PCIM Europe 2018, 5 – 7 June 2018, Nuremberg, Germany
www.pcim-europe.com

Impact of load profiles on power module design – a detailed analysis based on 7th generation of IGBT and diode technology

S. Buschhorn, Infineon Technologies AG, 59581 Warstein, Germany
A. Brodt, Infineon Technologies AG, 59581 Warstein, Germany
A. Lenze, Infineon Technologies AG, 59581 Warstein, Germany
A. Philippou, Infineon Technologies AG, 85579 Neubiberg, Germany
C. Jaeger, Infineon Technologies AG, 85579 Neubiberg, Germany
J. G. Laven, Infineon Technologies AG, 85579 Neubiberg, Germany
B. Sahan, Infineon Technologies AG, 59581 Warstein, Germany
C. R. Müller, Infineon Technologies AG, 59581 Warstein, Germany

Abstract

With focus on drives applications, the interaction between operating conditions and power module performance is analyzed. For different current and overload levels, the effect on junction temperature and temperature ripple is highlighted, and the impact of the heat sink design on the power module performance is derived. Based on an exemplarily chosen system, the interaction between heat sink and thermal stress is described, and the potential advantages of a temporary operation at elevated junction temperatures, e.g. 175°C, are presented. Finally, these results are applied to typical inverter designs, where one system has to support different load profiles.

1. Introduction

Variable speed drives are one of the most important segments with respect to their market share in the field of power electronics. At the same time, this segment is very diverse in terms of application conditions and requirements for power modules. These include, but are not limited to, switching slope constraints, continuous and overload output current capability, and temperature ripple limitations correlated to the used operation conditions, e.g. output current and output frequency. In this framework of different application requirements, actual benefits on system level coming from improvements of newer device generations are not always straightforward, i.e., achievable by, e.g., faster switching, lower losses, and higher continuous operation temperatures. Therefore, this article will focus on the analysis of the interplay between operation conditions and device requirements and, consequently, highlight the benefit of the new 7th generation IGBT and diode technology; a technology generation which is mainly targeting exactly on drives application segment.

The limitation of switching speed originates in the inherent isolation in motor and cables. Therefore, switching slopes (d*V*/d*t*) are restricted to the range of 2 to 10 kV/µs with its typical target of 5 kV/µs. In addition, typical switching frequencies f_{sw} are mostly limited to values below 8 kHz. Considering this, power semiconductor devices in drives application require lower static losses and an optimized switching performance at smaller d*V*/d*t* in contrast to devices designed for, e.g., solar application. It is worthwhile to mention that not only IGBTs but also diodes must fulfill these requirements. Hence, not only the individual optimization of each device is sufficient, but the mutual interdependency of diode and IGBT has to be taken into account. Focus on the optimal operation in the final system must be the target. More details on device design and balancing of switching and conduction losses can be found in Ref. [1].

Having these constraints for the power module design in mind, the power module choice is determined by application conditions such as switching frequency, cooling system $R_{th\mathrm{HA}}$, and the like. These define the power losses and junction temperature T_{vj}, and thus the maximum achievable output current I_{out}. Besides these general performance indicators, in drives – and also in traction – the load profile has to be considered: a variation of the output current leads to changing T_{vj} and thus temperature ripples ΔT on different timescales. On the one hand, this implies that the achievable output current has to be derived based on the overload requirements. On the other hand, the temperature ripples induce thermal stress to the power module. This thermal stress results in a deterioration of interconnections and is a typical figure-of-merit for evaluating the module performance under the given operation conditions. This impact of thermal stress is characterized and described by the power cycling (PC) capability [2]-[6]. Therefore, ΔT is an excellent indicator to evaluate the power module performance within the given system.

In the following, the focus is on the impact of load profiles of variable speed drives on the power module design and performance. In the first part, the interplay between power module parameters and application conditions is addressed: starting with limitations due to the allowed temperatures, it is followed by a discussion on temperature ripples and resulting thermal stress due to load profile and thermal conditions. In this way the predominant effects influencing the power module performance are described, analyzed, and a path to optimize an inverter system is offered accordingly. Finally, these general findings will be matched to existing typical inverter solutions.

2. Load profiles and output current

Variable speed drives are in use in a large variety of applications with different motivations; this ranges from pump and fan applications, where the focus is on partial load conditions and thus energy efficiency of the total system, to the needs of high-speed control of position and torque in servo drives. Since the variety of applications is too segmented to provide individual inverter drive solutions, the existing ones are standardized and rated accordingly.

In order to address the general impact of overload conditions on the power module performance, generic load profiles are used

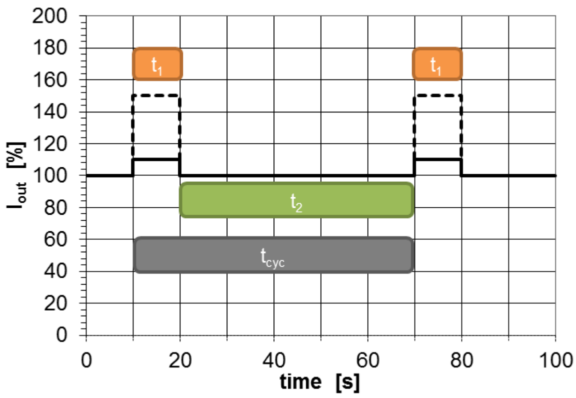

Fig. 1: Schematic drawing of a load profile comprised of an overload period during t_1 and a base-load period during t_2. Exemplarily, such a 10 s high load followed by 50 s base load is labelled as 10/50 throughout the paper. The 100 %-value is referred to as I_{base} and represents the effective current of a sinusoidal 50 Hz.

with load conditions of 110 % and 150 % as depicted in Fig. 1. Independent of specific power module conditions (switching losses, static losses, thermal behavior, and the like) there will be an increase of the junction temperature T_{vj} during the high-load period (t_1) and a typical, i.e., lower T_{vj} during base load (t_2). For a module with fixed T_{vjmax}, e.g. 150 °C, the temperature reached during high load will determine the achievable output current. In contrast to a steady-state output current, the base current will thus depend on the required overload range and time. The overload requirements lead to a reduction of the base current that can be provided by a given power module.

In addition, the thermal performance of the cooling system will have a strong impact on the achievable current. The overall behavior is depicted in Fig. 2 for a typical range of overload conditions (given as maximum I_{out} [%]) and R_{thHA}, using the electrical and thermal parameters for an EASY package [1].
For a maximum junction temperature of 150 °C, the overload condition defines the allowed base current in any scenario. With increasing overload requirements or R_{thHA} value, the allowed base current must be reduced to not exceed T_{vjmax} during overload. Especially at high load currents, the choice of R_{thHA} becomes critical. This implies also that, during base load,

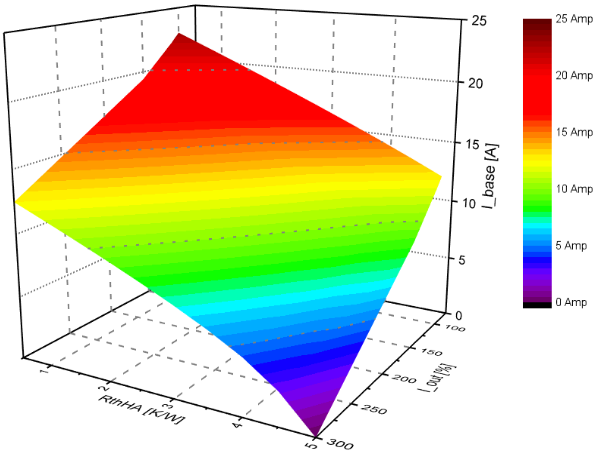

Fig. 2: Maximum base current I_{base} as a function of load-profile conditions and cooling system. The load profile assumes a 10/50 interval as shown in Fig. 1, and T_{vjmax} = 150 °C.

the devices are operating way below their maximum rating, leaving a temperature margin towards 150 °C for overload operation.

In order to utilize this temperature delta, Infineon's new IGBT7 and EC7 technology allows a temporary operation at 175 °C. The benefit is recognized in Fig. 3, which shows the achievable base current for different overload conditions: In the case of continuous operation (dashed lines), the curve is simply shifted to higher I_{base} values. For overload operation and typical R_{thHA}, since T_{vjmax} is the limiting parameter, the additional temperature budget of 25 °C offers an increase in current during overload in comparison to continuous 150 °C operation. For the 110 % profile, a higher I_{base} can be provided by the module together with an overload capability.

For rather poor R_{thHA} above 3.5 K/W, a kink is observed in the red curve (110 % at 175 °C) and a faster drop of I_{base}: Since the overload is small, the temperature during base load is reaching 150 °C and, consequently, limiting the output current. In this regime, T_{vj} does not reach 175 °C. It has to be pointed out that this constraint applies for small overload profiles in combination with high R_{thHA} where the benefit of temporary 175 °C may not be utilized fully in terms of T_{vjmax}. For the 150 % and 300 % load profile, this effect is not seen: the base current is reduced significantly, and T_{vjmax} during

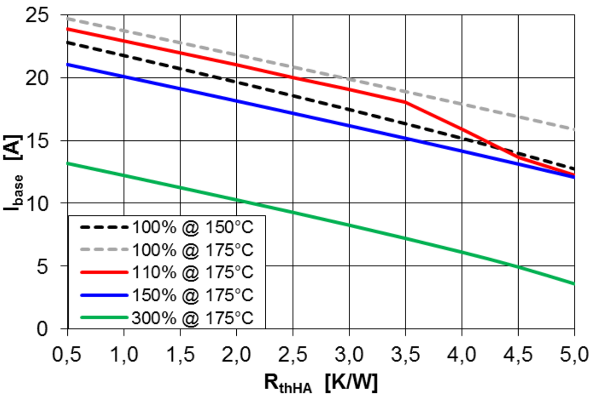

Fig. 3: Achievable base current for different overloads in a 10/50 interval as a function of R_{thHA}. The 100 %-curves refer to the base load situation, i.e. with constant output current.

overload is dominating the module performance, thus taking full advantage of the additional temperature budget.

Looking at the effective output current I_{eff} (and thus power), the benefit is even more pronounced, see Fig. 4. The continuous 175 °C line refers to the maximum achievable I_{eff}. Once a temporary operation at 175 °C is allowed, I_{eff} above the continuous 150 °C operation line can be accessed due to the additional temperature budget for overload operation. Both the 110 % and 150 % load curve show this behavior. For typical R_{thHA} the temperature during base load is below or equal to 150 °C. The increase in T_{vjmax} allows for the same effective output at much higher overload capability. Thus, for typical load profiles with repetitive overload, a temporary operation at 175 °C is sufficient. For this given setup, a rating for continuous operation at 175 °C does not provide a substantial advantage compared to temporary operation at this temperature in terms of effective current rating. In addition, a continuous operation at, e.g., 175 °C does not reflect the typical use-case in general purpose drive (GPD) applications.

Based on Fig. 3, the minimum heat sink requirements R_{thHA} for different I_{base} and load conditions are summarized in Tab. 1.

ISBN 978-3-8007-4646-0

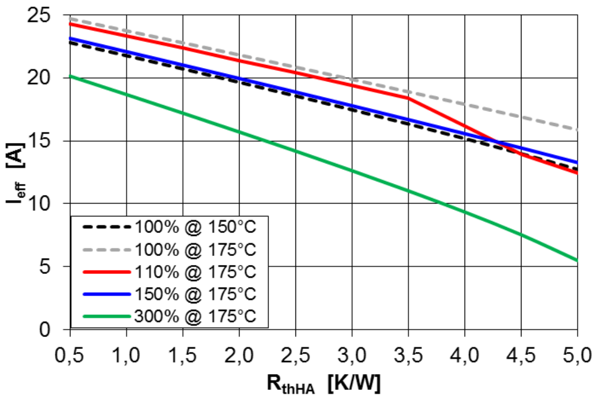

Fig. 4: Effective output current I_{eff} based on the base current shown in Fig 3.

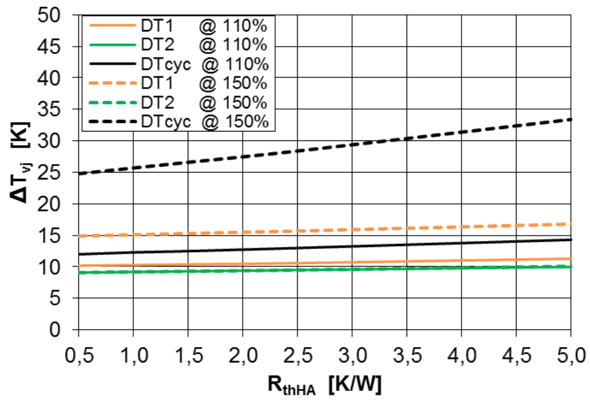

Fig. 5: Graphical representation of R_{thHA}, overload conditions, and resulting temperature ripple ΔT. The load profile is 10/50 as depicted in Fig. 1, and the base current is 12 A.

I_{base} \ I_{out}	100 %	110 %	150 %	300 %
16 A	4.9	4.0	3.1	--
12 A	>5	>5	5.0	1.1
8 A	>5	>5	>5	3.1

Tab. 1: Maximum allowed R_{thHA} [K/W] as a function of overload requirements (I_{out}) and base current.

3. Load profiles and temperature ripple

So far, the analysis focused on the limitations based on T_{vjmax}. When a load profile as given in Fig. 1 is run continuously, possible limitations due to the thermal stress on the power module may be considered as well: while following the load profile, different temperature ripples ΔT occur at chip level. These ripples induce thermal stress and may lead to long-term-deterioration of the interconnections inside the power module, as indicated by, e.g., the power-cycling curve provided by power-module manufacturers.

To gain a deeper understanding, here, a simplified approach is used assuming only three different temperature ripples during a load profile as depicted in Fig. 1. Though this is an approximation, it will clarify the influences of the main system parameters on the occurring temperature ripples. A more detailed description of thermal stress and the impact on power module performance can be found in [7].

On a short timescale, the ripples ΔT_1 and ΔT_2 (during t_1, and t_2, respectively, see Fig. 1) arise from the output frequency f_{out}, which is fixed at 50 Hz. In addition, there is a ΔT_{cyc} due to the overall temperature difference between overload and base load operation. These ripples are impacted by the overload conditions and R_{thHA} in different ways as can be seen in Fig. 5. The largest value is seen for ΔT_{cyc}, whereas ΔT_1 and ΔT_2 are rather small. This is predominant at a load current profile of 150 % (dotted lines), yet already visible for 110 % (solid lines). At the same time, there is a strong impact of R_{thHA} at 150 % load conditions, whereas it is almost negligible during 110 % load. This is easily understood, since both T_{vj} and ΔT directly depend on I_{out} and R_{thHA}.

Looking at the operation of a power module in the application, both the absolute temperature ripple ΔT as well as the number of cycles need to be considered. Each appearance of ΔT induces thermal stress and, as a consequence, a long-term deterioration will occur. Thus, in the application, the long-term deterioration is a combination of all individual ΔT occurred and the operated load cycles, where the impact of thermal stress is given by a technology-specific PC curve with all the implicit dependencies [2]-[6].

ISBN 978-3-8007-4646-0

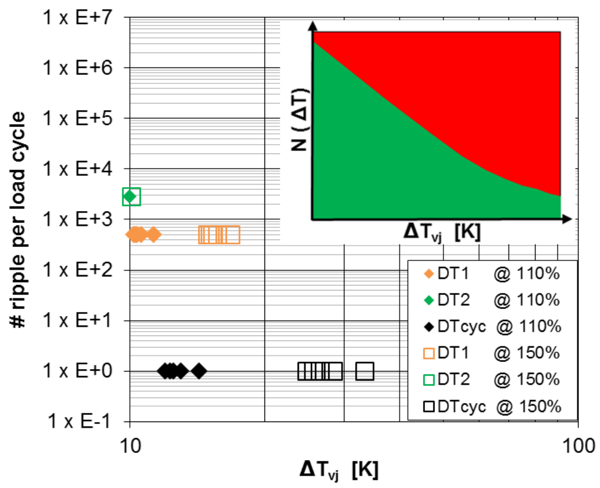

Fig. 6: Number of ripples at respective temperature delta using the generic mission profiles described in Fig. 5. Each group of data points represents the range of R_{thHA} values from 0.5…5.0 K/W. The inset depicts a typical power cycling curve with allowed (green) and critical (red) areas of thermal stress due to temperature ripples.

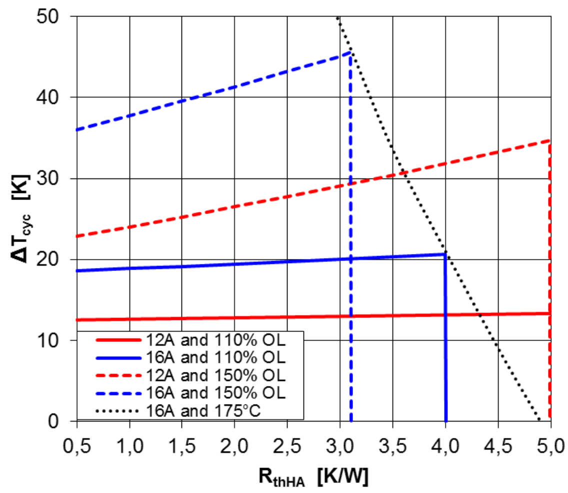

Fig. 7: Temperature ripple as function of the external heat sink for different load profiles and base currents. The black dotted line indicates the limit of operation due to 175°C for different overload conditions, indicating a fast increase of ΔT_{cyc} with overload.

Fig. 6 shows the temperature ripples seen during one load cycle, together with a schematic PC curve. Areas of allowed and critical thermal stress are indicated with green and red, respectively. It may serve as indication for the interaction between ΔT and number of cycles, i.e. $N(\Delta T)$.

Since ΔT_{cyc} is seen once during one load cycle, this temperature delta is seen at the bottom of the y-axis in the graph, yet the values are largest on the x-axis (black symbols). The two groups of symbols (filled and open) represent different load conditions, whereas within one group R_{thHA} varies from 0.5…5.0 K/W, and an R_{thHA} of 5 K/W is providing the largest ΔT_{cyc}. The load conditions, however, have a larger impact: comparing 110 % and 150 % load, all values are moved to the right as expected already from Fig. 5 (difference between filled and open symbols). This is equivalent to an increase in thermal stress during an individual cycle. The temperature ripples ΔT_1 and ΔT_2 are both much smaller (see Fig. 5), so they may be considered uncritical. However, since they are related to f_{out}, the number of ripples is much higher, and a further consideration should be done. The overall behavior with R_{thHA} and overload conditions is as discussed for ΔT_{cyc}, i.e. also here, shifting all points to higher ΔT.

In all cases, the increase in temperature ripple leads to a faster deterioration of the power module under elsewise the same operation conditions. In turn, to reduce thermal stress, a reduction of temperature ripple and count is desired. The count is defined by the operating conditions such as f_{out} and load profile. For a system designer, the overload conditions are usually given, and heat sink design may be hard to vary. This leaves ΔT as parameter to reduce thermal stress inside the power module. For a given power module, this can be achieved in two ways: on system design level, the heat sink can be adopted in order to reduce the temperature ripple, as depicted in Fig 5. From the application point of view, also the output current may be reduced in order to decrease the temperature ripple together with T_{vj}.

The interplay between these two effects is shown exemplarily for ΔT_{cyc} in Fig 7. Each curve represents a combination of base current and load profile. The temperature ripple is increasing with R_{thHA}, and so is the temperature (not shown). The vertical termination indicates the 175 °C limit of the power module during overload, as discussed in Fig. 3 and Table 1.

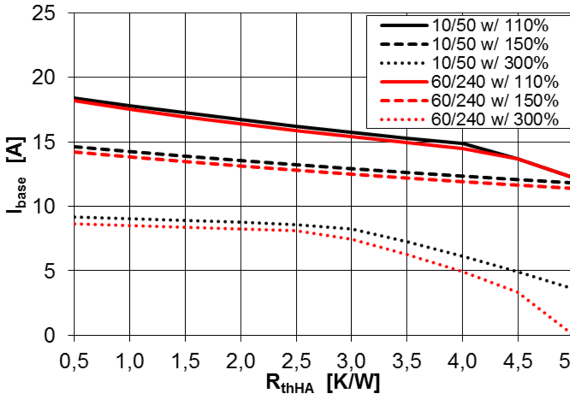

Fig. 8: The curves display the borders of accessible base current as function of R_{thHA}. Boundary conditions indicate similar thermal stress due to temperature ripples along the respective curves, and operation within temperature limits during both overload and base load.

Comparing the different curves, the temperature ripple is decreasing with I_{base} (blue to red), and also with reduced overload condition (dotted to solid). In addition, some curves terminate at a specific R_{thHA} value. Here, Fig. 3 serves as guide: the required base current and overload profile cannot be reached without exceeding T_{vjmax}. In this way, T_{vjmax} and the overload conditions clearly define the allowed range of R_{thHA} and resulting temperature ripple. From the graph it is obvious that a variation of the heat sink has only minor effect on the temperature ripple; the overload and base current are clearly dominating.

In any application where overload conditions are normal and frequent during operation, an understanding of the interdependencies between operating conditions and system design will support the optimal power module choice. Fig. 8 gives one example for this assessment, based on one specific set of operating conditions (such as f_{sw}, cos(phi), V_{CC}, and others). Each curve describes the maximum base current I_{base} for the respective load profile and identical thermal stress.

The predominant drop of base current occurs with increasing overload profile as clearly seen from the different curves. This has already been discussed briefly in the context of Fig. 2. The impact of R_{thHA} variation is weaker in general, yet more dominant for low overload requirements (i.e., 110 %). For a typical heat sink, this effect is clearly seen. Depending on the overload conditions, a faster drop of I_{base} is seen at rather large R_{thHA}. In this regime, T_{vj} is the limiting factor for output current, rather than thermal stress. Details of this behavior have been discussed in Fig. 3. While the maximum overload condition gives the accessible current range, an optimization of the heat sink is possible with respect to both the required base current and also the time periods (t_1 and t_2) of the load profile. If a longer overload period is needed (i.e., 60/240 rather than 10/50), the resulting heat sink has to be of higher performance to keep a constant level of thermal stress for a given base load. In turn, for a given heat sink – as is the case for an inverter system – the achievable output current strongly depends on the overload requirements. This effect on inverter use is discussed in the next section.

4. Implications for Inverter design

In the preceding sections, the focus was set to a general approach of the interplay between power module parameters and application conditions. This was used to analyze and describe the overall interplay between load profile and achievable output current, temperature ripple, and heat sink. To put this into practice, an example is given as to where the advantages of above shown features come to the fore.

As stated above, the large segmentation of applications for variable speed drives cannot be addressed by individual inverter drive solutions. Thus, the existing ones are standardized and rated accordingly. In case of general-purpose drives as one major group, this is realized with two rather generic load profile scenarios (light duty: LD, heavy duty: HD) as depicted in Fig. 9. Under LD conditions, the given GPD hardware is used up to a certain I_{out} and having a load profile of 110 %. In applications with a HD profile, a smaller I_{out} is provided by the same hardware, yet allowing for higher overload equivalent to a 150 % profile. In both cases, i.e., LD and HD, the profile allows a certain time span, e.g., 60 s, of overload operation within a defined periodicity, e.g., 300 s.

ISBN 978-3-8007-4646-0

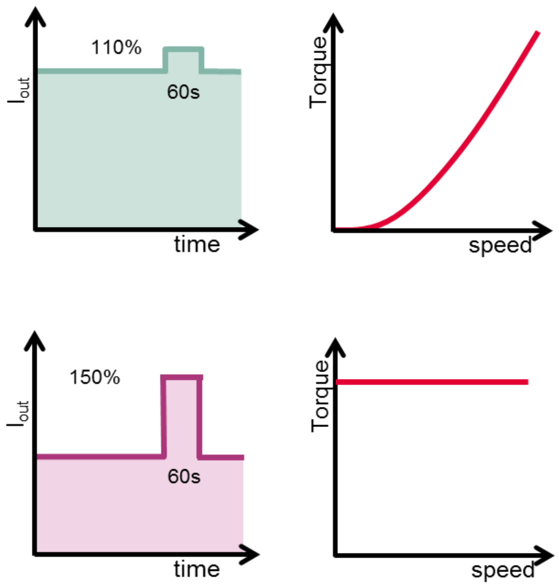

Fig. 9: Load profiles of LD (upper) and HD (lower part) operation, and typical torque-speed characteristic of the respective profiles.

Mapping these generic load profiles to the application needs, LD typically implies a square-torque speed characteristic in, e.g., pumps, fans, or compressors, while HD provides a constant torque-speed characteristic for, e.g., conveyors or hoists.

These two $I_{out,LD}$ and $I_{out,HD}$ enable a fast choice of the inverter drive depending on the application needs being more LD or HD like. While this is very convenient for the GPD user, this has implications for the power-module dimensioning: since the specific application is not given during the power-module design, the power module needs to support both scenarios. Especially, the critical parameter for the power module choice is different: on the one hand, the maximum operation temperature must not be exceeded during operation. This implies a proper balancing of power module and cooling conditions in the system itself. On the other hand, depending on overload and cooling conditions, also the temperature ripples may become a critical factor.

Having the need of a GPD to fulfill these different applications in mind, the separation into HD and LD becomes natural based on the analysis above. The base current of 12 and 16 A may refer to a motor power of 5.5 and 7.5 kW, respectively. Then, a heat sink of 4.0 K/W supports a GPD system with 7.5 kW in LD and 5.5 kW in HD operation based on Fig. 3 and Tab. 1, i.e., taking only the allowed T_{vj} into account. Depending on the repetition rate, this will be sufficient if the load profile is not run continuously since the thermal stress is small. For highly repetitive load cycles, however, the thermal stress may become critical. Looking at an R_{thHA} of 4 K/W a temperature ripple of 21 K is seen for 16 A and 110 %, while a profile with I_{base} of 12 A and 150 % has a ripple of 32 K. These two scenarios are equivalent to an HD and LD operation, respectively..

5. Summary

The paper analyzes and evaluates the interplay between different load profiles, thermal conditions, and available output current. In a first step, a generic load profile structure is introduced with load conditions of intermittent 110 % and 150 % operation. The allowed base current is evaluated for different cooling conditions and compared to continuous operation.

Based on a maximum junction temperature of T_{vj} = 150 °C, a continuous reduction of base load current is observed with increasing overload. In contrast, once a temporary operation at 175 °C is allowed, the available base current may exceed the value for continuous operation. More important, the effective output current for the 110 % and 150 % load profiles exceeds the output during continuous operation at 150 °C. This is a clear advantage of the partial overload allowed by Infineon's new IGBT7 and EC7 technology and valid for typical cooling systems. Only for large R_{thHA} a constraint due to T_{vjmax} occurs. A chip and module design optimized for continuous operation at 175 °C does not necessarily provide benefits in the application. Therefore, during the system design, a comprehensive understanding of the application needs is of advantage whether to go for a device optimized for continuous operation or for temporary overload.

In the next step, the temperature ripple during operation is considered. The accessible range of output current is discussed, and the interaction between temperature ripple, heat sink, and overload conditions is highlighted. For a given thermal stress, the overload conditions are dominating the accessible output current. A variation in $R_{th\mathrm{HA}}$ can adjust the temperature ripple and thus thermal stress moderately. In turn, for a given heat sink, a large spread is seen based on the load profile, and supports the use of one inverter system for different overload conditions in different power classes.

This connection towards the typical design of general purpose drives is made in the last part. Two operation profiles are used to describe the inverter capabilities, and matched to the findings of the preceding sections. A general purpose drive is usually designed in such a way that either a low overload is supported at one power class, or a high overload is allowed for a smaller power class. A thorough understanding of resulting thermal stress on the power module that originates from overload operation in typical GPD use profiles is important for optimal system design. In combination with a technology optimized for such overload cycles, i.e. partial overload for $T_{vj\mathrm{max}}$ and the corresponding temperature ripples, further advances in inverter development are enabled.

The paper highlights the benefits of temporary operation at 175 °C and supports the separation of different operation points for any GPD, based on allowed junction temperature and temperature ripples.

6. References

[1] C. Müller, et. al., PCIM Europe, Nuremberg, Germany, 2018

[2] R. Bayerer, T. Herrmann, T. Licht, J. Lutz, M. Feller; CIPS 2008, Nuremberg, Germany

[3] Application Note AN2010-02, Infineon Technologies AG

[4] U. Scheuermann, PCIM 2015, Nuremberg, Germany

[5] S. Schuler, U. Scheuermann, PCIM 2010, Nuremberg, Germany

[6] Application Note 5SYA 2043-04, ABB, Switzerland

[7] K. Mainka, M. Thoben, O. Schilling, EPE 2011, Birmingham, UK

