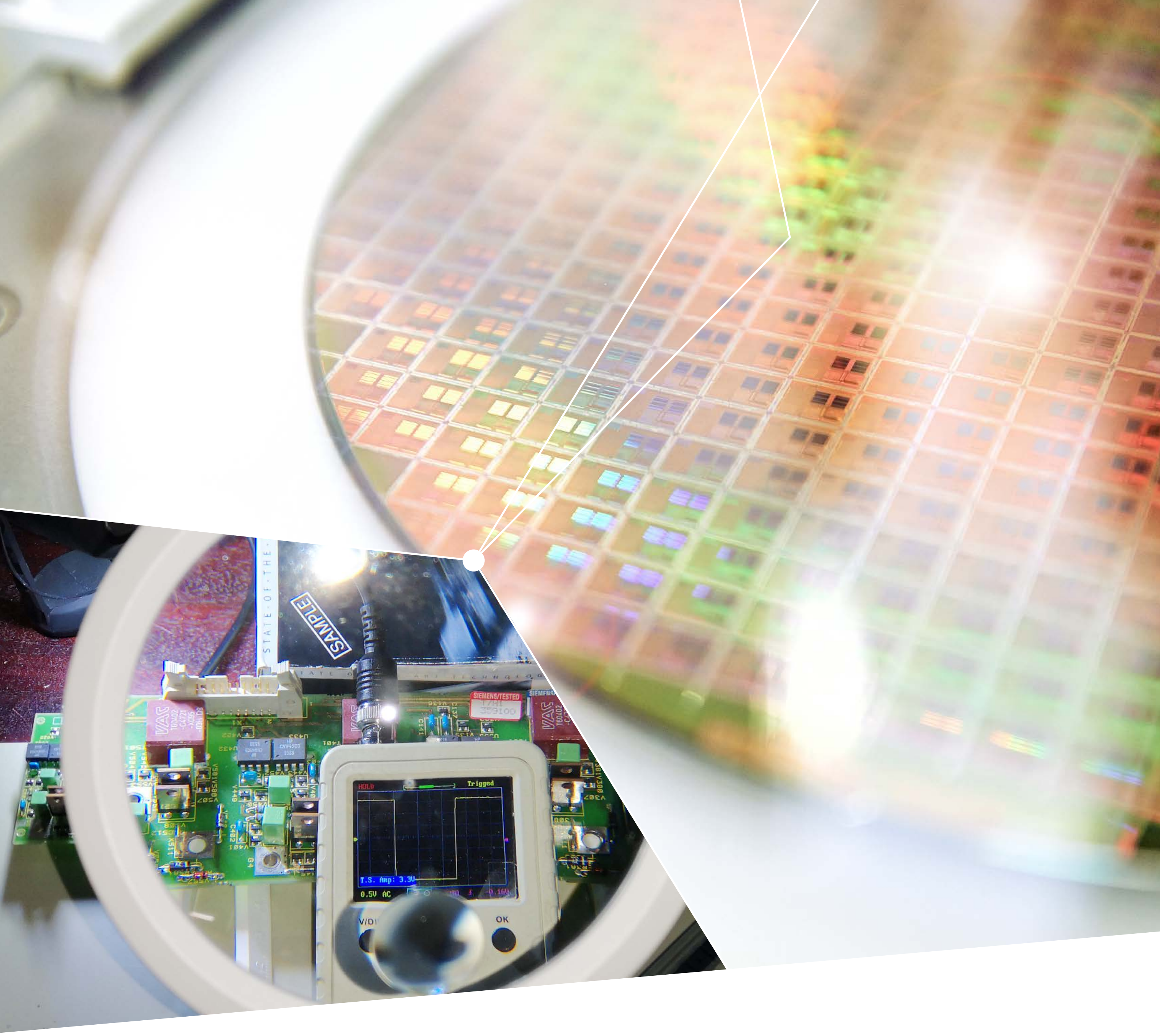


IGBT-basic know-how

IGBT: how does an Insulated Gate Bipolar Transistor work?

Dr. Martin Schulz
Principal Application Engineering
Infineon Technologies

www.infineon.com

v1.0

About the author
Dr. Martin Schulz has been with Infineon since 2005. In 2011, he joined the application-engineering group. His responsibilities are in the area of electrified commercial and agricultural vehicles (CAV). Furthermore, thermal management and interconnection technologies are his field of expertise. Martin Schulz holds a Dr.-degree in electrical engineering, gained at the University of Siegen at the department of Power Electronics and Electrical Drives. He holds several patents in the field of power electronics and is a Senior IEEE-Member.

Dr. Martin Schulz

Today, the IGBT comes very close to being considered an ideal switch. Then again – what is the difference between an IGBT and a MOSFET? What advantages does an IGBT offer and how does it work?

In technical communities focusing on power electronics, questions like this one regularly arise: "I have to design an H-bridge to control a motor. Voltage is 320 V, the current is 2 A, switching frequency is 30 kHz. To remain on the safe side, I'm searching for a switch with 600 V blocking capability. I have no idea whether to use MOSFET or IGBT. Any hints as to criteria to do a proper selection?"

In this case, there is no simple decision, as some important parameters are missing. For the target set, solutions with 600 V MOSFET as well as using 600 V IGBT come to mind. Important criteria not mentioned in the query, relate to size, efficiency and cost targets.

The IGBT, or Insulated Gate Bipolar Transistor, became the most used power electronic component in industrial applications. In the meantime it has become a central component in inverters for all types of electric drives, battery chargers, and solar and wind power plants. But why? What is so special about this component? What are the strengths and what challenges have to be handled when using this technology? The answer to these questions lies within the technology itself.

The wide portfolio of available parts

From speed-controlled, low-power compressor drives in refrigerators to traction drives in railways: the IGBT has taken over a dominant position within the last decades.

From a multitude of packages, the user can choose devices from 300 V in discrete designs to power modules supporting 6500 V. Current-carrying capability of a single transistor spans a range from a few amps to several kilo-amps.

Besides the well-established TO-package series, SMD-components are available, accompanied by power modules for the highest power demands.

Depending on the power to be handled, soldering or press-in connectors are in use, while currents exceeding 200 A typically demand screw-type terminals. Figure 1 includes a minute section of packages available on the market.

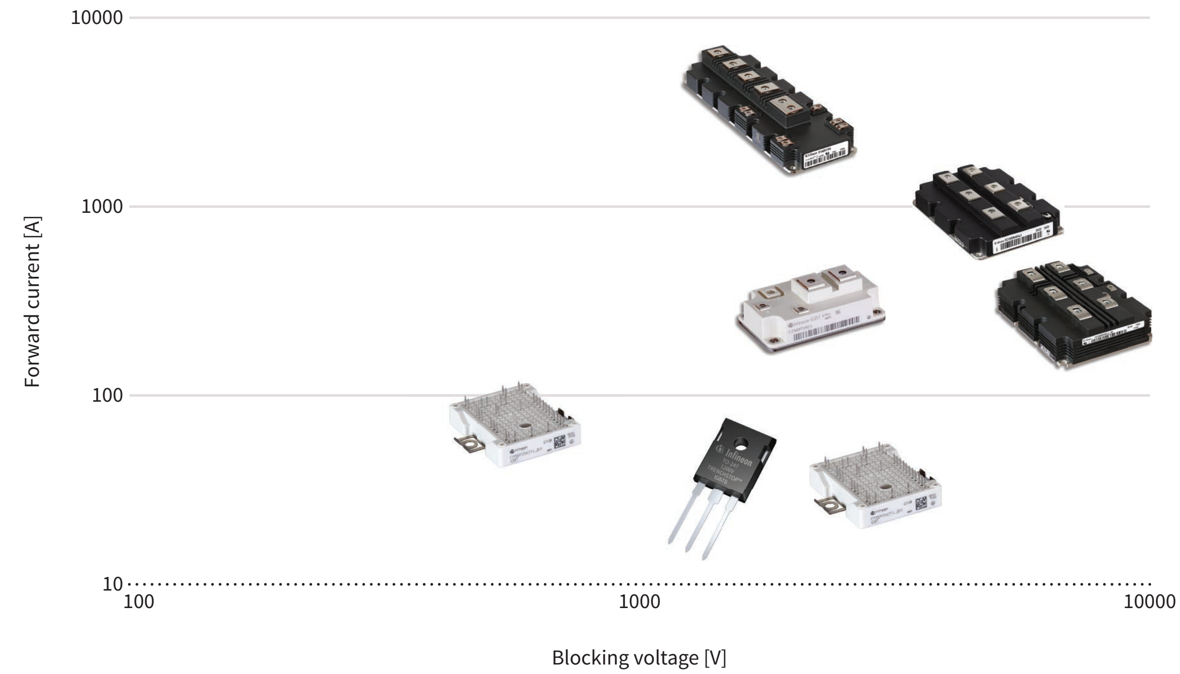


Figure 1: IGBT-Overview on dimensions

IGBT: a simple technology

The most basic function of an IGBT is the fastest possible switching of electric currents, thus achieving the lowest possible switching losses. As the name "Insulated Gate Bipolar Transistor" reveals, an IGBT is a bipolar transistor with an isolated gate structure; the gate itself is basically a MOSFET. Therefore, the IGBT combines the advantages of high current-carrying capabilities and high blocking voltages of a bipolar transistor with the capacitive, almost zero-power based control of a MOSFET. Figure 2 depicts how a MOSFET and a Bipolar Transistor combined lead to the IGBT.

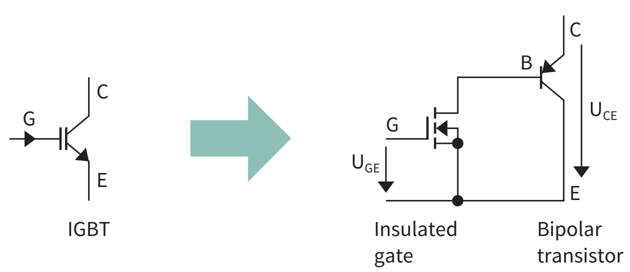


Figure 2: IGBT in detail – the MOSFET represents the gate, the bipolar transistor the output stage

The schematic only depicts the general structure. In reality, the technical design is not based on two independent devices. The overall function is the consequence of integrating the structure at the chip level.

With the MOSFET acting as a gate structure, the Base of the bipolar transistor is no longer available. The device is now connected via Collector, Gate and Emitter.

The fundamental function of the IGBT is rather simple. A positive voltage U_{GE} from gate to emitter turns on the MOSFET. Then, the voltage connected to the collector can drive the base current through the bipolar transistor and the MOSFET; the bipolar transistor turns on and the load current can flow.

Vice versa, a voltage $U_{GE} \leq 0$ V turns of the MOSFET, the base current is interrupted, and the bipolar transistor turns off as well.

Due to the capacitive nature of the MOSFET, the gate current only needs to charge the gate capacity. The RMS value of the gate current sums up to almost zero. Therefore, you hear very often that the power to control an IGBT is zero.

This simplification often is a root cause for troubles in designing the application. Developing hardware to control an IGBT – a gate driver – is a task that may keep a small development team busy for a while.

However, this much effort is most likely unnecessary. Some semiconductor manufacturers offer suitable hardware with a wide variety of functionalities as integrated solutions. A suitable gate driver can be designed by utilizing dedicated gate driver ICs and sticking to the proposals given in datasheets and application notes.

As a power electronic device, the IGBT is optimized for high switching speeds. Operating it in linear mode similar to MOSFETs in former audio amplifiers is highly undesirable. This mode of operation would lead to massively increased losses.

With the output characteristics of the bipolar transistor, further features of the device result. An IGBT can carry current in one direction only, and during operation there is always a forward voltage correlated to a PN junction. IGBTs are well suited for a switching frequency range up to 30 kHz. Using special techniques, so-called resonant topologies, the switching losses can be reduced, and higher switching frequencies can be achieved.

In contradiction to a MOSFET, IGBTs can be built to withstand very high voltages. With an overlap between 300 V and 600 V, the low-voltage domain is covered by MOSFETs, while voltages exceeding 600 V today are dominated by IGBTs.

Other than with a MOSFET, an IGBT does not inherently contain a freewheeling, or body, diode by design. This diode, however, is a part needed to protect the switch providing a freewheeling path to prevent reverse current. When choosing a component, care has to be taken to either add a suitable diode or go for a component with an integrated diode die.

The schematics of the components given in figure 3 suggest devices containing an IGBT only or a so-called co-pack including IGBT and diode.

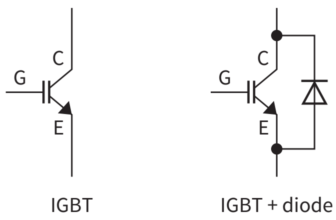


Figure 3: Only IGBT, and IGBT co-packed with freewheeling diode

To improve the switching performance of an IGBT, auxiliary emitters are commonly used. This connection reduces the influence of stray inductances within the gate circuit. What has become a de-facto standard in power modules, has also recently reached discrete components in the newly designed TO247-4. Figure 4 depicts the details in the differences between the two packages.

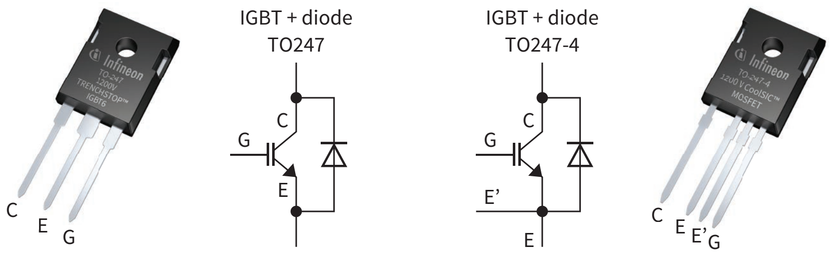


Figure 4: Difference between TO247 and TO247-4

The auxiliary Emitter E' does not contribute to carrying the load current. This reduces the distortion resulting from inductive coupling. A current change di/dt within the gate circuit is eliminated, so is an induced voltage. As a result, the switching gets cleaner, easing the work to be done to achieve EMI targets.

IGBT and more – cleverly integrated in power modules

In most cases, a single switch is not enough for a developer to build the design. Within a frequency converter, typically two units are necessary. First, the supplying voltage taken from the grid has to be rectified, and the DC-voltage level sometimes needs to be adapted or stabilized. Afterwards, an inverter is used to convert the DC-link voltage into the AC system desired, which can be different from the supplying grid in frequency, amplitude and even number of phases.

In case the application does not demand regenerative operation, a simple diode rectifier can be chosen. The energy from the application leads to an increase in the DC-link voltage. Here, a break chopper is installed, and in the case of excess energy, it provides a path for handling energy safely by converting it into heat.

To support building common designs and to minimize the effects of unwanted influences, semiconductor manufacturers combine the necessary components into power modules. The schematic given in figure 5 includes a rectifier, a break chopper and the inverter needed to form a converter. The colors denote groups, which are available as individual components; table 1 summarizes names and contents.

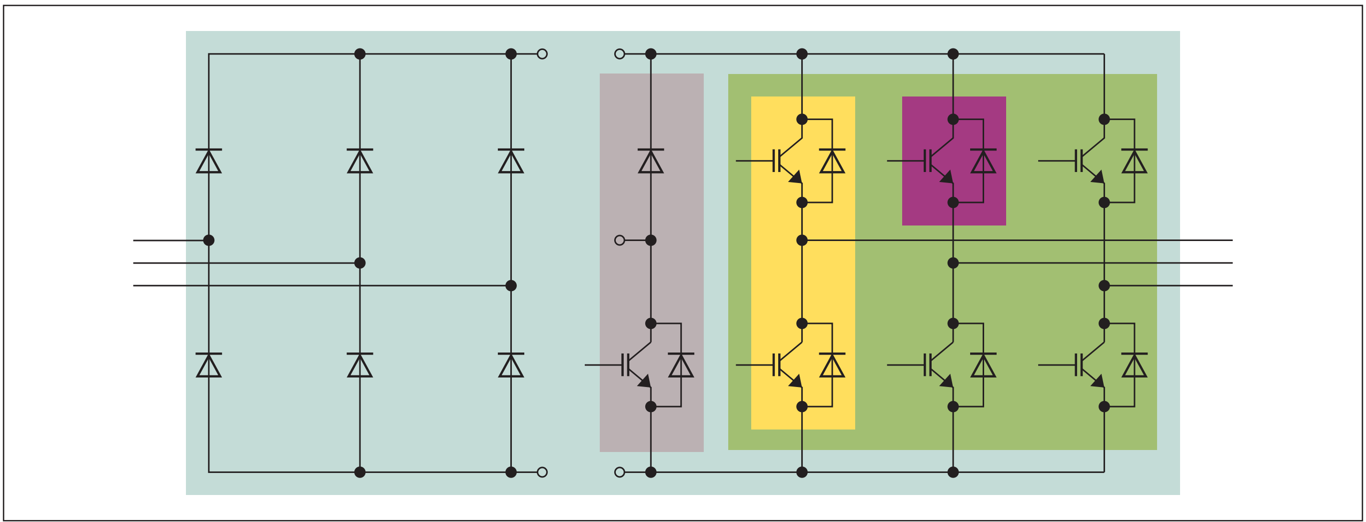
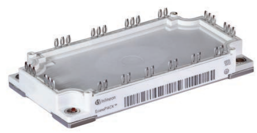
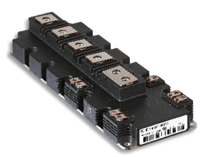
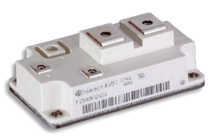
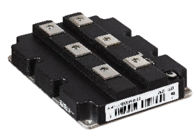


Figure 5: Semiconductors, grouped in power modules

Table 1: Choice of devices and basic parameters

Name	Content	Voltage [V]	Current [A]	Example
PIM or CIB Power Integrated Module Converter, Inverter, Break	Rectifier, break chopper, inverter	600–1700	6–150	 
Sixpack or full bridge	Inverter DC to 3~	600–1700	6–600	 
Break Chopper	Diode/IGBT with freewheeling diode	600–1700	25–1400	 
Half bridge	Inverter DC to 1~	600–6500	200–1800	 
Single switch	IGBT with freewheeling diode	1200–6500	200–3600	 

About 90% of the industrial applications are pumps, fans and other systems that do not demand a bidirectional flow of energy. The solution based on a diode rectifier therefore serves the majority of systems. Besides the most common topologies, advanced combinations of semiconductors are available. Among other things, this includes various multi-level designs as well as Vienna rectifiers or matrix-converter structures.

Controllable thermal properties

Today's IGBTs are quite similar to what is considered the ideal switch. An ideal switch is characterized by zero current when turned off, and by zero voltage across the device when turned on. As a consequence, an ideal switch does not generate any losses, and therefore does not create heat. Modern IGBTs reach efficiency levels of > 99% for the individual switch, however, thermal management is an important topic that should not be neglected.

Considering power levels where discrete components are sufficient, assembling the power semiconductors is business as usual. As known from TO-packages, for example, the component is mounted to a heat sink, which in turn is fixed to the PCB by means of soldering or screwing. Attention has to be paid here too, as most discrete packages feature an electrically active back side, typically the collector of a switch.

On a common heat sink, only parts that share a common voltage can be grouped. Failing this, to avoid short circuit, isolation barriers between the switch and the heat sink become mandatory. These in turn reduce the thermal transfer and therefore the performance of the semiconductor.

In higher power levels, IGBTs grouped in power modules are used. The thermally active backside of these modules is galvanically isolated. This way, all dies involved share a common surface that can be mounted to a single heat sink. To improve thermal performance, applying a thermal interface material is mandatory. For this, care has to be taken to choose a material that can support the thermal situation as well as the lifetime demands of the application.

Despite the efficiency levels reached today, power losses can be serious. In a windmill application with 5 MW throughput, power electronics generate, to put it simply, 100 kW of losses if the overall efficiency is 98%. This is heat in other words, which needs to be handled and dissipated in a safe manner.

Though the voluminous high-power modules appear to be massive, solid entities, mechanical handling and mounting deserves some caution. Despite the solid design, mechanical issues can later be distinguished as the root cause of the damage, be it done during mounting or failure in operation.

Here too, the manufacturer's application notes give an insight into tried-and-tested procedures. Respecting the given limits and instructions is a first step towards a reliable, long-lasting design.

Easy-to-estimate dimensioning

Back to the posting found on the Internet about which component to use – IGBT or MOSFET, from the few details given, a first estimate can still be made.

The voltage is rated 320 V, a typical value when rectifying a 240 V line voltage. This does not take into account that line voltages include some tolerances, which also reflect in the DC voltage after rectifying. With a 10% adder, the maximum DC-link voltage within the system can easily reach 350 V. This eliminates devices rated 400 V or less from the list. The reason behind this is a transient phenomenon, creating a voltage spike during turn-off. As a rule of thumb, a device should not be driven with voltages higher than about 2/3rd of the rated blocking, or break through, voltage. The remaining 33% are kept as a margin for transient overvoltage spikes.

To carry a motor current of 2 A, a device rated 2 A is not sufficient either. The reason is to be found in the thermal budget of the switch. This includes the forward losses when the switch is turned on, as well as the switching losses and thermal resistances of the device itself. At the same time, over-dimensioning by factor ten is undoubtedly too conservative.

Comparing switching losses, a MOSFET outperforms an IGBT when both have the same current rating, making it the predestined device for higher switching frequencies. However, the static losses grow by I^2 in the MOSFET according to $P_{VMOS,Stat} = I^2 \cdot R_{DS}$.

Due to its bipolar character, losses in an IGBT only grow linearly with current according to $P_{VIGBT,Stat} = I \cdot U_{CE}$. Typically, this makes it the better choice in high-current applications.

With a few fundamental values taken from a datasheet and a little mathematical effort, the thermal correlations can be evaluated. This allows for a first estimation whether or not a considered component could be a suitable choice. An important prerequisite for this thermal estimation is an anchor point to start from, given by a temperature and the thermal connection. Using the chain of thermal resistances R_{thJH} from the chip's junction to the heat sink, and the maximum heat sink temperature T_{HS} presents a suitable approach. A further alternative would be to choose the ambient temperature T_{amb} as a reference, accompanied by the thermal resistance R_{thJA} from chip to ambient. In this case, the heat sink's value R_{thHA} is included.

Table 2: Basic math for thermal evaluation

Parameter	Switching losses	Static losses	Chip temperature
E_{on}, E_{off}	$P_{dyn} = (E_{on} + E_{off}) \cdot f_{sw}$		
R_{DS}		$P_{VMOS,Stat} = I^2 \cdot R_{DS}$	
U_{CE}		$P_{VIGBT,Stat} = I_C \cdot U_{CE}$	
T_{amb}			$T_{Chip} = T_{amb} + (P_{dyn}+P_{stat}) \cdot R_{thJA}$
T_{HS}			$T_{Chip} = T_{HS} + (P_{dyn} + P_{stat}) \cdot R_{thJH}$

In case the maximum chip temperature calculated remains within safe operation limits, the component generally can be considered as suitable.

Whether or not the component provides a certain lifetime demands a more accurate examination including that of the application's load profile. A lab's equipment, an experiment or another setup rarely in use has totally different requirements as compared to an industrial drive in permanent operation.

But then again, the question "How long does my setup last?" is rather asked by professionals than by someone searching for help in an Internet forum.

Overview figures and tables

Published by
Infineon Technologies AG
81726 Munich, Germany

Order Number: B114-I0931-V1-7600-EU-EC
Date: 11 / 2019