constant current sources (designed by series combination of MOSFET and resistor) and two complementary active voltage clamp circuit employing P- and N-channel MOSFETs as described in [16] have been used. Switching pattern of active switches is depicted in Fig. 8b. $S_3$ works as an active freewheeling circuit for instantly inductor energy damping. Fig. 9 also demonstrates the associated experimental setup. At the instant of IGBT $V_{CE}$ measurement, the system with 5 μs time overlap for inductor switching transition is stopped for 1 ms and in this period (measurement period) low current source (22.5 mA) via $S_a$ is injected to the IGBT. During this period the data acquisition measures and saves collector-emitter voltage of IGBT. Based on the saved data and the algorithm described in the previous subsections, one can easily estimate junction temperature of IGBT through TSEP. During this period output capacitor is in charge of supplying output energy. At the instant of diode forward voltage measurement, converter is stopped working via $S_2$ with again 5 μs time overlap for inductor current transition from main switch to the freewheeling switch. At the same time, IGBT turns off and a low current source (22.5 mA) is injected into the diode via $S_b$. During this period, $V_f$ has been saved through data acquisition. Fan velocity of main power switches (IGBT and diode) has been selected as what explained in the Section 3.2. In this test bench, for all the cases, totally 100 times for IGBT and 100 times for diode junction temperature measurements have been performed. 5 sets of 20 times was considered for each of them. Before measurement starting in each set, power DC-DC converter has worked for 30 min to insure thermal stability of power devices. After that the measurements have been done for 20 times for both IGBT and diode. This procedure was repeated for 5 times. Finally, the junction temperature of IGBT and diode has been estimated by averaging this 100 times. The results are listed in Table 4.

4. Results and discussion

In this section, effects of coupling and self-degradation of IGBT and diode on each other in the practical DC-DC boost converter have been experimentally analysed. Since the most critical failure mechanism of power semiconductors is the thermo mechanical fatigue, junction temperature of IGBT and diode has paramount of importance in their degradation. Accordingly, in these four cases, junction temperatures of IGBT and diode have been experimentally estimated based on the procedure described in the previous section via TSEP and the equipped conventional DC-DC boost converter. The thermal modeling of this converter has been experimentally validated. One can find that experimental results, regarding Table 4, have validated what had been expected in theory and simulation. The calculated and measured junction temperatures of either IGBT or diode have an acceptable maximum error of 3.4 °C (in case I for diode). In case I in which all the components are new, junction temperatures of IGBT and diode are 140.3 and 122.6 °C respectively. In case III in which IGBT is completely degraded, junction temperatures of IGBT and diode are 165.6 and 140.3 °C. In case III in which IGBT is completely degraded, junction temperatures of IGBT and diode are 165.6 and 129.8 °C. One can find that how IGBT aging can affect its junction temperature (25.6 °C increase) leading to the accelerated aging and the useful life time reduction. It is also evident that IGBT aging has a coupling effect on the diode junction temperature by 7.2 °C also leading to the diode accelerated aging. It is also true for diode aging effects on itself and IGBT junction temperatures by 19.3 and 4.8 °C respectively.

5. Conclusion

In this paper, self and coupling thermal influences of power semiconductors of a conventional 200/400 V DC-DC boost converter were analysed. The procedure of thermal modeling was thoroughly discussed. Thermo sensitive electrical parameters were employed for estimating IGBT’s and diode’s junction temperatures as root causes of failure in power semiconductors. It was experimentally shown that either IGBT or diode aging can have self and coupling effects on each other leading to the much more accelerated degradation which has to be considered in reliability assessment.

This present work is the beginning of an ambitious research study to estimate the self- and coupling degradations on the ULE of power
devices in the power converters. In this paper, the sensitivity of self- and coupling parameters’ drifting of IGBT and diode owing to the degradations was studied (see red transparent part in Fig. 10). It was shown that these parameters’ drifting can have significant effects on the thermal operating point of power converter leading to the accelerated degradation. In the future as a continuous work, we will use these analyses for accurate ULE of power converters.

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References