The Grey Area

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Data sheet specifications for power semiconductors are values which are assured by the manufacturers. But they can only be used to a limited extent for dimensioning and calculation.

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Even semiconductor parameters which at first glance appear mundane and often negligible, such as the reverse current, can become crucial for the operational reliability of the entire system when they are examined in more detail and there is an appropriate operational mode. Another “static” parameter alongside the blocking characteristic is the forward voltage of semiconductors. Contrary to the blocking behaviour where the residual current through the semiconductor is specified in the turned-off state, the forward voltage VF, VT or VCE(sat) describes the voltage which remains across the element when it is in the turned-on state. Depending on the technology and the type of semiconductor, the forward voltage is in the range of approx. 1V (for thyristors and diodes) up to approx. 5V (for high-blocking transistors). For power semiconductors which are typically used in switching operations, the forward voltage is portrayed in trends as a function of the current, the temperature and the activation conditions. What these diagrams do not reflect is the fact that, in the transition from the blocking to the conducting state, it takes a certain amount of time until the forward voltage reaches its static value which is stated on the data sheet. The "forward-recovery" voltage arises when the junction areas are not yet fully inundated with charge carriers and only partial conductivity arises. The voltage swell, which is also again dependent on other parameters such as temperature or the di/dt of the current, takes a few microseconds even with fast components such as IGBTs or epi-diodes and, if the elements only conduct for very short periods of time, this can easily increase the forward power losses considerably compared with the value on the data sheet.

The following example shows the turn-on of a 400A/3300V free-wheeling diode in an IGBT module. In spite of the really low di/dt of the current, an anode-cathode voltage of almost 20V is produced, which reaches its static passage value only after approx. 10 µs. It is only after this time that the junction of the diode is completely inundated with charge carriers – the diode is in the saturated conducting state.

When the semiconductors are operated with very short current pulses, there is another critical operating point whose effects are not specified on any data sheet. By means of suitable diffusion profiles and strengths, the charge carrier life spans are set in such a way that the flooding and evacuation of the junction regions takes place continuously, i.e. adapted to the load current. However, this requires that the junction is also completely inundated with charge carriers. Power semiconductors which are fabricated with such doping profiles are noted for having a so-called "soft" switching behaviour. The current transitions are constant, without any steps. But even elements with "soft" switching behaviour also change their characteristics if, as a result of very short turn-on or turn-off times, the static states of "blocking" or "conducting" are not achieved.

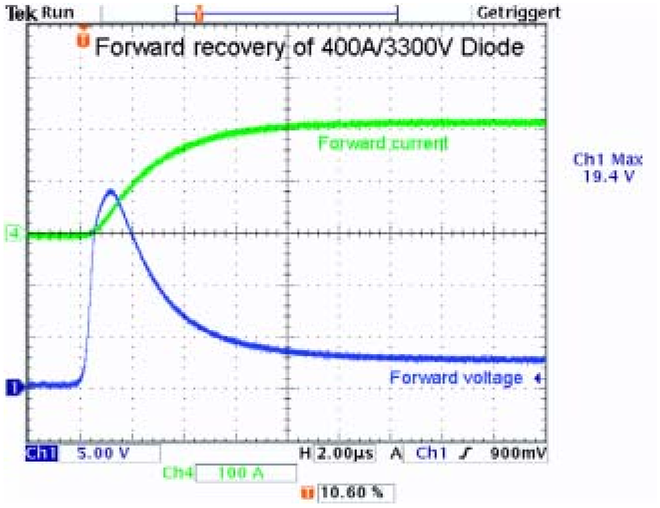


Figure 1: Forward recovery behaviour of a 400A/3300V IGBT free-wheeling diode

Example:

The active input rectifier of a 3-level NPC converter works perfectly at full load and partial load. However, in low partial-load operation and when in idle mode, the electromagnetic interferences increase so much that the signal transmission and communication within the converter repeatedly grinds to a halt and failures of IGBT modules were also seen.

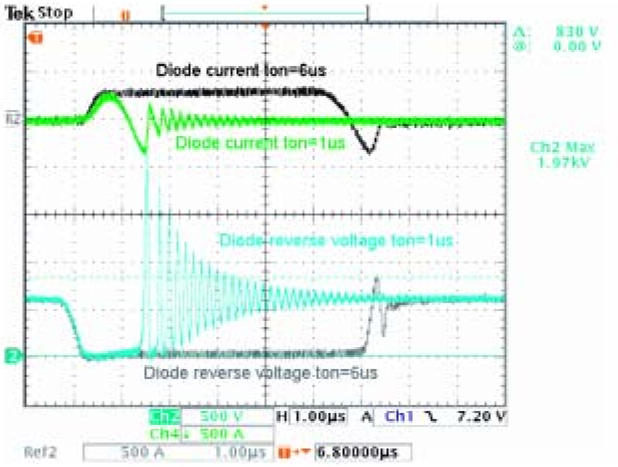
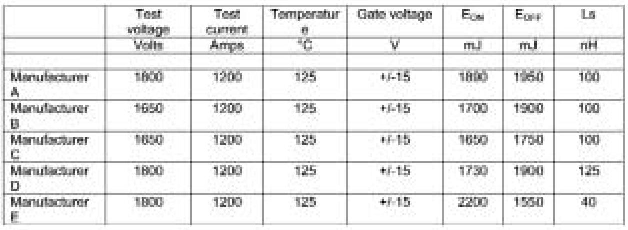


Figure 2: Turn-off behaviour of a 1200A/3300V IGBT free-wheeling diode with a long turn-on time (6µs) and a short turn-on time (1µS)

The cause of this were, owing to the control behaviour, short pulses in the range of 2-3µs relating to the neutral point diodes. As can be seen from the "forward recovery" in figure 1, the diodes are not yet fully turned on after this time. If the junction is now removed from the charge carriers again by the application of the reverse voltage, this will happen very quickly on account of the non-existent saturation of the diode. The forward current through the diode breaks off with a very high di/dt and this produces high overvoltages coupled with severe oscillations.

The two measurements were each performed with 300A diode current and 600V DC-link circuit voltage. With a turn-on time of 6µs, the diode is almost completely saturated. The subsequent commutation process is gentle, the clearance of the charge carriers is continuous and the resulting overvoltage is low. The non-saturated diode interrupts its reverse recovery current very quickly, and the high di/dt produces a switching overvoltage which can become so high that the limit voltage of the semiconductors is exceeded.

Conclusion: Alongside the obligatory low-inductance execution of the commutation pathways, the control process of the semiconductors can also bring about problematic operating states. Particularly in the case of IGBT modules with reverse voltages of >= 2500V, it is therefore absolutely essential to comply with minimal turn-on and turn-off times.



	Test voltage	Test current	Temperature	Gate voltage	E_{ON}	E_{OFF}	Ls
	Volts	Amps	°C	V	mJ	mJ	nH
Manufacturer A	1800	1200	125	+/-15	1890	1950	100
Manufacturer B	1650	1200	125	+/-15	1700	1900	100
Manufacturer C	1650	1200	125	+/-15	1650	1750	100
Manufacturer D	1800	1200	125	+/-15	1730	1900	125
Manufacturer E	1800	1200	125	+/-15	2200	1550	40

Table 1: Switching energy specifications for various 1200A/3300 IGBT modules

Another aspect which is very important for the dimensioning and functional reliability is the dynamic losses of the power semiconductors which, depending on the application, can account for more than 75% of the total power loss of a system. Reliable data sheet specifications are vital here, but the interpretation of the specified values is just as difficult as the interpretation of the reverse currents. Most manufacturers of power semiconductors, especially IGBT power modules, only provide typical specifications both in the characteristic values and in the diagrams relating to the switching energies. Even if the power and voltage specifications under which the values were determined are handled almost uniformly, they still differ on one important point, the leakage inductance of the test benches. The following table shows the EON/EOFF specifications for 1200A/3300V IGBT modules from different manufacturers:

If you take account of the slightly lower test voltage with two of the manufacturers, the switching energies for manufacturers A to D are of the same order of magnitude. Only manufacturer E deviates from this, but with lower values for the leakage inductance. This has a substantial influence on the relation between EON and EOFF. A simple test makes the influence of the leakage inductance clearly visible. In an existing converter output stage, the electrolytic capacitors which were originally provided were replaced with polypropylene capacitors. The mechanical structure, that is to say the inductance of the feed lines and the DC link bus bar configuration, remained the same. The internal inductance of the electrolytic capacitor bank was approx. 250nH, and that of the film capacitor bank was approx. 40nH.

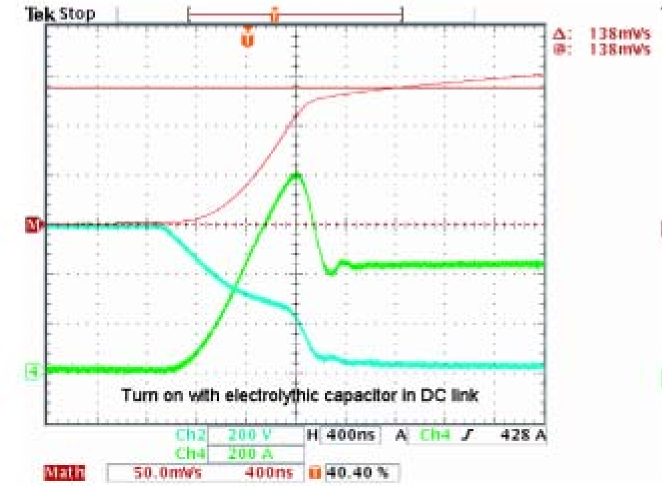


Figure 3: Turn-on behaviour with electrolytic capacitors

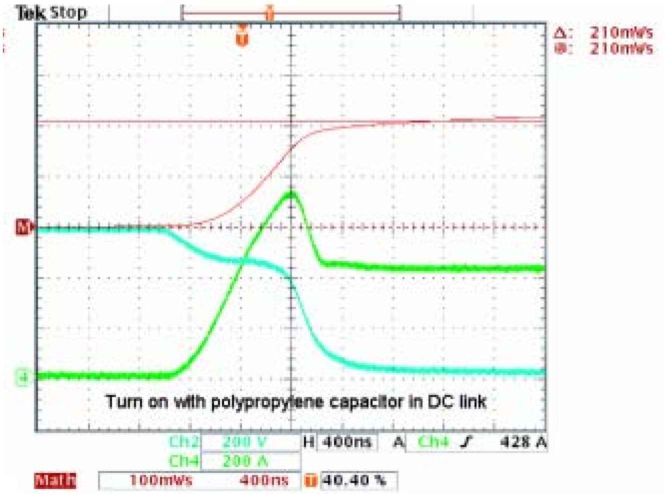


Figure 4: Turn-on behaviour with film capacitors

The inductive voltage drop which is caused by the leakage inductance when the IGBT is turned on reduces the turn-on energy.

However, when the power is turned off, exactly the opposite is achieved and the increased leakage inductance generates higher turn-off voltages and thus also higher turn-off losses:

In this example alone, the total switching losses EON+EOFF increase from 281mJ to 337mJ, and this is primarily as a result of the changed turn-on behaviour.

This means that the varying data sheet specification of manufacturer E in Tab. 1 can also be explained. The much lower leakage inductance leads, as a result of the lower inductive voltage drop on the collector of the test specimen, to higher turn-on losses, but also to lower turn-off losses. This correlation puts the high EON and lower EOFF values of manufacturer E into context. In a test environment which displays the same leakage inductances of the other competitors of approx. 100nH, the dynamic losses will also approximate one another. The first impression does not always have to be the right one.

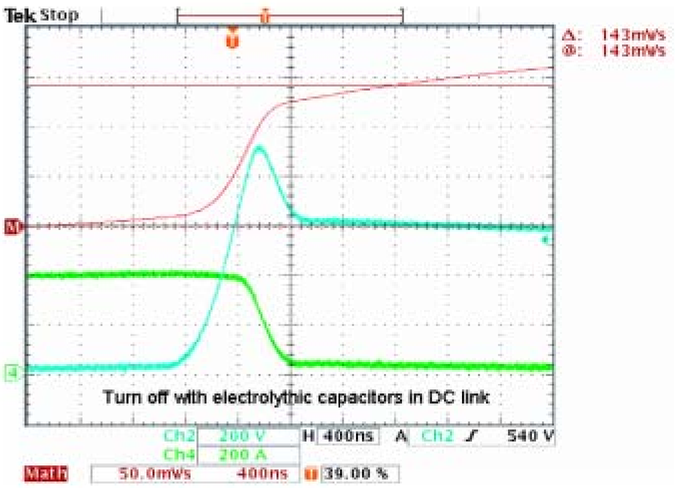


Figure 5: Turn-off behaviour with electrolytic capacitors

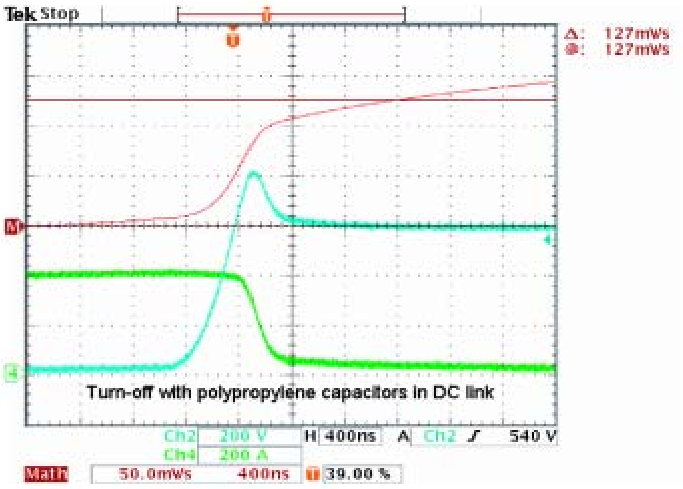


Figure 6: Turn-off behaviour with film capacitors

The leakage inductance is of course not the only thing that determines the switching losses. The activation of the IGBTs largely governs the dynamic behaviour, and a powerful driver output stage which also quickly provides the required gate voltage of +15V offers the best prerequisite for an optimum design.

In addition to the actual semiconductor parameters, specifications such as the external thermal transfer resistance RTHCH are also of key significance for the thermal design and operating reliability. Although this value is governed by purely mechanical conditions and material properties, very high deviations often occur here between the real structure and the data sheet values. The optimum heat transfer would result if there were a firmly bonded connection between the semiconductor base plate and the heat sink, so without any air pockets and with contact over the full area. However, as this cannot be achieved in reality, an attempt is made to avoid the air pockets which occur between the semiconductor and the heat sink during assembly by using elastic, thermally conductive materials such as films or viscous pastes. But these auxiliary thermal materials generally display much poorer thermal conductivity than metals and therefore the application thickness of the pastes or the thickness of the films has to be chosen to be sufficiently high on the one hand to avoid any "gaps" in the thermal conductivity path but on the other hand it must be as low as possible in order to keep the thermal resistance at its minimum.

In modern, thermally optimised designs, attempts are increasingly being made to calculate the chip temperature which is produced during operation by means of a thermal simulation running in parallel with the gate pulse pattern and thus improve the performance capacity of the output stage. However, the simulation requires exact knowledge of the thermal conditions and thus the reproducibility of the transfer resistances which occur when the semiconductors are assembled. The best option for this is to adopt a screen printing method as the quantity of paste and the distribution on the cooling surface are then defined.

But even if these requirements are met, the data sheet value for the RTHCH must be examined very critically in a new design. The power loss in an IGBT module does not arise evenly distributed across the entire cooling surface, but only in the active areas which are covered by the semiconductor chip. If the thermal transfer is now to be verified by way of measurement, the measurement points must be located exactly at these "hot spots".

Specifically, they must be located in the module base plate and on the side lying directly opposite in the heat sink. If the measurement is only carried out on the edge of the module, the values will be distorted on account of the lateral thermal conductivity of the base plate material and the cooler material.

As has been shown, especially when the power components have a thermally tight design, the data sheet specifications for power semiconductors must always be critically examined and scrutinised. What may appear at first glance to be advantages or disadvantages often appear in a different light in the real device.

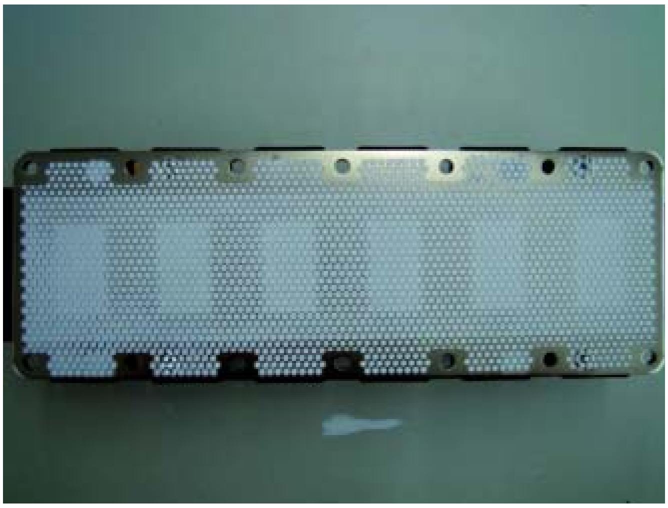


Figure 7: Application of the thermally conductive paste using the screen printing method