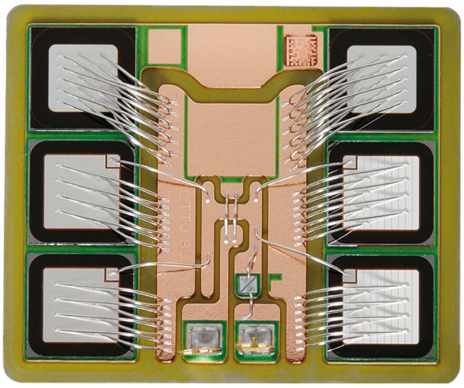
Application Note 5SYA 2058-03

Surge currents for IGBT diodes

Hitachi Energy's IGBT modules contain two different types of semiconductors, the IGBT and the anti-parallel fast recovery diode. The current through the IGBT can be switched on and off through the gate-emitter voltage, whereas the diode is not self-controlled. When it is biased in forward direction, the resulting current depends on external conditions.



1. Introduction

During fault cases – as after a load short circuit or the failure of adjacent devices in the inverter – the combination of inductances and capacitances will lead to a surge current through the diode. The specific waveform and duration depend on the type of fault and can vary from fractions of milliseconds up to many milliseconds. The peak currents are far beyond the nominal rated currents. During the fault case, the peak junction temperature can far exceed the maximum allowed temperature. This may lead to a certain degradation of the diode at each surge event. Therefore it is mandatory to know the number of fault cases during the diode lifetime to correctly specify the maximum allowed surge current.

1.2. Surge current properties

A surge current can appear in various waveforms. Standard tests and data sheet ratings typically use a half-sine wave with a duration between 100 µs and 100 ms. The following parameters influence the peak junction temperature:

- Initial diode junction temperature T_{vj}
- Pulse duration tp and surge current amplitude I_{FSM}
- Diode forward voltage V_F (as a function of temperature and current)
- Thermal impedance Z_{th} of the diode
- Initial module case temperature T_c (for long pulses only)

The losses generated in the diode during the surge current event depend on the forward voltage of the device, which again depends on the current and the device temperature. However the voltage can not always be measured or simulated, therefore the surge current integral I^2t is introduced, which eliminates the need to know the forward voltage waveform as long as the current waveform is similar to the specified half-sine pulse. The surge current integral I^2t of a half-sine wave with current amplitude I_{FSM} is calculated using equation 1 from the Standard IEC 60747 [1]:

$$\int_0^{tp} I^2(t) \cdot dt = \frac{1}{2} \cdot I_{FSM}{}^2 \cdot t_p \qquad \text{Eqn. 1}$$

The accumulated energy deposited during the pulse can be calculated using equation 2 if v_F, the voltage across the diode, and i_F, the current through the diode, are measured:

$$E_{surge}(t) = \int_0^t i_F(t) \cdot v_F(t) \cdot dt \qquad \text{Eqn. 2}$$

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The surge current capability is limited by thermal effects. The temperature reached during the surge current event can be calculated through convolution using the power generated in the diode and the thermal impedance Z_{th} of the diode. This is shown in equation 3.

$$T_{vj}(t) = T_{start} + \int_0^t i_F(\tau) \cdot v_F(\tau) \cdot \dot{Z}_{th}(t-\tau) \cdot d\tau \qquad \text{Eqn. 3}$$

with $$\dot{Z}_{th}(t) = \frac{d}{dt} Z_{th}(t)$$

If the voltage cannot be measured or a current different than a half-sine waveform should be simulated, the use of a temperature dependent forward voltage model of the diode is appropriate. It is important to properly model the areas of interest, especially the high current and high temperature behaviour of the diode. As the models for forward voltage and thermal impedance normally assume homogeneous conditions, a margin has to be taken into account for non-ideal cases.

1.3. Failure mechanisms

The thermal stress introduced by the surge current pulses will potentially cause damage due to thermal fatigue cumulated during the lifetime of the diode. The degradation of the diode can be detected in the electrical parameters.

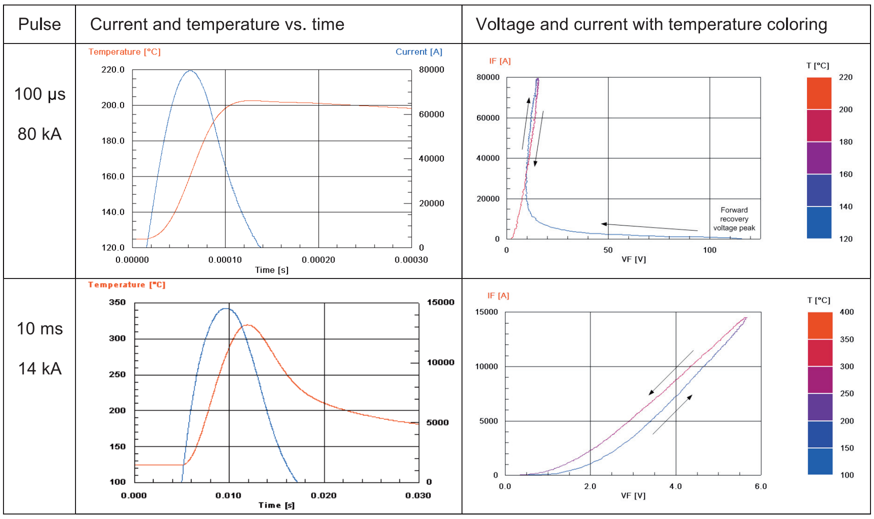
- Increase of the forward voltage
- Degradation of blocking capability, increase of leakage current
- Reduction of dynamic SOA capability
- The degradation is caused by the diffusion of surface contact metal into the silicon (Al-spiking), melting of the contact metal near the bond wires (long pulses) or melting of the silicon in overstressed areas, especially at short pulses (figure 1).

The conditions under which critical temperatures are reached are influenced by the diode design and packaging technology. Additional de-rating maybe necessary if a nonuniform current distribution occurs, for instance through unequal contact impedances from the module to the rest of the circuit (contact resistance, loop inductance), or if a different forward voltage drop occurs, due to chip to chip variation or temperature differences between the diodes due to cooling or loss differences.

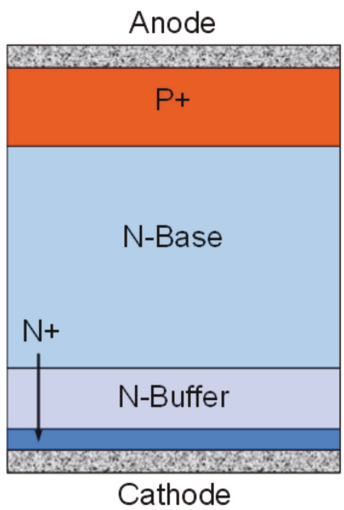
2. Surge current capability of Hitachi Energy's IGBT modules

2.1. IGBT diode technology to achieve high surge current capability

Hitachi Energy's IGBT diodes use the well proven SPT and SPT+ concept which results in a positive temperature coefficient at nominal current. During a surge current event, the current distribution is therefore well balanced among parallel diode chips, resulting in homogeneous current distribution up to very high temperatures. The strong P+ anode (figure 2) together with an optimized local lifetime control helps to provide an excellent low forward voltage characteristic at high current. This is mandatory to limit a rise in temperature and therefore allows a higher surge current capability.
In the Hitachi Energy's IGBT modules the packaging of the diode



01 Calculated temperature rise during two surge current events and their influence on the forward voltage drop (5SNA 1500E330300)



02 Cross-section of Hitachi Energy's diode utilizing a strong P+ anode design

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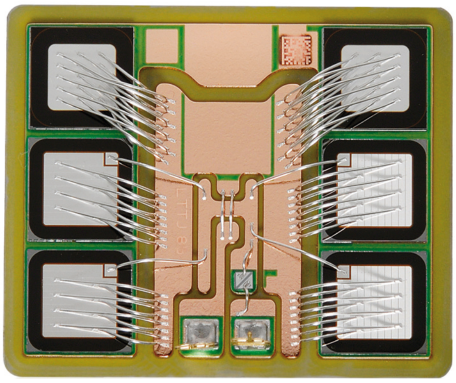
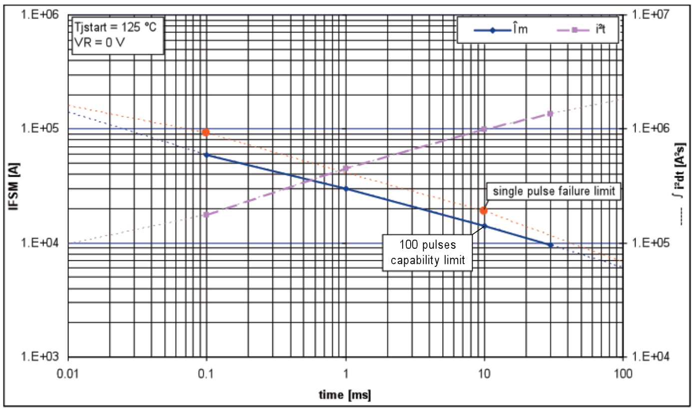


03 Layout of a substrate to optimise current sharing between the diode dies

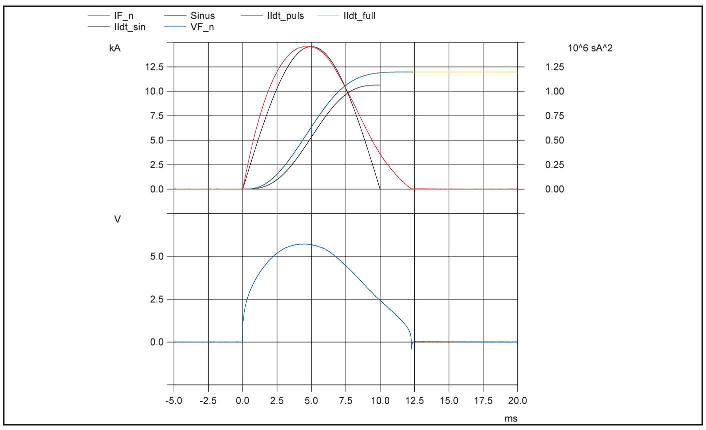


04 Surge on-state current vs. pulse length, half-sine wave

is optimized to distribute the resistances in the package evenly between the diode chips, helping to balance the currents. In addition, the contact through bond wires is optimized (figure 3) to achieve homogeneous current flow through each diode die, avoiding excessive temperatures at local hot spots.

2.2. Definition of surge current capability

Hitachi Energy's IGBT diodes are designed to survive 100 thermally independent pulses of the maximum current specified in the device data sheets. If the surge current stresses are kept within the given limits the diode will stay within the guaranteed data sheet characteristics and it will still fulfill the guaranteed safe operating area (SOA) conditions. In addition, the anti-parallel IGBT will not be not deteriorated. Surge current testing is part of type testing, but not part of outgoing inspection.
As an example the graph in the figure 4 shows the surge current characteristics for a 3300 volts 1500 ampere HiPak2 module when half-sine waves are applied. The dashed red graph, using the right scale, indicates the value I^2t as function of the pulse width. The continuous black graph, using the left scale, indicates the peak current in function of the pulse width. Both graphs are the limit for 100 non consecutive surge pulses. The gray dashed graph indicates the peak current for single surge events. The graph points with marker are tested values. Other graph data is extrapolated based on technology parameters and cross correlation factors.
The black waveform in the figure 5 shows an ideal half-sine current of 10ms base width and 14.5 kiloampere peak current, resulting in a surge current integral of 1.05 x 106 A^2s. The red curve is a typical test waveform; the resulting surge current integral is slightly above the target. The forward voltage of the diode during the pulse is shown in blue on the lower axis.
Figure 4 is made for half-sine waves and cannot be used for current wave forms deviating significantly from half-sine. For current wave forms deviating significantly to the sine current a type test may be needed to correctly assess the feasibility.



05 Typical wave forms at surge current testing

3. Surge current capability per voltage class

In the following section the surge current capabilities are shown according the chip and structural technology applied and voltage class and current rating. For module specific surge current capabilities, find the required module associated graph and verify the values according the pulse duration of your application.

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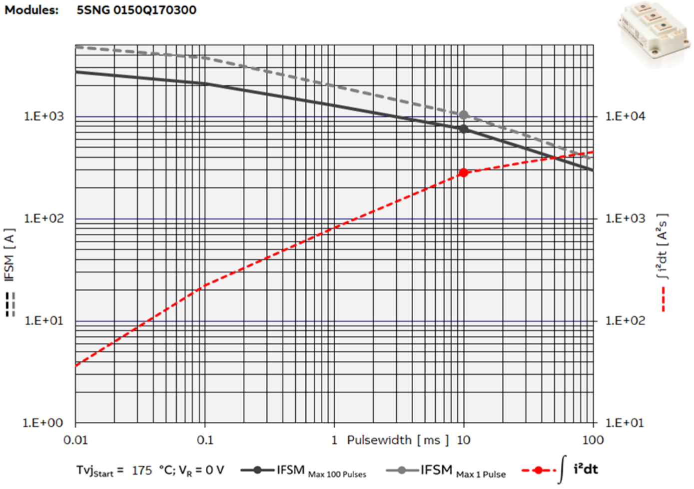
3.1. 1700 V HiPak

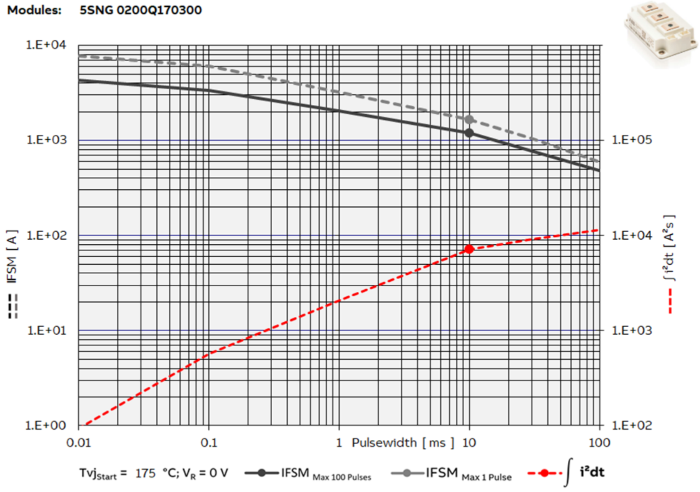
3.1.1. 1700 V and 150 A with SPT++ technology

Modules: 5SNG 0150Q170300



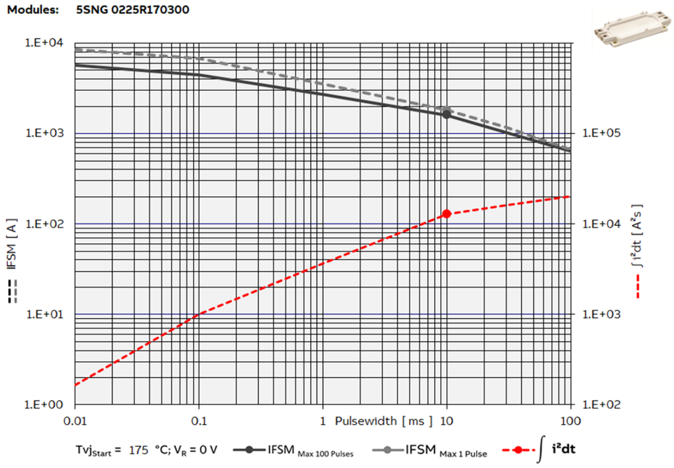
3.1.2. 1700 V and 200 A with SPT++ technology

Modules: 5SNG 0200Q170300



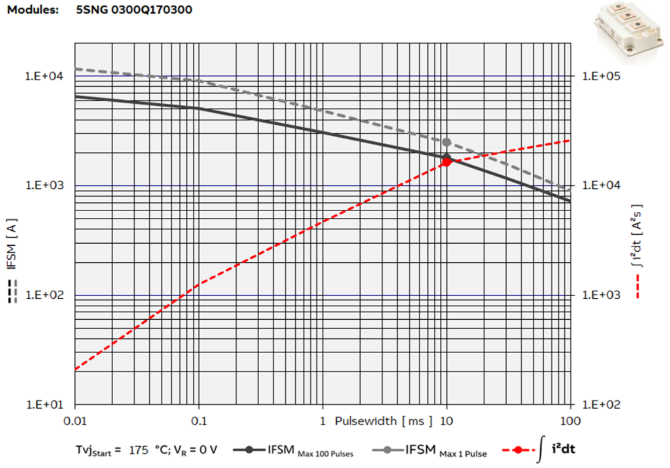
3.1.3. 1700 V and 225 A with SPT++ technology

Modules: 5SNG 0225R170300



3.1.4. 1700 V and 300 A with SPT++ technology

Modules: 5SNG 0300Q170300



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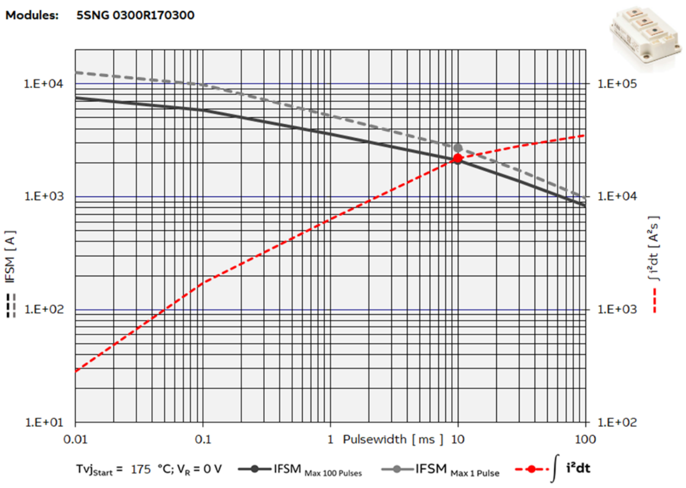
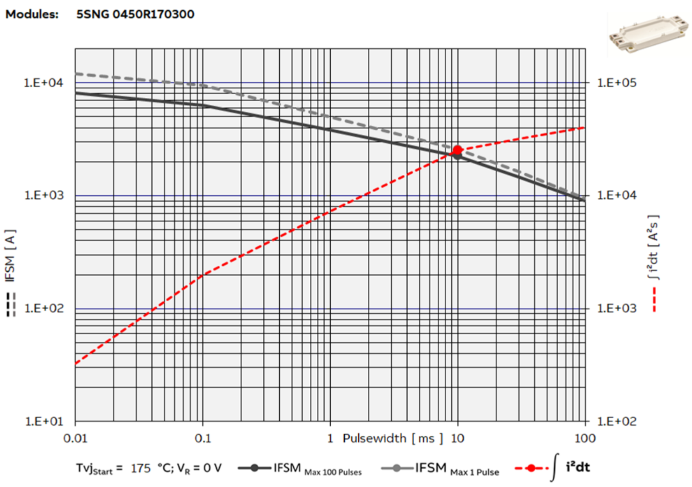
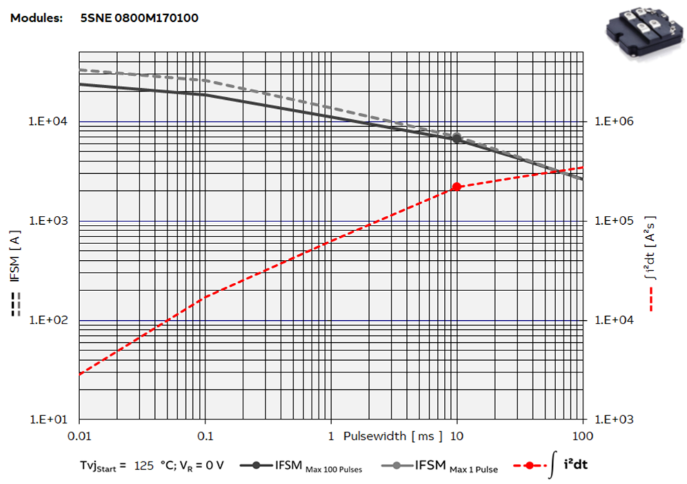
3.1.5. 1700 V and 300 A with SPT⁺⁺ technology



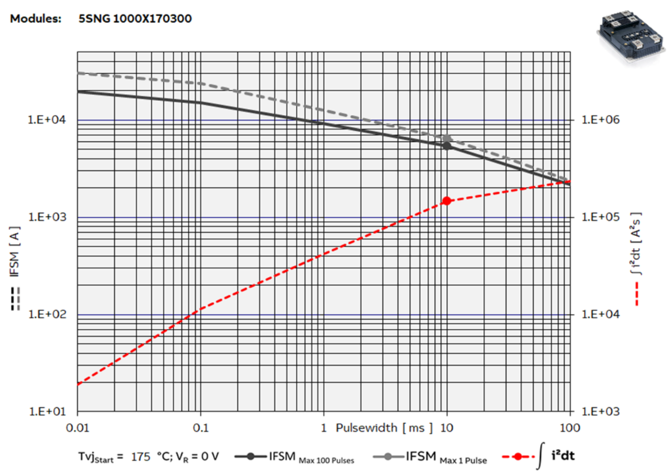
3.1.6. 1700 V and 450 A with SPT⁺⁺ technology



3.1.7. 1700 V and 800 A with SPT technology



3.1.8. 1700 V and 1000 A with SPT⁺⁺ technology



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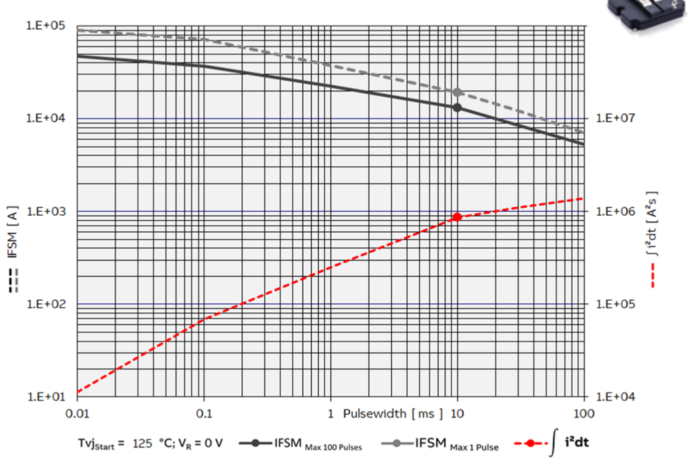
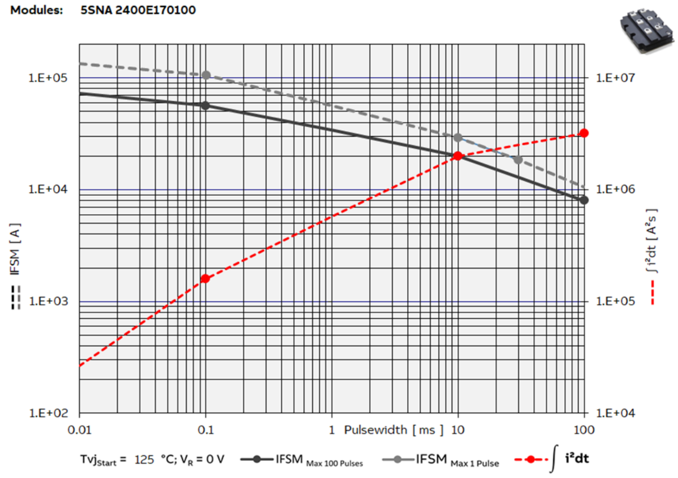
3.1.9. 1700 V and 1600 A with SPT technology

Modules: 5SNA 1600N170100



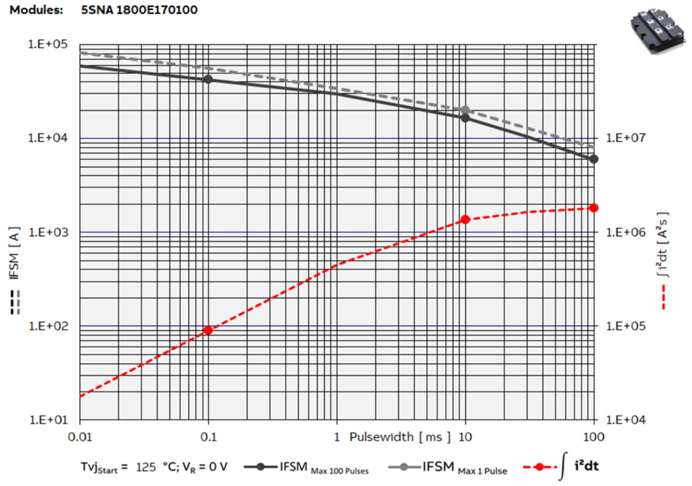
3.1.11. 1700 V and 2400 A with SPT technology

Modules: 5SNA 2400E170100



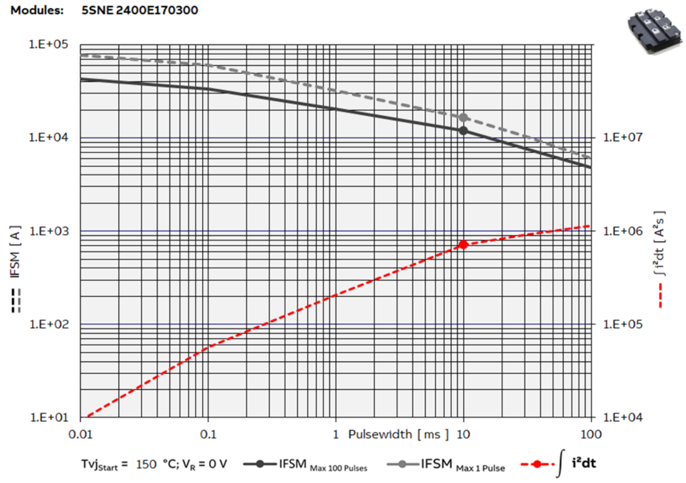
3.1.10. 1700 V and 1800 A with SPT⁺ technology

Modules: 5SNA 1800E170100



3.1.12. 1700 V and 2400 A with SPT⁺ technology

Modules: 5SNE 2400E170300



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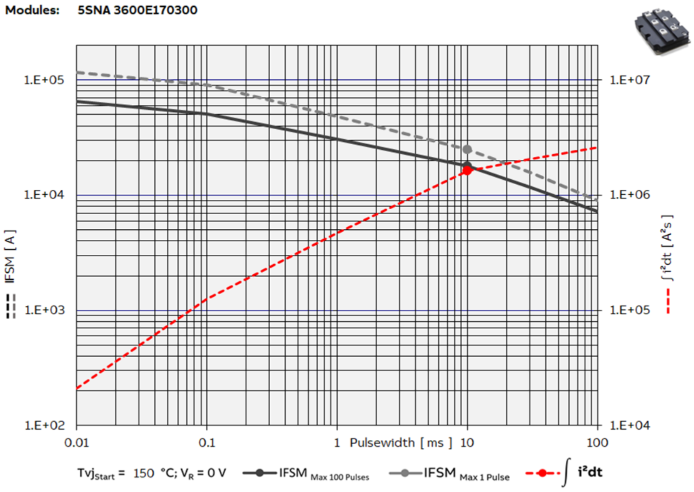
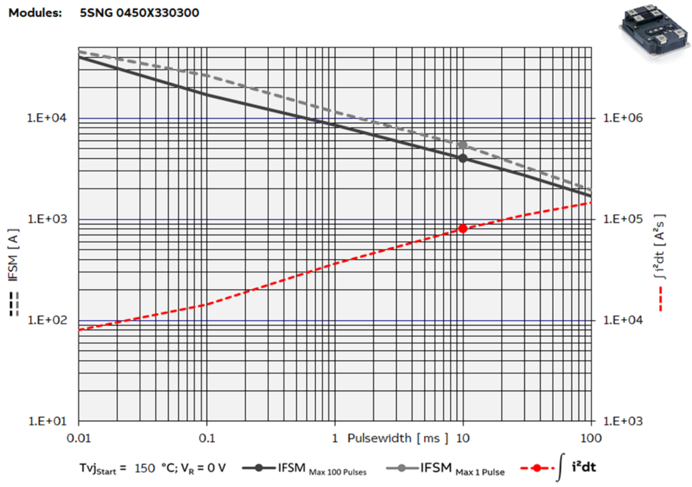
3.1.13. 1700 V and 3600 A with SPT+ technology

Modules: 5SNA 3600E170300



3.2.2. 3300 V and 450 A with SPT+ technology

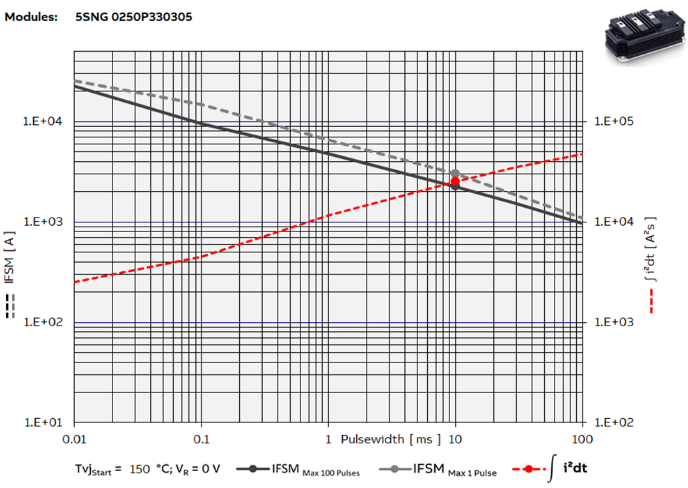
Modules: 5SNG 0450X330300



3.2. 3300 V

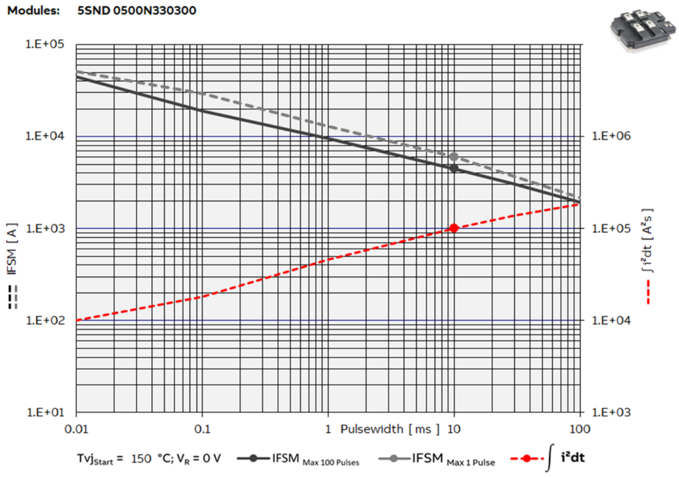
3.2.1. 3300 V and 250 A with SPT+ technology

Modules: 5SNG 0250P330305



3.2.3. 3300 V and 500 A with SPT+ technology

Modules: 5SND 0500N330300



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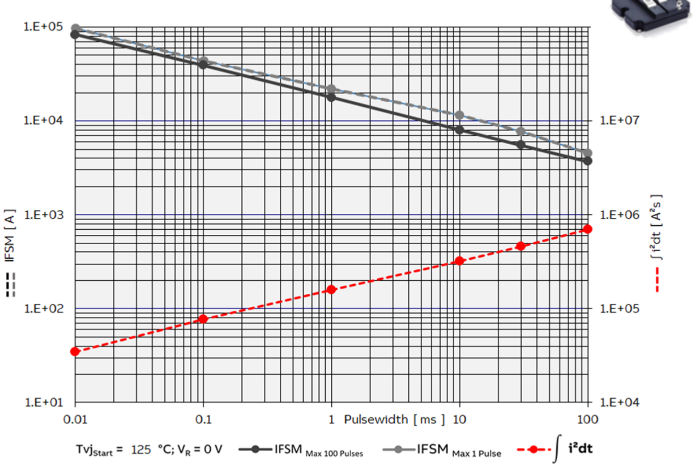
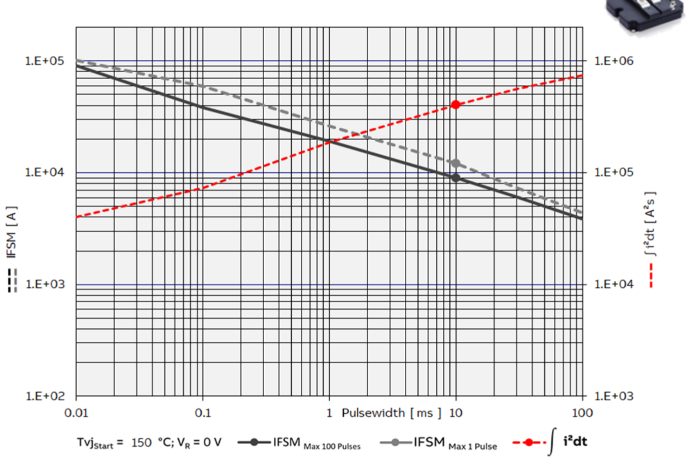
3.2.4. 3300 V and 800 A with SPT technology high overvoltage

Modules: 5SNA 0800N330100



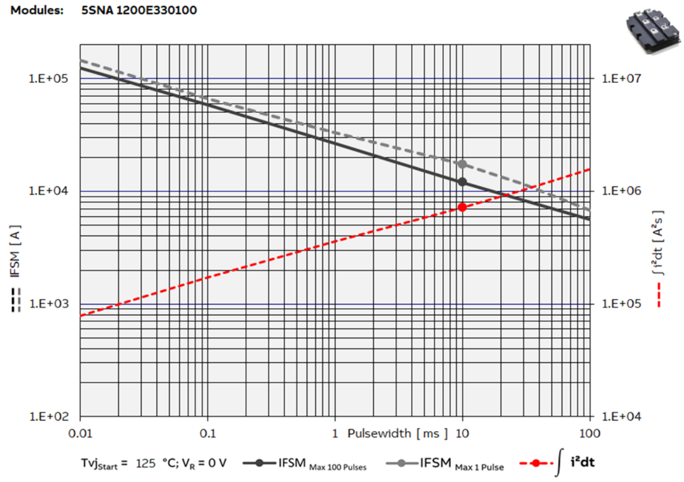
3.2.5. 3300 V and 1000 A with SPT+ technology

Modules: 5SNA 1000N330300



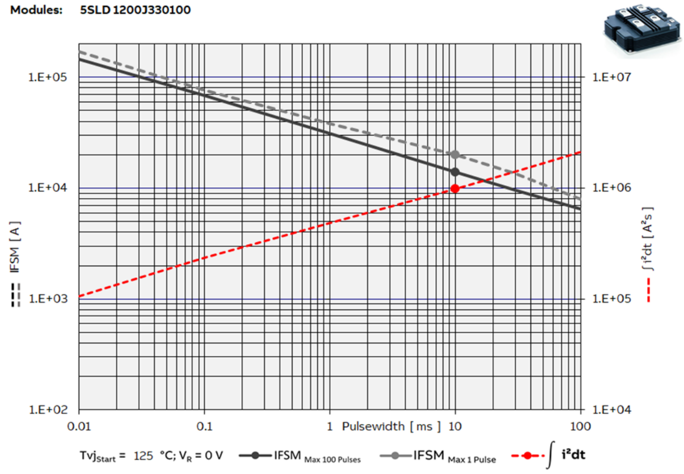
3.2.6. 3300 V and 1200 A with SPT technology

Modules: 5SNA 1200E330100



3.2.7. 3300 V and 1200 A with SPT technology

Modules: 5SLD 1200J330100



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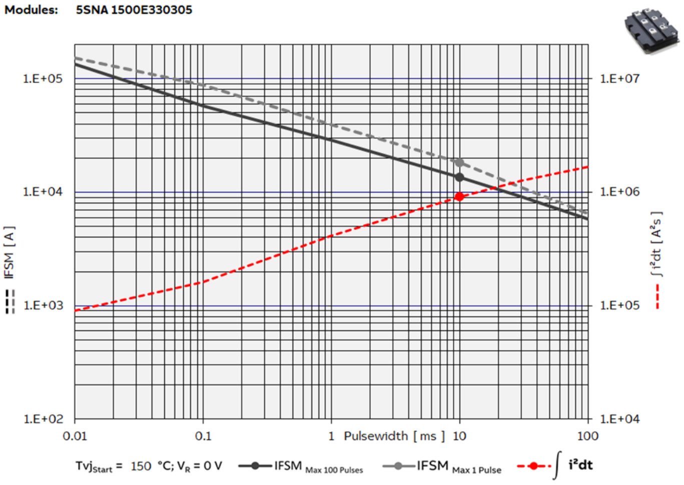
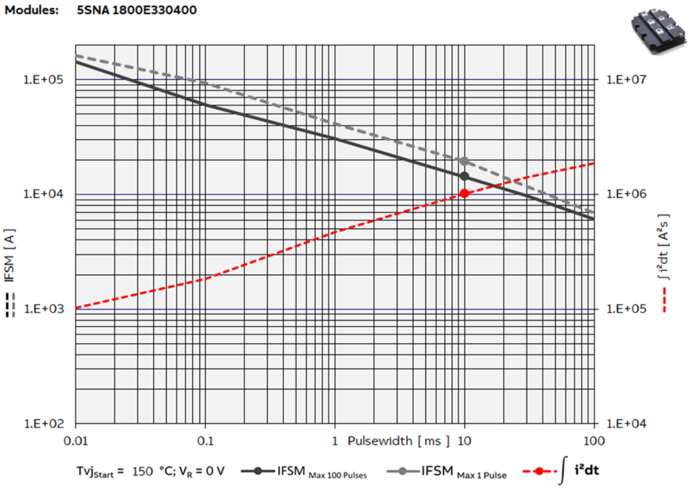
3.2.8. 3300 V and 1500 A with SPT⁺ technology

Modules: 5SNA 1500E330305



3.2.9. 3300 V and 1800 A with TSPT⁺ technology

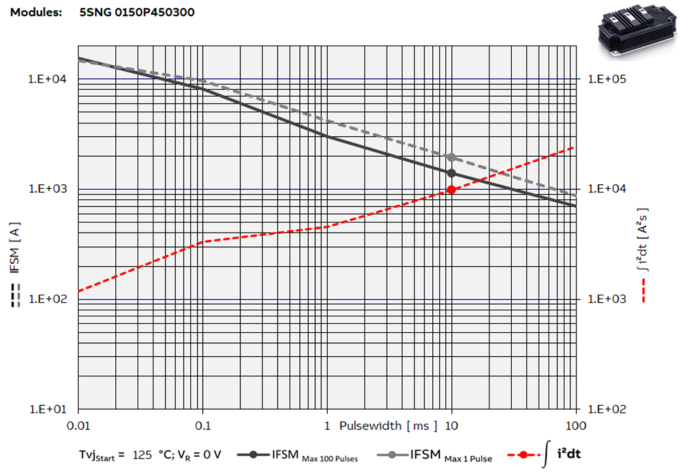
Modules: 5SNA 1800E330400



3.3. 4500 V

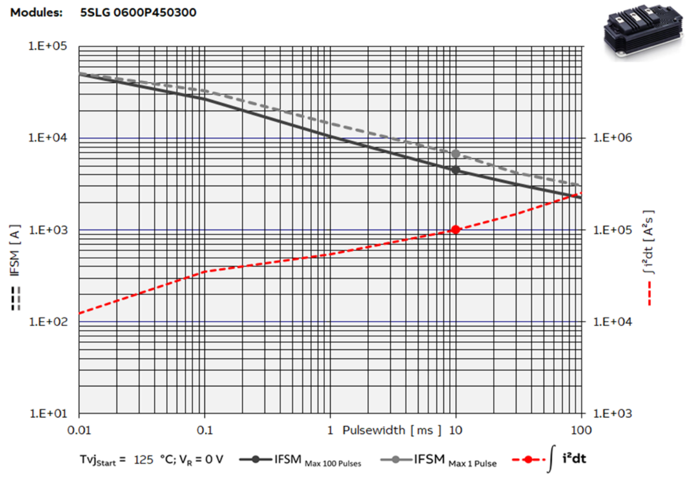
3.3.1. 4500 V and 150 A with SPT⁺ ("fast") technology

Modules: 5SNG 0150P450300



3.3.2. 4500 V and 600 A with SPT⁺ technology

Modules: 5SLG 0600P450300



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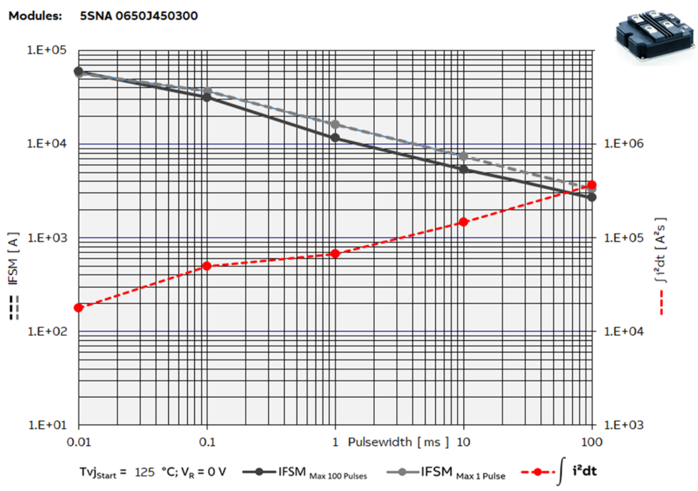
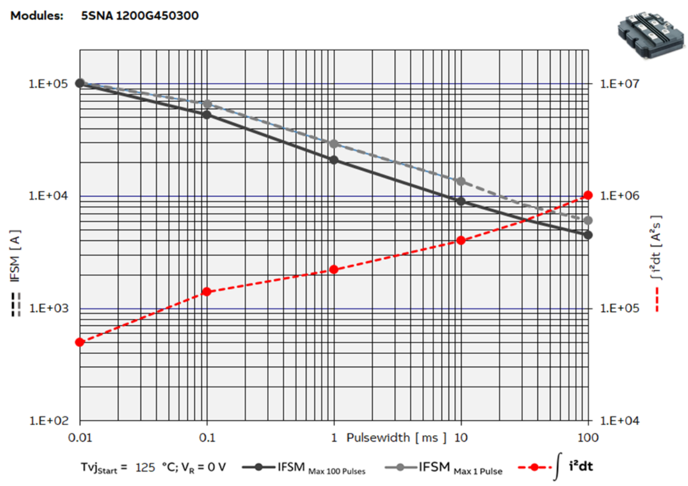
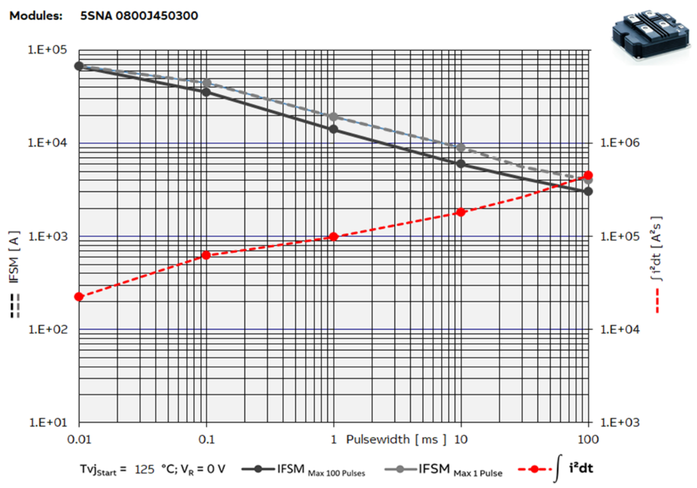
3.3.3. 4500 V and 650 A with SPT⁺ (“fast”) technology



3.3.5. 4500 V and 1200 A with SPT⁺ technology

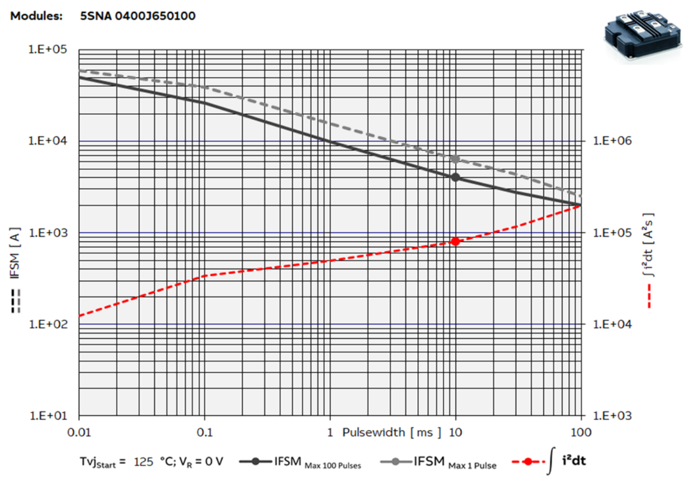


3.3.4. 4500 V and 800 A with SPT⁺ technology



3.4. 6500 V

3.4.1. 6500 V and 400 A with SPT⁺/SPT technology



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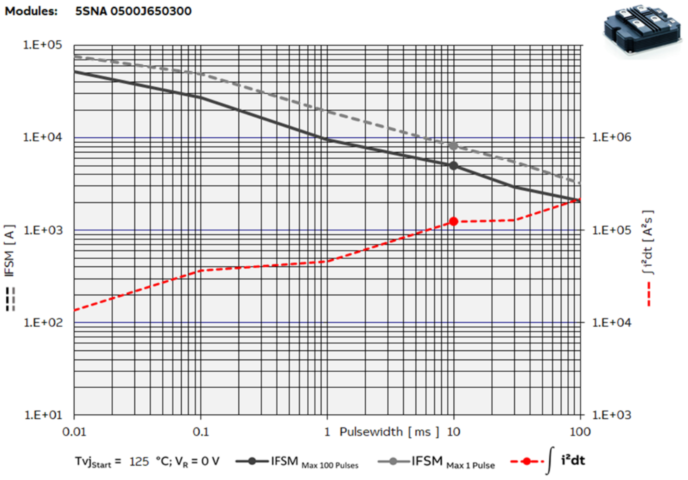
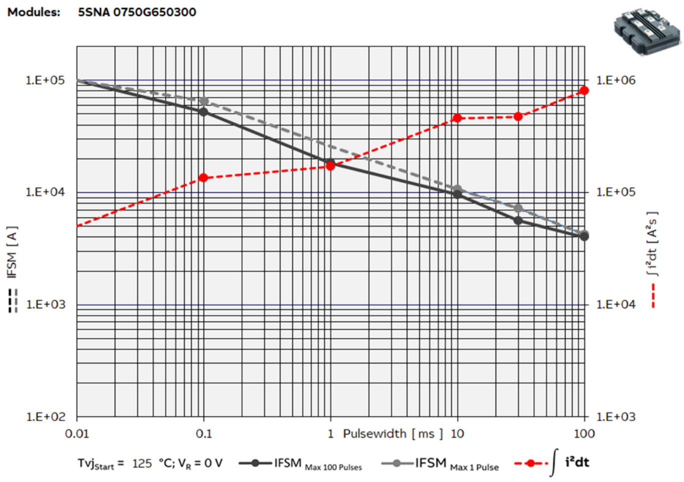
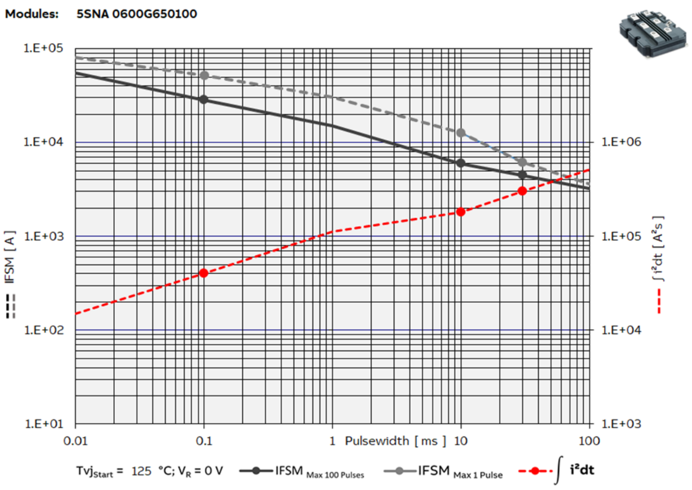
3.4.2. 6500 V and 500 A with SPT⁺/SPT technology



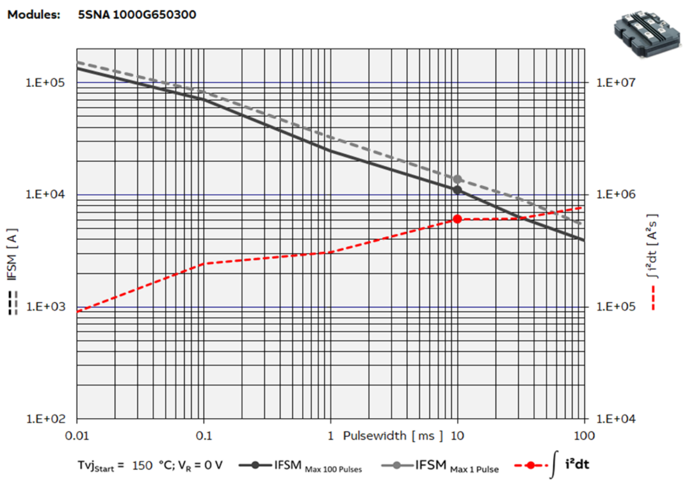
3.4.4. 6500 V and 750 A with SPT⁺ technology



3.4.3. 6500 V and 600 A with SPT⁺ technology



3.4.5. 6500 V and 1000 A with SPT⁺⁺ technology



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4. Additional notes

4.1. Reapplied voltage

The surge current limits described so far will not allow a reverse voltage to be reapplied directly after the pulse, because the diodes are running too hot during the pulse and will not be able to stabilize the leakage current. If reapplied voltage is needed, a further derating has to be taken into account to prevent thermal runaway after the pulse. See more details in [2], [3]. Application specific support can be provided upon request.

4.2. Further improvements

The trend towards higher junction temperatures at operation conditions further reduces the surge current capability when a higher starting temperature is assumed. A careful assessment of the needed surge current capability will be mandatory. As the limiting factor for today's diode is the peak temperature, three possible working areas are given to further increase the surge current capability. Firstly the reduction of the forward voltage drop, secondly the reduction of the thermal impedance of the diode and lastly an increase of the maximum allowable temperature during the surge current event.

4.3. References

[1] IEC Standard 60747 "Semiconductor Devices"
[2] 5SYA2053 "Applying IGBT"
[3] 5SYA2042 "Thermal Runaway"

5. Revision history

Version	Change	Authors
02	August 2013	A. Baschnagel Ulrich Schlapbach
03	August 2019	Felix Mathis

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