Novel Method for Active Short Circuit (ASC) Tests of Power Module in Automotive Traction Application

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Keywords

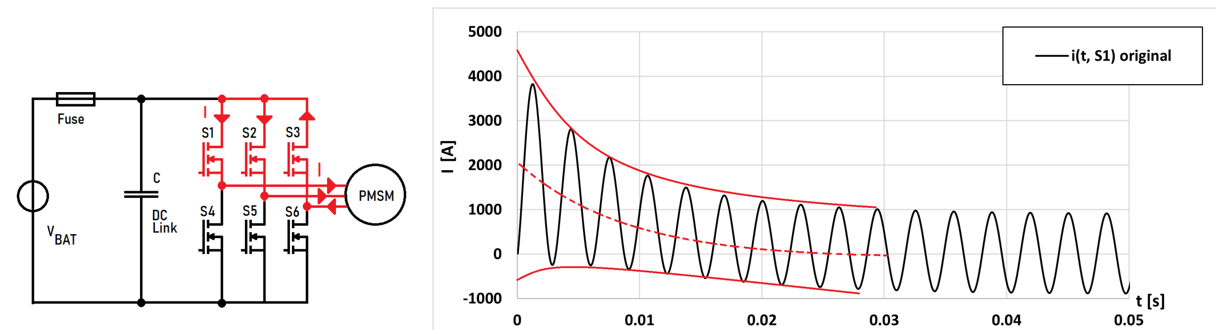
≪Permanent magnet motor≫, ≪Short circuit≫, ≪Machine emulation≫, ≪Control methods for electrical systems≫, ≪Traction application≫ .

Abstract

Active short circuit is a special operation for power modules in automotive traction applications. For safety reasons, it must be qualified in detail during the design phase. Therefore, this article presents a novel method allowing power module manufacturers to test the ASC robustness of the device before an inverter unit is built.

Introduction

E-mobility, with its demand for efficiency, cost-efficiency, and safety, requires the development of new products, processes, and test methods because there are different drive systems in electrically powered vehicles. In this article, the focus is set on those inverters with batteries, inverters with DC link capacitors, and permanent magnet synchronous motor (PMSM), which are also operated in the field weakening range. This is one of the most popular systems in vehicles, as the PMSM is very efficient and requires little maintenance.



(a) Schematic of the inverter during ASC on the high side

(b) Current $i(t)$ of transistor S1 during ASC

Fig. 1: ASC currents in the inverter

Due to the permanent excitation of the machine, this drive requires an inverter with a sophisticated safety concept [1] in case the main controller of the inverter fails, for example. There are two modes in which the system can be set in that case. One is the state with all switches open, called free-wheeling (FW), where only the diodes or body diodes are conducting current. The other one is the case where all switches of the high (Fig.: 1a) or low side are conducting current, called active short circuit (ASC).

As long as the connection between the inverter and the battery is intact and the battery is not fully charged, the FW is one potential safety mode. Due to the voltage (EMF) of the machine in full speed, it needs to be considered that FW means that a negative torque is applied and so the car brakes. The ASC can be used in various cases and is, therefore, one of the standard solutions in case the controller fails. If the ASC is applied during normal operation, a typical current known from short-circuits of 3-phase systems near a generator occurs. A detailed calculation of the current, according to IEC 60909, is given in [2]. The worst-case current for the power module is an asymmetric current, as shown in Figure 1b. Initially, sub-transient currents with high peak values occur; these sub-transient currents subside and change into a continuous short-circuit current [2]. With its high amplitude and high dissipated energy, the sub-transient current is a challenge for the semiconductors and the power module, even though no switching losses occur. The current could lead to overheating of the semiconductor switches, as well as critical hot spots.

Potential hot spots can be enlightened with a 3D finite element analysis (FEA). The first step is to evaluate the average temperature of the semiconductors. With the use of bipolar devices, such as IGBT, the so-called virtual junction temperature (T_{vj}) is simulated or calculated. To perform this in the most efficient way is to use a calculation as described in [3]. The approach is to apply the instantaneous dissipation power stepwise to the transient thermal resistances Z_{th}. The resulting T_{vj} is the base for every next time step and used for the calculation. This method is validated by measurement and FEA. The Z_{th} for the tested modules is known from measurements. With this input data, the calculation can provide the $T_{vj}(t)$ with the same accuracy as a transient FEA. Therefore, this method is used for all shown temperature simulations in this article.

Despite all scientific efforts, the validation of the ASC mode must be done in the final application. This is possible for OEMs, but not for the component manufacturers due to confidentiality and availability of the drive train. In order to conduct adequate tests during the design phase of the power modules, basic test methods are needed.

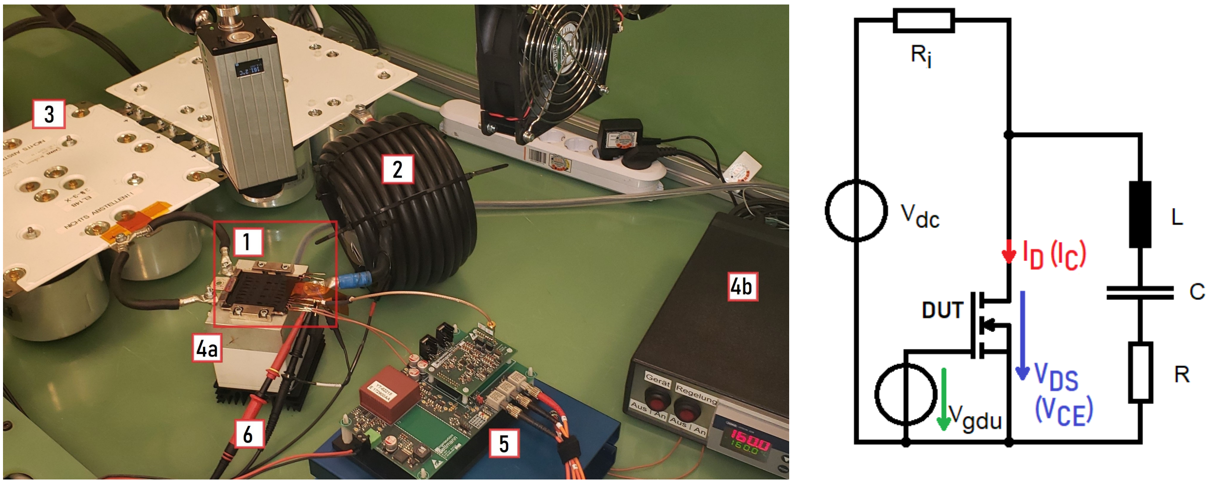
One of these is a 50 Hz surge current test as described in [4] and [5] where a half-sine wave of a 50 Hz current is applied to the device. The focus of interest in these tests is the maximum temperature of the junction of an IGBT. A test series with increasing current shows the limits of the module. The pulse before the device is destroyed is the last good pulse. Its peak temperature must not be exceeded at ASC, according to [4] and [5]. For a more general description of the last good pulse, the I^2t value is introduced. It is a metric to characterize the energy a semiconductor can withstand, as described in [5] for an RC-IGBT inverter.

An improvement of this approach by introducing a laboratory setup emulating the ASC current is shown in the following sections.

Test Setup and Parameters for Testing with Oscillating Current

In this section, the test setup and a method for dimensioning the components is described. The experiment is designed to emulate the ASC current of the application, as closely as possible, by using a resonant circuit. A picture and a schematic of the circuit is given in Figure 2.

The resonant circuit as shown in Figure 2 consists of the choke L (Fig. 2b) (2 (Fig. 2a)), a capacitor bank C (3), and their parasitic resistances R. The capacitors are charged by a voltage source (V_{dc}). The used voltage source needs a sufficient high internal resistance (R_i) not to influence the signal. To switch the transistor, a gate driver (5) and interface are needed. To perform the tests with elevated temperature, a heating plate (4a) with a controller (4b) is used. To measure the temperature, the option of the controller to connect the module internal PT1000 is used. The electrical signals are measured with passive voltage probes, a rogowski coil (6), and an oscilloscope.



(a) Photo of the test setup

(b) Schematic of the test setup

Fig. 2: Test setup and schematic

The resonant circuit can be dimensioned with the set of equations 1 - 3 and the elements of the setup are dimensioned targeting the specified parameters i_{max}, I^2t and f. A detailed discussion of the parameters is given in the section below.

The blocking capability of the power module can be used as V_{c0}. With the equations 1 and 2, L and C can be determined. Equation 1 is derived from the stored energy in L and C and provides the starting current $\hat{i}$ of the damped oscillation. However, the maximum current i_{max} during ASC has to be calculated by equation 3 at $sin(\omega \cdot t) = 1$.

$$\hat{i} = V_{c0}\sqrt{\frac{C}{L}} \tag{1}$$

$$\omega = \sqrt{\frac{1}{L \cdot C}}, \qquad f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{L \cdot C}} \tag{2}$$

$$i(t) = \hat{i} \cdot e^{-\delta \cdot t} \cdot \sin(\omega \cdot t), \qquad \delta = \frac{R}{2L} \tag{3}$$

$$I^2t = \int_0^{\infty} (i^2(t))dt = \hat{i}^2 \frac{1}{4}(\frac{1}{\delta} - \frac{\delta}{\delta^2 + \omega^2}) \tag{4}$$

Once L and C are determined, the parameter I^2t is only influenced by the damping ratio (δ) of the resonant circuit. If high I^2t is needed, it is advisable to dimension the inductance of the coil as high as possible because the parasitic resistance decreases disproportionately.

The I^2t value of the total current can be calculated by equation 4. The envelope of the damped oscillation is almost symmetric with respect to the x-axis compared to the current in Figure 1b. A slightly asymmetric envelope is caused by the damping. Since the current signal starts with a positive peak and due to the damping, the amplitude of positive peaks is always higher than the one of negative peaks. When this effect is neglected the I^2t of the positive current through the IGBT is half of the value calculated by equation 4. The equation 4 is derived by the integration of the damped oscillation (eq. 3).

To perform an ASC test with this method, the following steps after calculation of parameters and assembling the circuit are needed: The switch under test (DUT) is blocked by a negative voltage of the gate driver (5). The capacitor C (3) 2 is charged by the voltage source (Vdc). With a V_{gdu} pulse of a sufficient length, the test is performed. A long "ON"-time is important so that the switch does not turn off the oscillating current.

Laboratory Testing Results

In a laboratory test using the novel method to evaluate the ASC robustness, one 1200V SiC and two different 750V Si power module types have been investigated.

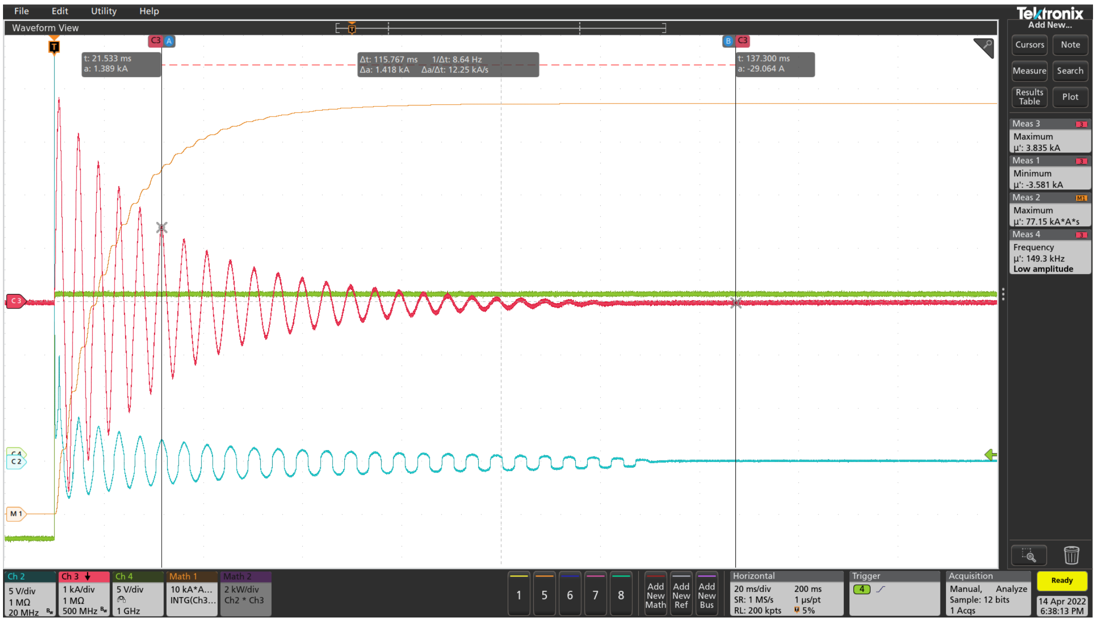


Fig. 3: Oscilloscope screen shot during the $77kA^2s$ test; (blue (Ch 2): V_{CE}, red (Ch 3): I_C, green (Ch 4): V_{gdu}, gold (Math 1): I^2t)

An exemplary scope picture is shown in Figure 3. It is the test with highest I^2t of the Table I. Besides waveforms of current and voltage, it includes the evolution of the $I^2t(t)$.

The test evaluates the ASC case shown in Fig 1 by the scope snapshot. All parameters are chosen to hit the evolution of $I^2t(t)$ best, as discussed in the next section. Tests were performed with elevated temperature. Specifically, 750V-900A-Module test is done at 165°C. This is the temperature of the last working point before the ASC occurs in the application.

Table I: Parameters of Test for different Power Modules

	i_{max} $[A]$	I^2t $[kA^2s]$	f $[Hz]$	L $[\mu H]$	C $[mF]$	Vdc $[V]$	$R[m\Omega]$
750V-900A-Module	3835	77	240	110	4	660	9
750V-650A-Module	1980	30.7	175	204	4	490	13
1200V-660A-Module	1675	6.642	415	72	2	342	17.5

In Table I, the values and parameters of the three tests are shown. The I^2t values of Table I are calculated from the application ASC currents. The calculated values and the actual values in the experiment slightly differ due to the damping of the forward voltages of the transistor and the diode.

With the components used, it is possible to test up to an I^2t of $77kA^2s$ at a peak current of 4 kA. To test beyond this value, the damping of the oscillating circuit must be decreased. For this purpose, the coil must be designed by an expert. Increasing the copper cross-section beyond the skin depth is usually counterproductive. The AC-resistance of an inductor also depends on number of layers, due to the proximity effect. For testing with lower I^2t values, the damping has to be increased by introducing longer cables or washers.

The power modules that were tested using the novel method show results which can help to investigate the robustness during ASC, as well as determine limits of the semiconductors and power modules. For this purpose, all tested modules were checked for deviations in an end-of-line test. The limits of the deviations correspond to those of a reliability test. In addition, a reliability test (e.g. H3TRB) can be performed with these modules.

Discussion of the Novel Test Method and Surge Current Tests

It is shown that with the novel test method, a current close to the ASC current in the application can be applied to the module. With the set of equations, the needed parameters can be calculated accurately. The following section will show why the new method is an improved test approach. It is also discussed on which parameters the main focus should be set.

To analyze the difference between the surge-current [4] test and the novel test method, a comparison of the current, the calculated $I^2t(t)$, and the resulting simulated junction temperature is given in Figure 4.

Framework of displayed curves

The current curves are measured, except for the ”initial ASC current (240 Hz)” (Fig. 4b). This is a fictive ASC current, due to the lack of measurement of the ”emulated current (320 Hz)”. The $I^2t(t)$ is calculated on the basis of the currents, it is the integration of the square of the current function. The temperature is simulated by the method described in the introduction and in [3].

The currents as shown in Figure 4a and 4b are only positive due to usage of an IGBT module test. The ASC current requirement as shown in Fig 1b is the basis for the investigation and is given in Fig 4, indicated as ”i(t, IGBT) initial”. Comparing the initial and the emulated current by the previously described test setup, some differences can be observed. The main difference is that the emulated current shows pure sine half-waves, whereas the initial current has a DC-offset.

To verify whether the emulated ASC testing is valid, thermal simulations with ASC, emulated, and the initial currents were made. The results (Fig.: 4e, 4f) show the junction temperature of the six different currents. The curves, ”T(t,IGBT) initial,” are the result of ASC during a full working inverter. If the junctions of the IGBT are heated up to 165°C by this working inverter, through which the 65°C coolant flows, the modules experience different thermal fields.

The resulting temperature development of the currents ”T(t,IGBT) emulation” is simulated in the same way with a 165°C pre-heated module as starting condition. This is needed to perform a lab test without a full functional inverter including cooling and sufficient power-supplies. The surge current curves, ”T(t,IGBT) surge,” are simulated under the same starting conditions. Due to the pre-heating, a homogeneous temperature field is present in the module.

Testing ASC with focus on the I^2t value

The emulated current of Figure 4a is tuned to get the best matching $I^2t(t)$ curve. This is the approach of the left side. Therefore, the frequency and the damping of the emulated current is lowered to 240 Hz. A longer first sine half-wave and higher following ones cause best tracking of the $I^2t(t)$. With the standard surge current test [4], a 50 Hz half-sine wave is applied to the power module.

Looking at the pure I^2t values in Figure 4c at the end of the tests, there is no difference between all method and the one of the ASC in the application. The time progression of the $I^2t(t)$ curve is also significant, due to different peak temperatures. The initial and emulated $I^2t(t)$ curves are looking similar despite the smaller slope of the emulated one. In contrast, the shape of the $I^2t(t)$ curve of the 45 Hz surge current test clearly deviates from the others.

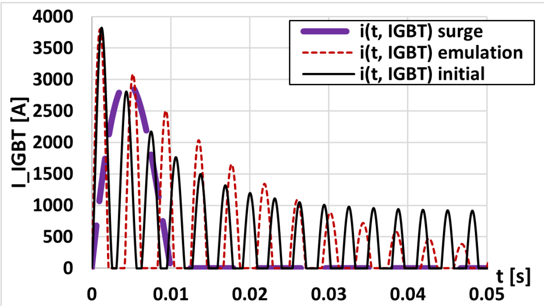
As can be seen in the figures 4e, the temperature curves show deviations from those of the ASC application. It is noticeable that the surge current causes an enormous overshoot. Unrealistic high temperatures can destruct the semiconductors or the module.

Testing ASC with focus on the temperature development

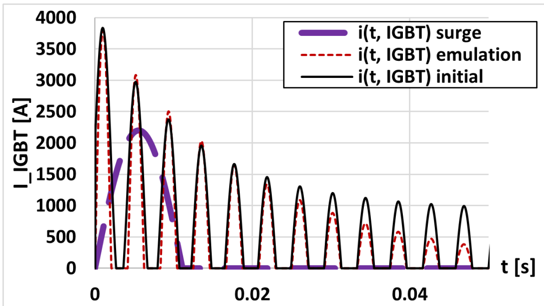
To determine the parameters of the laboratory test, thermal simulations (Fig. 4f) are carried out upfront with various emulated currents (surge current and pre-heated modules. The goal is to hit the temperature curve of the ASC in the application.

The emulated current in Figure 4b is the same as on the left and the "initial ASC current" is changed. The simplest way is to cover the current envelope and the parameters i_{max},and f of the initial current. This approach is shown here because of its reasonably good temperature matching and its simplicity. With the surge current test, a 45 Hz half-sine wave with lower i_{max} is applied to the power module to hit the envelope of the temperature.

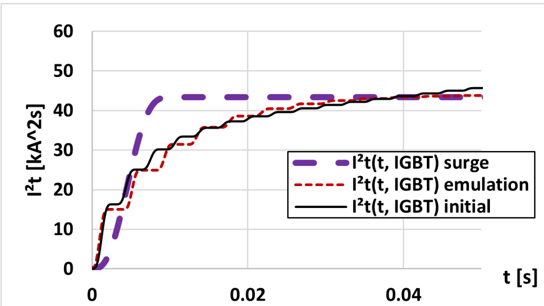
The $I^2t(t)$ and temperature curves on the right are calculate in the same way as on the left. The matching of $I^2t(t)$ curve plays a minor role. The $I^2t(t)$ curves shown in Fig. 4d have bigger differences at the end.



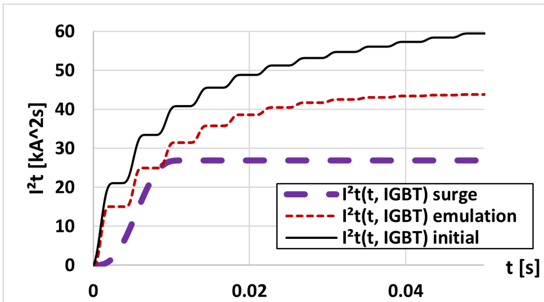
(a) Initial ASC current (320 Hz), Surge-current (50 Hz) and the emulated current (240 Hz)



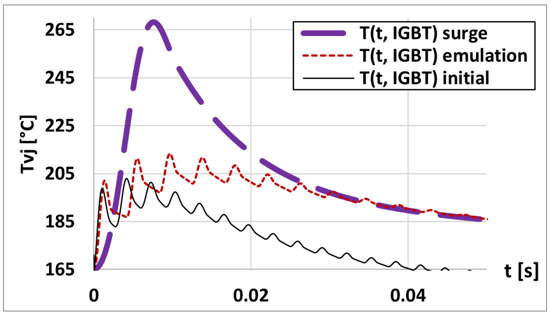
(b) Initial ASC current (240 Hz), Surge-current (45 Hz) and the emulated current (240 Hz)



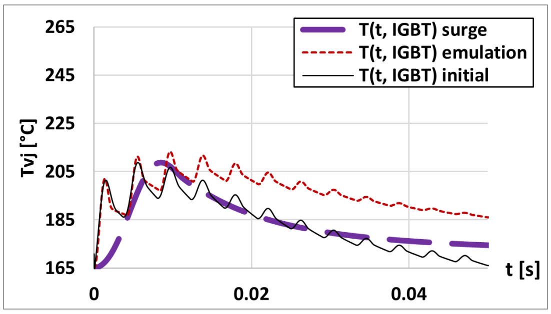
(c) $I^2t(t)$ values of ASC current (320 Hz), Surge-current (50 Hz) and the emulated current (240 Hz)



(d) $I^2t(t)$ values of initial ASC current (240 Hz), Surge-current (45 Hz) and the emulated current (240 Hz)



(e) Module heating with Initial ASC current (320 Hz), Surge-current (50 Hz) and the emulated current (240 Hz)



(f) Module heating with initial ASC current (240 Hz), Surge-current (45 Hz) and the emulated current (240 Hz)

Fig. 4: Comparison of $I^2t(t)$, time-dependent currents, and the virtual junction temperatures with original ASC , LC resonator and surge current tests.

Comparing the different focal points

As seen in Figures 4e and 4f, the temperatures on the right side (Fig.4f) are matching better to each other despite different I^2t values than those on the left side (Fig. 4e). Because of different thermal fields due to different cooling and heat generation conditions, the amount of stored heat can also be different without significant temperature rises.

The emulated current of Figure 4b causes the same junction temperature as the initial ASC current in the first sine half-waves. However, after reaching similar peak values, the temperature in the test with emulated current, ”T(t,IGBT) emulation,” decays much slower. The temperature development of the surge current shows in the beginning a bigger tracking error because temperature rise is delayed.

The analysis of the temperature shows that the parameters have to be set to hit the best possible match of the temperatures. Therefore, the emulated current could cover at least the envelope of the initial current. A finer tuning of the damping of the emulated current or a turn off the DUT in the right moment would lead to the best result.

The $I^2t(t)$ and I^2t are only sufficient values for tests if the cooling and heating is identical.

The correlation of temperature and current (Fig.:4) has to be considered, as well. As shown in Fig 4f, the corresponding thermal responses and the emulated current are almost identical to those of the initial current for the first sine half-waves. This is the range of interest, due to occurring simultaneously very high current amplitudes and temperatures.

It is also possible to test the peak current and the correlated heating of the semiconductor for a SiC MOSFET or a diode-IGBT pair in only one test.

Summary

A novel test method for testing the ASC fault condition, without the original inverter and drive train, in the laboratory is described here. It is shown how the original ASC current can be emulated with a resonant circuit and how the elements of the resonant circuit and the pre-charge voltage are calculated. In the laboratory test described in this article, it is shown that the novel method can test a wide range of different ASC and different module types such as Si and SiC (Tab. I).

Conclusion

It is possible to test all critical values of the ASC ($i_{max\ D,IGBT}$, T_{max}). Therefore, the current shape must be emulated accurately and the I^2t value can be neglected.

It is shown that the method allows a more accurate reproduction of the ASC temperature profile in the range of interest as compared to surge current tests.

Because of similar currents and temperatures in the range of interest, the novel method can test the ASC in the lab best. The new method benefits from the similarity with the ASC in application.

Outlook

In order to strengthen the evidence shown in this method, further investigations will be conducted. Some of these investigations include FEM simulations with dynamic ASC currents, further reliability studies, testing of the limits, and analysis of the destruction patterns and measurement of T_{vj}.

References

[1] Aravind Ramesh Chandran, Martin D. Hennen, Antero Arkkio and Anouar Belahcen, Safe Turn-off Strategy for Electric Drives in Automotive Applications, Published in: IEEE Transactions on Transportation Electrification (Early Access), DOI: 10.1109/TTE.2021.3104461
[2] Poulain, Christophe & Metz-Noblat, B. & Dumas, F.. (2005). Calculation of short-circuit currents.
[3] Arne Bieler, Ole Mühlfeld, Analytical Modelling of Dynamic Power Losses Inside Power Modules for 2-Level Inverters, PCIM Europe 2018, 5 – 7 June 2018, Nuremberg, Germany
[4] Antoni Ruiz et al.: Active Short Circuit Capability of Half¬-Bridge Power Modules Towards E¬-Mobility Applications, PCIM Europe digital days 2021, 3 – 7 May 2021
[5] Hayato Nakano et al.: Impact of I2t capability of RC-IGBT and Leadframe combined structure in xEV active short circuit survival, PCIM Europe 2018, 5 – 7 June 2018, Nuremberg, Germany