Thermal analysis of MegaDiscaP semiconductor devices

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Summary
This technical report presents a thermal analysis of the MegaDiscaP semiconductor devices. This analysis evaluates the thermal cycling of representative devices in order to estimate the expected lifetime. Simulation results based on manufacturer specifications are presented.

1 Introduction

In order to choose devices capable of operating under the desired conditions, it is necessary to analyze semiconductors characteristics such as: maximum blocking voltage, maximum forward current and safe operating areas (SOA) [1]. These features are generally evaluated from the data provided by the manufacturer and the converter operation range. However, other important characteristics that should be considered are the maximum junction temperature, $T_{j\text{max}}$, and its maximum variation, $\Delta T_{j\text{max}}$. Actually, during the last few years, thermal cycling has become a great concern as regard to IGBT modules reliability. In high power applications, thermal stress leads to mechanical wears generated by different thermal expansion coefficients of the materials used in the IGBT modules construction [2, 3]. Based on the technical information provided by manufacturers and operational characteristics of the converter it is possible to estimate lifetime expectancy of the semiconductor devices.

In order to evaluate the thermal stress applied on the MegaDiscaP IGBT modules, the converter operation will be revisited. Figure 1 shows the MegaDiscaP converter topology that will be used for the Booster injection with Linac 4 operation, where the active filter stage has been omitted for clarity.

![MegaDiscaP converter topology](image)

Figure 1: MegaDiscaP converter topology (active filter stage omitted).
The basic topology is an IGBT-diodes bridge completed with a coupled IGBT-diode stack [4, 5]. This converter is used to generate trapezoidal current pulses, whose main parameters are listed in Table 1.

Table 1: Pulse current parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference current ( (I_{REF}) )</td>
<td>2 kA</td>
</tr>
<tr>
<td>Rise and fall times ( (t_r, t_f) )</td>
<td>1 ms</td>
</tr>
<tr>
<td>Flat top duration ( (t_{FT}) )</td>
<td>5 ms</td>
</tr>
</tbody>
</table>

The operational principle of this topology is summarized as follows:

**Rise time:** The high voltage part of the converter (stage 1) is used to ramp the current up to the flat-top reference current, \( I_{REF} \). Switches \( S_1 \) and \( S_2 \) are turned ON and \( S_4 \) is OFF. Therefore, \( i_1 = i_L \) and, if the load resistance is neglected, the magnet current increases with a slope given by \( V_{C1}/(L_1 + L) \). Hence, the rise time is given by \( t_r = I_{REF} \cdot (L_1 + L)/V_{C1} \).

**Flat top:** When \( i_L \) reaches \( I_{REF} \), the high voltage part (stage 1) is disconnected from the load by the turn off of \( S_1 \) and the low voltage (stage 2) is used instead. This low voltage part is used to control the \( i_1 \) mean current using \( S_4 \) in switch mode operation. Since stage 2 must handle the high load current, a medium switching frequency \( (f_{S4}) \) must be adopted, leading to a low precision current regulation. The active filter stage (which has been omitted) is connected to point A and is used in parallel to stage 2 to obtain the required high precision.

**Fall time:** To decrease the load current, all switches are turned OFF. The energy stored in the load and in the inductor \( L_1 \) returns to the capacitor bank \( C_1 \) through \( D_1 \), \( D_2 \) and \( D_4 \). The current difference between \( i_{L1} \) and \( i_L \), when the active filter is disconnected, flows through \( D_5 \) or \( D_3 \).

The operation mode of the semiconductor devices is summarized as follows:

- \( S_1 \) and \( S_2 \) are used to ramp the current to its maximum value, \( I_{REF} \). \( S_2 \) also carries the flat-top current.
- \( S_4 \) and \( D_4 \) are used to control the current during the flat-top. These devices operate in switch-mode with a medium switching frequency. \( D_4 \) is also used to ramp down the load current.
- \( D_1 \) carries the load current \( i_L \), during the flat-top and fall times.
- \( D_1 \) and \( D_2 \) are used to ramp down the current when all the IGBTs are turned off.

Taking into account the requirements of Table 1 and the magnet load characteristics, the semiconductors maximum ratings using commercial devices are shown in Table 2 [6].

Table 2: Semiconductors maximum ratings

<table>
<thead>
<tr>
<th>Devices</th>
<th>Voltage</th>
<th>Current</th>
<th>Operation frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1, S_2, D_1, D_2 )</td>
<td>( V_{C1} = 2.1 \text{kV} )</td>
<td>( I_{REF} = 2 \text{kA} )</td>
<td>( f_P = 1.1 \text{Hz} )</td>
</tr>
<tr>
<td>( S_4, D_4 )</td>
<td>( V_{C2} = 600 \text{V} )</td>
<td>( I_{REF} = 2 \text{kA} )</td>
<td>( f_{S4} = 10 \text{kHz} )</td>
</tr>
</tbody>
</table>
2 Thermal analysis

In order to evaluate the $\Delta T_{jc,max}$ of different devices, the thermal equivalent network shown in figure 2 is used. This network is composed by individual RC elements that correspond to partial fraction coefficients and have no physical signification. The temperature calculated with this model is referenced to the case temperature, $T_{\text{case}}$. Therefore, $\Delta T_{jc} = T_j - T_{\text{case}}$. The RC time constants are provided by the manufacturer in tabular form. This thermal model (also known as Foster model or pi model) is the most frequently used thermal equivalent circuit even if it has no relation to the real physical structure of the device [7].

![Thermal equivalent network.](image)

Figure 2: Thermal equivalent network.

The electrical power source, $P(t)$, represents the power dissipated in the device including switching losses, conduction losses and recovery losses. $P(t)$ is modeled by different pulses, one for conduction losses and other for switching losses. The conduction pulses have an amplitude $P_c$ and a width $t_c$, while the switching pulses have an amplitude $P_{\text{swON/OFF}}$ and a width $t_{\text{on/off}}$. The mathematical expressions for dissipated power are the following:

\[
\text{Dissipated power} = \frac{E}{\Delta t} = \int_{0}^{\Delta t} v(t)i(t)dt
\]

\[
\text{Dissipated power} = P_c + P_{\text{swON}} + P_{\text{swOFF}}
\]

\[
\text{Dissipated power} = \frac{1}{t_c} \int_{0}^{t_c} (V_0 + R_C i_C)i_C dt + \frac{E_{\text{ON}}}{t_{\text{on}}} + \frac{E_{\text{OFF}}}{t_{\text{off}}}
\]

where $V_0$ represents the ON-state zero-current forward voltage, $R_C$ is the ON-state resistance, $E_{\text{ON}}$ is the turn-on energy loss and $E_{\text{OFF}}$ is the turn-off energy loss.

3 Thermal cycling of MegaDiscaP devices

The MegaDiscaP devices considered for the thermal analysis are as follows:

- $S_1, S_2$: FZ1500R33HL3
- $D_1, D_2$: DD800S33K2C
- $S_4$: FZ2400R12HP4_B9
- $D_4$: DD800S17K3_B2

In this section the junction temperature variations of the semiconductors devices are calculated based on data provided by manufacturers and the operating parameters. In order to determine the junction temperature, the case temperature of each device will have to be measured.
To evaluate the dissipated power, conduction and switching losses have to be estimated. The conduction losses are easily calculated from the datasheet curves and operational parameters. Concerning the switching losses, their estimation is much more difficult as they depend on a lot of different parameters. In this document, the goal is to evaluate the junction temperature of the semiconductors in order to validate the design and estimate the lifetime expectancy of the devices. Then some simplifications have been made to evaluate the semiconductors switching losses:

- for the diodes, the turn-on losses have been neglected. For their turn-off losses, the recovery energy have been estimated from the datasheets parameters and distributed over $t_{off} = t_{rr}$, the recovery time of the diode.

- for the IGBT, the turn-on losses have been evaluated from $E_{ON}$ given in the datasheet and scaled to the operating conditions of the considered device. $E_{ON}$ have then been distributed over $t_{on} = t_{r} + t_{rr}$ where $t_{r}$ is the IGBT estimated rise time and $t_{rr}$ the estimated recovery time of the diode. The turn-off losses have been evaluated from the datasheet, adapted to the operating parameters and distributed over $t_{off} = t_{f}$, the fall time of the IGBT.

### 3.1 $S_1$ thermal analysis

$S_1$ has a conduction time that is equal to rise time and must handle the source maximum voltage and current ($V_{C1}, I_{REF}$). Figure 3(a) shows the power dissipation profile related to the load current. To calculate the dissipated power, the turn-off energy and conduction losses are considered. The turn-on energy is considered negligible compared to the turn-off energy, as the ON commutation is performed with zero current. Figure 3(b) shows the FZ1500R33HL3 considered parameters used in simulations.

![Figure 3: Thermal analysis of $S_1$ FZ1500R33HL3. (a) Power dissipation profile. (b) Simulation parameters.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{CE}$ [kV]</td>
<td>2.1</td>
</tr>
<tr>
<td>$I_C$ [mA]</td>
<td>2</td>
</tr>
<tr>
<td>$T_{j,max}$ [°C]</td>
<td>25</td>
</tr>
<tr>
<td>$E_{rec}$ [J]</td>
<td>-</td>
</tr>
<tr>
<td>$E_{ON}$ [J]</td>
<td>-</td>
</tr>
<tr>
<td>$E_{OFF}$ [J]</td>
<td>3.73</td>
</tr>
<tr>
<td>$R_C$ [mΩ]</td>
<td>0.926</td>
</tr>
<tr>
<td>$V_0$ [V]</td>
<td>1.5</td>
</tr>
<tr>
<td>$t_{off}$ [μs]</td>
<td>0.4</td>
</tr>
<tr>
<td>$t_{on}$ [μs]</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$ [K/kW]</td>
<td>0.7</td>
</tr>
<tr>
<td>$r_2$ [K/kW]</td>
<td>5.45</td>
</tr>
<tr>
<td>$r_3$ [K/kW]</td>
<td>1.83</td>
</tr>
<tr>
<td>$r_4$ [K/kW]</td>
<td>0.55</td>
</tr>
<tr>
<td>$\tau_1$ [s]</td>
<td>0.004</td>
</tr>
<tr>
<td>$\tau_2$ [s]</td>
<td>0.045</td>
</tr>
<tr>
<td>$\tau_3$ [s]</td>
<td>0.5</td>
</tr>
<tr>
<td>$\tau_4$ [s]</td>
<td>1</td>
</tr>
</tbody>
</table>
Equation (1) shows the \( P_c \) and \( P_{swOFF} \) calculation:

\[
P_c = \frac{V_0I_{REF}}{2} + \frac{R_CI_{REF}^2}{3} = 2.73 \text{kW}
\]

\[
P_{swOFF} = \frac{E_{OFF}}{t_{off}} = 9.33 \text{MW} \quad (1)
\]

Figure 4(a) shows the junction-case temperature variation in steady state condition. Figure 4(b) shows a zoom of this temperature and power dissipation profile. It can be seen that the maximum \( \Delta T_{jc} \) is close to 1.9°C. Since this device operates below its nominal operational ratings, a low temperature variation is obtained.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{Thermal simulations of \( S_1 \). (a) Temperature variation. (b) Detail of the temperature variation.}
\end{figure}

### 3.2 \( S_2 \) thermal analysis

Concerning \( S_2 \) blocking voltage and forward current ratings, they are similar to those of \( S_1 \). However, unlike \( S_1 \), this device presents a larger conduction time, as it must conduct the load current during the flat-top. For a more detailed analysis, the device power profile under conduction operation is divided in two parts, one of \( P_{c1} \) amplitude and \( t_r \) duration, and another of \( P_{c2} \) amplitude and \( t_{FT} \) duration. \( P_{c1} \) pulse only includes the conduction power losses during \( t_r \) and \( P_{c2} \) involves conduction losses during the flat-top. The switching losses only include turn-off power at the end of flat-top, since the turn-on process is performed with zero current. The amplitude of switching losses is \( P_{swOFF} \) and the width is \( t_{off} \). Figure 5(a) shows the \( S_2 \) power dissipation profile and figure 5(b) shows the FZ1500R33HL3 considered parameters.

Equation (2) shows the \( P_{c1}, P_{c2} \) and \( P_{swOFF} \) calculation:

\[
P_{c1} = \frac{V_0I_{REF}}{2} + \frac{R_CI_{REF}^2}{3} = 2.73 \text{kW}
\]

\[
P_{c2} = (V_0I_{REF} + R_CI_{REF}^2) = 6.7 \text{kW}
\]

\[
P_{swOFF} = \frac{E_{OFF}}{t_{off}} = 9.33 \text{MW} \quad (2)
\]

Figure 6(a) shows the junction-case temperature variation in steady state condition and figure 6(b) shows a zoom of this temperature and power dissipation profile. The maximum \( \Delta T_{jc} \)
obtained is close to 8.9°C. The increase in the temperature variation of $S_2$ compared to $S_1$, is due to the fact that this device handles the load current during the flat-top.

### 3.3 $D_1$ thermal analysis

$D_1$ is used to block the high voltage ($V_{C1}$) used in stage 1, in order to allow the use of lower voltage devices for stage 2. Since this device is in series with stage 2, it must handle the maximum load current. Therefore, $D_1$ has the maximum blocking voltage and forward current characteristics. The conduction time of this device corresponds to the sum of the flat-top and fall times. Similarly as what has been done for $S_2$, for a more detailed calculation, the device power profile modeling the conduction losses is divided in two parts, one of $P_{c1}$ amplitude for the flat-top and another of $P_{c2}$ amplitude for the fall time. Concerning the turn-on losses, it would be necessary to evaluate this power experimentally as this value is not provided in the manufacturer data due to the strong dependance of the associated device. However, this effect can be neglected due to the value of the conduction losses. Figure 7(a) shows the $D_1$ power dissipation profile and figure 7(b) shows the DD800S33K2C considered parameters.

Equation (3) shows the $P_{c1}$ and $P_{c2}$ calculation:

$$P_{c1} = \frac{V_0 I_{REF}}{2} + \frac{R_C I_{REF}^2}{4} = 3.13 \text{ kW}$$

for each diode of a module

$$P_{c2} = \frac{V_0 I_{REF}}{4} + \frac{R_C I_{REF}^2}{12} = 1.33 \text{ kW}$$

for each diode of a module

For $D_1$, two devices installed in the same module are used in parallel. The expressions given for the dissipated power consider the power dissipated in one diode. In order to evaluate the whole dissipated power, two diodes have to be taken into account. Figure 8(a) shows the junction-case temperature variation in steady state condition and figure 8(b) shows a zoom of this temperature and power dissipation profile. It can be seen that the temperature variation is close to 7.3°C.
Figure 6: Thermal simulations of $S_2$. (a) Temperature variation. (b) Detail of the temperature variation.

Figure 7: Thermal analysis of $D_1$ DD800S33K2C. (a) Power dissipation profile. (b) Simulation parameters.
3.4 $D_2$ thermal analysis

$D_2$ is used during fall time in order to provide a conduction path for the load energy recovery. This device must handle the source maximum voltage and current ($V_{C1}$, $I_{REF}$). In this case, the switching losses at turn-on and turn-off are negligible as regards to the conduction losses value. Figure 9(a) shows the power dissipation profile related to the load current. Figure 9(b) shows the DD800S33K2C considered parameters used in simulations. Equation (4) shows the $P_c$ calculation:

$$P_c = \frac{V_0 I_{REF}}{2} + \frac{R_C I_{REF}^2}{3} = 3.6 \text{ kW}$$  (4)

Figure 10(a) shows the junction-case temperature variation in steady state condition and figure 10(b) shows a zoom of this temperature and power dissipation profile. It can be seen that the maximum temperature variation is $1.7^\circ C$. Since this device operates far below its nominal operational ratings, a low temperature variation is obtained.

3.5 $S_4$ thermal analysis

$S_4$ operates in switch-mode during the flat-top with a low voltage ($V_{C2}$) and with load current, $I_{REF}$. The power dissipation profile is a set of pulse train of period $T_s = 100 \mu s$, which represents conduction and switching losses. Figure 11(a) shows the power dissipation profile and figure 11(b) shows the FZ2400R12HP4_B9 considered parameters.

The pulses representing the conduction losses have an amplitude $P_c$ and a width of $D \cdot T_s$, where a duty cycle $D = 0.5$ is considered. The switching losses have an amplitude $P_{swON/OFF}$ and a width of $t_{on/off}$. The reverse recovery losses have been included in $P_{swON}$ and $t_{on}$ has been considered as the sum of the IGBT rise time and diode reverse recovery time estimated from Infineon documents. The corresponding pulses amplitude are shown in (5).

$$P_c = V_0 I_{REF} + R_d I_{REF}^2 = 3.6 \text{ kW}$$

$$P_{swON} = E_{ON}/t_{on} = 0.5 \text{ MW}$$

$$P_{swOFF} = E_{OFF}/t_{off} = 2.09 \text{ MW}$$  (5)
Figure 9: Thermal analysis of $D_2$ DD800S33K2C. (a) Power dissipation profile. (b) Simulation parameters.

<table>
<thead>
<tr>
<th>$V_{AK}$ [kV]</th>
<th>$2.1$</th>
<th>$\tau_1$ [K/kW]</th>
<th>$11.7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_F$ [kA]</td>
<td>$2$</td>
<td>$\tau_2$ [K/kW]</td>
<td>$6.5$</td>
</tr>
<tr>
<td>$T_{j \text{max}}$ [$^\circ$C]</td>
<td>$25$</td>
<td>$\tau_3$ [K/kW]</td>
<td>$1.56$</td>
</tr>
<tr>
<td>$E_{\text{rec}}$ [J]</td>
<td>$-$</td>
<td>$\tau_4$ [K/kW]</td>
<td>$6.24$</td>
</tr>
<tr>
<td>$E_{\text{ON}}$ [J]</td>
<td>$-$</td>
<td>$\tau_1$ [s]</td>
<td>$0.03$</td>
</tr>
<tr>
<td>$E_{\text{OFF}}$ [J]</td>
<td>$-$</td>
<td>$\tau_2$ [s]</td>
<td>$0.1$</td>
</tr>
<tr>
<td>$R_C$ [m$\Omega$]</td>
<td>$1.43$</td>
<td>$\tau_3$ [s]</td>
<td>$0.3$</td>
</tr>
<tr>
<td>$V_0$ [V]</td>
<td>$1.7$</td>
<td>$\tau_4$ [s]</td>
<td>$1$</td>
</tr>
</tbody>
</table>

Figure 10: Thermal simulations of $D_2$. (a) Temperature variation. (b) Detail of the temperature variation.
Figure 11: Thermal analysis of $S_4$ FZ2400R12HP4_B9. (a) Power dissipation profile. (b) Simulation parameters.

Figure 12(a) shows the junction-case temperature variation in steady state condition and figure 12(b) shows a zoom of this temperature and power dissipation profile. The maximum temperature variation is $19.2^\circ C$. As can be seen in Eq. (5), the high temperature variation is mainly given by the switching power losses. In this analysis a hard switching process is assumed, which leads to the worst case operation.

3.6 $D_4$ thermal analysis

$D_4$ operates in switch mode during the flat-top and continuous mode during the fall time, and must handle a low voltage ($V_{C2}$) and the load current, $I_{REF}$. The power dissipation profile during flat-top is a set of pulse train of period $T_s = 100\,\mu s$, which involves conduction and switching losses. During fall time, conduction losses are considered. Figure 13(a) shows the power dissipation profile and figure 13(b) shows the DD800S17K3_B2 considered parameters.

The conduction pulses at flat-top have an amplitude $P_{c1}$ and a width of $D\cdot T_s$, where a $D = 0.5$ is considered. The switching losses have an amplitude $P_{swON/OFF}$ and a width of $t_{on/off}$. In this case, the diode switching losses cannot be neglected. However, the main part of the switching losses are the turn-off losses and turn-on losses can be neglected. To evaluate precisely the turn-off losses, it would be necessary to measure the diode current and voltage under the worst case operating conditions ($dI/dt$, operating voltage and current, leakage inductances, etc). For a first approximation, the recovery energy given in the datasheet has been considered and, as this value is highly dependant of the operating voltage, scaled down to the 600V operating voltage. The pulses representing the conduction losses during fall time have an amplitude $P_{c2}$.
Figure 12: Thermal simulations of $S_4$. (a) Temperature variation. (b) Detail of the temperature variation.

Figure 13: Thermal analysis of $D_4$ DD800S17K3_B2. (a) Power dissipation profile. (b) Simulation parameters.
and a width of $t_f$. The corresponding pulses amplitude are shown in (6).

$$P_{c1} = V_0 I_{REF} + R_c I^2_{REF} = 5.38 \text{ kW}$$

$$P_{swON} = \frac{E_{ON}}{t_{on}} \text{ -neglected-}$$

$$P_{swOFF} = \frac{E_{OFF}}{t_{off}} = 325 \text{ kW}$$

$$P_{c2} = \frac{V_0 I_{REF}}{2} + \frac{R_c I^2_{REF}}{3} = 2.21 \text{ kW} \quad (6)$$

Figure 14(a) shows the junction-case temperature variation in steady state condition and figure 14(b) shows a zoom of this temperature and power dissipation profile. The maximum temperature variation is $23.4\degree C$. It can be seen that, even when the turn-on losses have not been considered, the temperature deviation is appreciable.

Figure 14: Thermal simulations of $D_4$. (a) Temperature variation. (b) Detail of the temperature variation.

4 Expected lifetime

The expected lifetime can be estimated with data obtained from temperature cycling amplitude, maximum junction temperature and power cycling capability curves provided by manufacturers. Concerning the converter for the Booster injection with Linac 4, the semiconductors must operate for at least 150000 hours with an ambient temperature of $40\degree C$. This requirement translated in terms of power cycling capability leads to a number of pulses given by [6]:

$$150000 \text{ hours} \cdot 60 \frac{\text{min}}{\text{hour}} \cdot 60 \frac{s}{\text{min}} \cdot 1.1 \frac{\text{pulse}}{s} = 600 \cdot 10^6 \text{ pulses}$$

In the following, the expected lifetime of $S_2$ and $S_4$ will be estimated, since they have the most stringent requirements.

4.1 Calculation of $S_2$ expected lifetime

$S_2$ is a module FZ1500R33HL3 from Infineon. These modules are using IGBT3 field stop plus trench chips housed in a IHM-B package. For this kind of module, the number of cycles can be calculated from Figure 15, which is presented in [8].
With a $\Delta T_j = 30^\circ$C, the number of cycles is $2 \cdot 10^7$. In this case, $\Delta T_{jS2} = 9^\circ$C, which is not provided in this curve. In order to obtain the number of cycles by extrapolation, the Coffin-Manson model is applied. Figure 16, which is presented in [2], shows the prediction of cycling capability expression.

From figure 16 data, a $k = 6$ is obtained. Therefore, the number of cycles of $S_2$ is given by:

$$n_{S2} = 2 \cdot 10^7 \cdot \left(\frac{30^\circ}$C}{9^\circ}$C\right)^6 = 27.4 \cdot 10^9$$  \hspace{1cm} (7)

Since $n_{S2}$ is obtained for a $T_{jMAX} = 150^\circ$C is necessary to adjust it for the operational junction temperature. Assuming a ambient temperature of $40^\circ$C and a case temperature of $60^\circ$C, the maximum junction temperature will be $T_{jMAX} = 60^\circ$C + $8.9^\circ$C $\approx 70^\circ$C. Figure 17, which is presented in [2], is used to make this adjustment. This figure shows the acceleration factor as a function of the temperature difference between junction temperature of curve of figure 15 and operational junction temperature. In this case this difference is $80^\circ$C, which leads to a deceleration factor of 20. Then, $n_{S2}$ is given by:

$$n_{S2} = 27.4 \cdot 10^9 \cdot 20 = 548 \cdot 10^9$$  \hspace{1cm} (8)

It can be seen that the obtained number of cycles is one thousand times larger than the required one and the thermal cycling is not an issue for $S_2$ using such semiconductors devices.
4.2 Calculation of $S_4$ expected lifetime

$S_4$ is a module FZ2400R12HP4_B9 from Infineon. These IGBT modules are using IGBT4 technology that employs trench chips exhibiting relatively soft commutations. For this type of module, the number of cycles can be calculated from Figure 18, which is presented in [9].

With a $\Delta T_j = 30^\circ$C, the number of cycles is $7 \cdot 10^6$. Using the Coffin-Manson model for a $\Delta T_{jc} = 19.17^\circ$C, $n_{S4}$ is obtained:

$$n_{S4} = 7 \cdot 10^6 \cdot \left( \frac{30^\circ C}{19.17^\circ C} \right)^6 \approx 100 \cdot 10^6$$  \hspace{1cm} (9)

In order to obtain the accelerator factor $a T_{JMAX} = 60^\circ$C +19.17°C $\approx 80^\circ$C is used. This temperature leads to a deceleration factor of 10. Then, $n_{S4}$ is given by:

$$n_{S4} = 100 \cdot 10^6 \cdot 10 = 1000 \cdot 10^6$$  \hspace{1cm} (10)

This number of cycles represents a lifetime expectancy of approximately 252000 hours that is far over specifications.

5 Conclusion

The thermal behavior of the MegaDiscaP semiconductor devices has been analyzed. In particular, the analysis has been focused on the junction-case temperature variation, in order to
estimate the expected lifetime of critical devices. The calculations have been made from data provided by the manufacturer considering hard switching operation.

The results show that it is possible to identify three levels of temperature requirements for the semiconductors. A first level, where the requirements are the lowest, concerns $S_1$ and $D_2$, which have a junction-case temperature variation less than 2°C. This low variation is due to the fact that their operating mode is below their nominal capability, since these devices operate only during the rise or fall times with a low repetition frequency (close to 1 Hz).

A second level is related to $S_2$ and $D_1$, which show a temperature variation below 10°C. These devices are operated during the flat-top of the current pulse and their power losses are mainly given by conduction losses. Their junction-case temperature variations are directly related to the flat-top duration.

A third level involves $S_4$ and $D_4$, which exhibit a junction-case temperature variation close to 20°C. These devices are directly concerned by thermal cycling issues. The high temperature variation is mainly due to the operation mode of these devices that operate in switch mode during the flat-top. In this case, the power dissipation is mainly due to switching losses. A careful circuit design of this stage has to be realized and the IGBT drivers have to be studied and optimized with a lot of details.

The lifetime expectancy of $S_2$ and $S_4$ has been evaluated. For $S_2$, its low junction temperature variation excludes any reliability problems due to thermal cycling. Concerning $S_4$, the expected lifetime is close to 250000 hours, which is well over the specifications.

References


