Fast Switching Power Module Solutions for Applications with 1200V Component Rating

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Power applications are forced to work at higher frequencies. This is caused by increased demand on motor drives with special capabilities for high speed, low noise or ultra high dynamic as well as the fact that higher frequencies reduce the mechanic size of the passive components as transformers, inductors and capacitors. This means if the switching frequency will be increased, the volume will be correspondingly smaller at the same power level. But with high switching frequencies the challenge is to optimize the overall efficiency of the inverter, as the switching losses become a significant portion of the total losses in the system.

Abstract

The market for power semiconductors is still dominated by industrial motor drive applications with switching frequencies less than 5 kHz. But more and more drive solutions use higher PWM-frequency (up to 20 kHz) to avoid audible noise. In other power applications like welding and power generation even higher frequencies are required to reduce the size, weight and cost of the passive components. Compared with 600V only a small amount of 1200V rated components are available for higher power applications running at 10 kHz < f_{PWM} < 50kHz.

In drive applications the switching losses and the resulting de-rating are usually accepted. But the trend towards solutions with higher efficiency is clearly visible. And this goal is achievable without increase of costs.

Switching losses are often underestimated. In applications with 1200V power components the dynamic losses are often already dominant at switching frequencies above 8 kHz. Power losses at higher frequencies are managed in two ways; either by using bigger, thermal optimized semiconductors and heatsink or by selecting the optimum component technology. While the first solution is introducing higher system cost, optimizing components matching and arrangement can provide similar or even better results at lower cost. Power integrated modules are able to offer these advantages over discrete solutions and provide higher switching speed at lower total losses.

The paper is focusing on:

- hard switching motor drive applications,
- hard switched generator/UPS topologies,
- SMPS or welding inverters with zero-voltage switching,

using switching frequencies of 10kHz and higher and providing electrical output power of more than 4kW.

The paper provides:

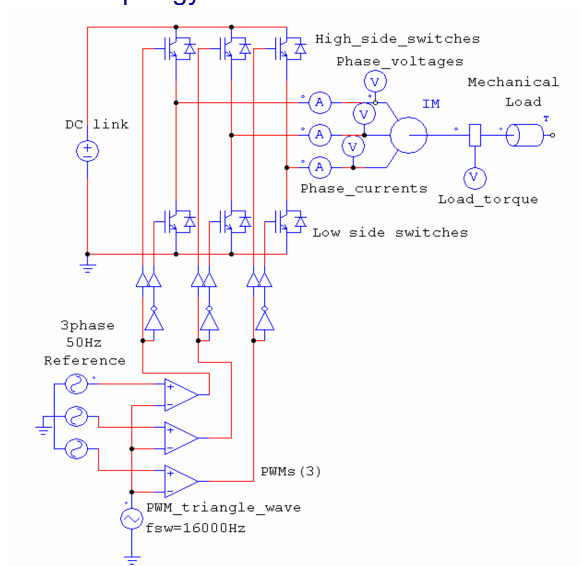
- Introduction of different 1200V IGBT technologies (e.g. NPT-, Planar Cell Field Stop, Trench) with its specific advantages and disadvantages
- Comparison of the IGBTs in the respective switching mode
- Selection guide for application and PWM-frequency dependent component ranking

The performance comparison is based on simulations with measured parameters.

Applications and Topologies

Motor Drive Applications

In Motor Drive Applications typically a 3-phase inverter topology is used:

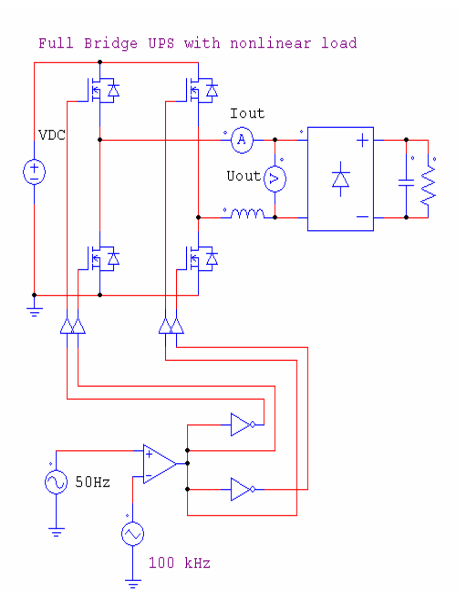


The standard topology for the conversion of DC-current into AC current with variable frequency in motor drive inverters uses triple ½ bridges. Frequency converters for motor drives do not have inductive components where a size reduction can be achieved by higher frequency operation. In standard applications the PWM frequency is a compromise between audible noise and switching losses. New applications with the need of an ultra high dynamic operation or an ultra high motor frequency require higher PWM frequencies than the usual maximum of 4 kHz. The transistors are typically used in hard switching mode. Both the IGBTs and the freewheeling diodes influence the switching losses of the system. A special challenge for the power electronics is the variable motor frequency. At very low motor frequencies e.g. 0,1Hz the same IGBT is used over a period of several seconds. Such a long time cannot be averaged by the thermal capacity of the chip and the used substrate. Therefore, the maximum current at low frequencies normally limits the performance in dynamic applications.

Generator / UPS Topology

Generator or UPS applications use dependent on the number of output phase's and topology single, dual or triple ½-bridges. The system has almost the same requirements as motor drive applications with the following exceptions:

- The output frequency is fixed to 50/60Hz
- The output voltage is fixed
- The size of the required output inductor is dependent on the PWM frequency. A higher PWM frequency helps to reduce the size and cost of the passive components.



Simplified conditions for UPS calculation:

- Hard switching environment
- Identical components in UPS phases
- Static load
- Stable DC link voltage
- Symmetrical load of half bridges
- Fixed frequency operation (50Hz)
- Modulation frequency >> UPS frequency (50/60Hz)
- Dead time is neglected
- Undistorted sinusoidal current for linear load
- Distorted sinusoidal current waveforms or square wave output current for nonlinear load

Equations for calculation:

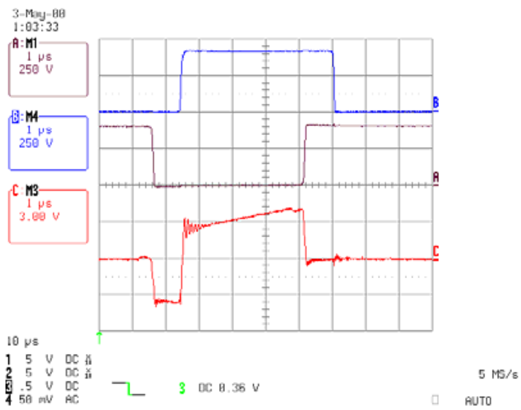
- For linear load same as FC
- Current limit mode dependent for nonlinear loads

Applications with ZVS

In ZVS (Zero Voltage Switching) applications the transistor is switched on at 0V. In applications with a transformer in the output a ZVS is the standard configuration. In these applications the current in the transformer will change the polarity during every switching cycle. In that case the transistor will take over the current from the free wheeling diode at the zero crossing of the voltage. The switch-on losses are zero and the switching losses are only turn-off losses. At switch-off the situation is the same as in hard switching circuits. For a reduction of the switch-off losses usually snubber capacitors are placed parallel to the used Transistor. In this arrangement a low inductive DC-circuit will minimize the voltage overshoot and further reduce the losses.

Model for calculation:

- Zero Voltage Switching environment
- The half bridges are not equally loaded due to asymmetry of circulating current
- Calculation like for DC applications but the variable parameter is the phase shift
- The maximum duty cycle for switch is limited to 0,5
- Eon turn on energy is considered to be zero
- Eoff turn-off energy at full load condition can be further decreased by parallel capacitors



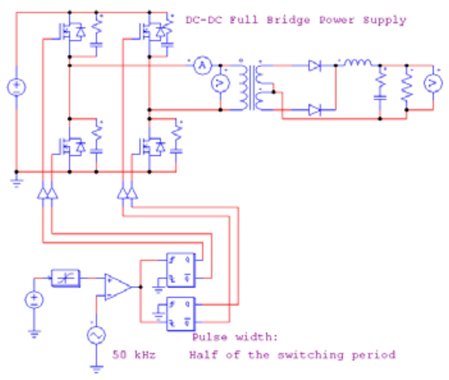
The prediction of losses is much easier for systems where fluctuation of variables is not present. The values can be averaged for a single switching cycle and the losses equal the average losses. The conduction losses can be calculated as following:

$$Pst_{SWITCH} = (Uth * Iout + rt * Iout^2) / 2 * \varphi$$

Where $0 <= \varphi <= 1$ is the phase-shift in a ZVS system.

The switching losses can be estimated to:

$$Psw_{SWITCH} = fsw * Eoffn * \frac{Iout}{In} * \frac{UDC}{Un}$$



Using the thermal model

Below is the equation describing the thermal conditions of the semiconductor.

$$Ptot_{SWITCH} = Pst_{SWITCH} + Psw_{SWITCH} = \frac{Tj\max - Th}{Rthjh}$$

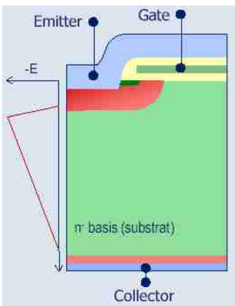
By fixing the T_{Jmax} temperature we can solve the equations for available current at fixed application parameters and can check the influence of semiconductor characteristic parameters for best performance.

IGBT Technology

The comparison is done with 3 different IGBT technologies:

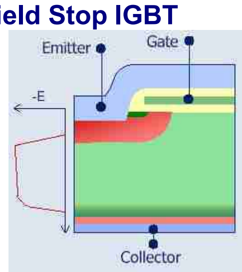
1. Fast- NPT
2. Planar Cell Field Stop
3. Trench Field Stop.

Standard NPT

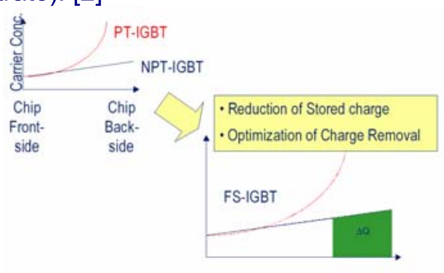


The base material of the NPT (non punch through) structure is a homogeneous n- -doped wafer. On the backside, a specially formed p-layer is created during wafer processing
The typical IGBT cell structure is formed on the front side [1].

Planar Cell Field Stop IGBT

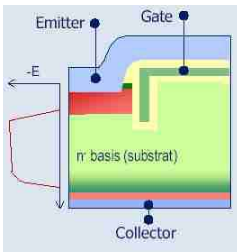


This technology differs from original NPT with an additional weak doped n-Field Stop layer between the backside p layer and the n-basis (substrate). [2]



The Field Stop layer reduces the stored charge in the chip. This leads to higher switching speed. Additional the implanted Field Stop enables a thinner base region [2]. The result is a reduced V_{CEsat}.

Trench Field Stop IGBT

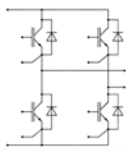


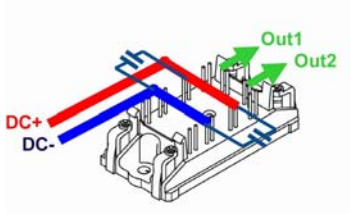
An additional trench structure increases the carrier concentration on the front side [2]. This is leading to a further reduction of the V_{Cesat}.

Comparison

The IGBT technologies are compared in the introduced applications. For the comparison power modules with direct pressed DBC are used. All transistors are controlled with an additional emitter contact directly wire bonded onto the chip. This construction has the advantage that the parasitic inductance has no influence into the gate-emitter-voltage of the transistor control. If module technology is used for fast switching applications this topology provides a significant improvement at almost no effort.

For the comparison the package of the module V23990-P629-F40 is used:





Other conditions for the comparison:
The components for each comparison have about the same nominal current. In additional the comparison is done for components with the same chip size. The max junction temperature of the chip is limited to125°C. This is important because the conditions used for the calculation are based on lifetime and not the maximum values of the components. With respect to the fact that mechanics as chip solder or wire bonding are usually determined at the end of life limit of the semiconductors this parameters are independent from the given chip and its manufacturer specification.
The used NPT IGBT is a fast version of the 2nd generation IGBT technology of Infineon. The figures shown compare either available output power or efficiency. If the chip area is the same, output power and efficiency comparison will have the same result. The output power is given as a function of the heatsink temperature. In the comparison the available output power at 80°C heatsink temperature is always used.

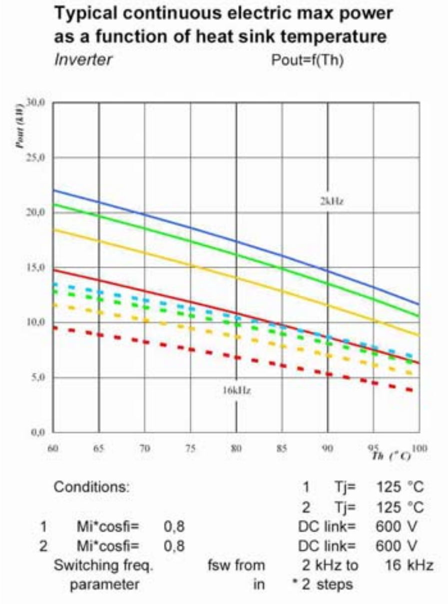
In principle it is possible to develop with all 3 technologies IGBTs with different switching speed. The adjustment of the switching speed is normally a trade-off between static and switching losses. So the result will not be a general statement about the used chip technology, but it is a valid comparison for the tested chip in the selected application.
In advance the comparison of the on state forward voltage at nominal current of 25A at chip temperature of 125°C is given for the tested IGBTs:
Fast-NPT (SIGC42T120CS): V_{cesat} = 3,85V
PLANAR CELL FS (SIGC42T120Q): V_{cesat} = 2,18V
Trench FS: (SIGC32T120R3L): V_{cesat} = 1,89V
For a comparison of the same chip size also a 35A Trench Field Stop IGBT is included. The V_{CEsat} is given here also for 25A.
Trench FS: (SIGC41T120R3L): V_{cesat} = 1,60V

Performance Comparison - Motor Drive

Motor drive applications are usually running in hard switched mode. Here the freewheeling diode is commutated at maximum current. In such a configuration the IGBT and the corresponding freewheeling diode influence each other in performance and efficiency. For this comparison all IGBTs are using the same freewheeling diode: Infineon EMCON-H (SIDC14D120H6).

Comparison (Motor Drive) NPT vs. Planar Cell Field Stop

The picture below shows the comparison of the available electrical output power for components based on following technologies:
- Fast-NPT: dotted lines
- PLANAR CELL FS: solid line

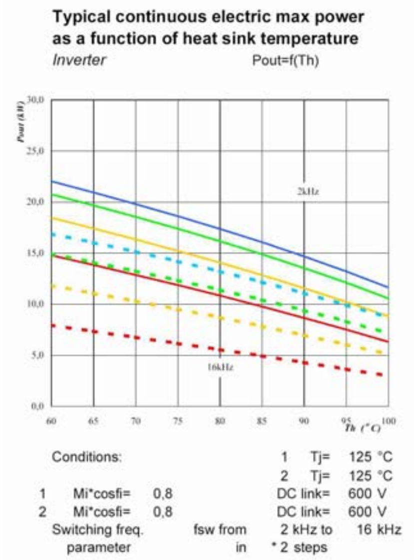


Results:
Whereas the switching losses in the IGBT are nearly identical the static losses in the Planar Cell Field Stop components are significantly lower. The achieved maximum electrical output power for the PLANAR CELL FS IGBT at a PWM frequency of 16 kHz and heatsink temperature of 80°C is 11kW, the respective output power for the fast NPT is only 7kW.

Comparison (Motor Drive) Planar Cell Field Stop vs. Trench Field Stop IGBT

With the trench technology a reduction of the on-state losses is achieved. This improvement is even more respectable knowing that the chip shrink is approx. 30%!
But the switching losses of this Trench Field Stop IGBT are considerably higher.

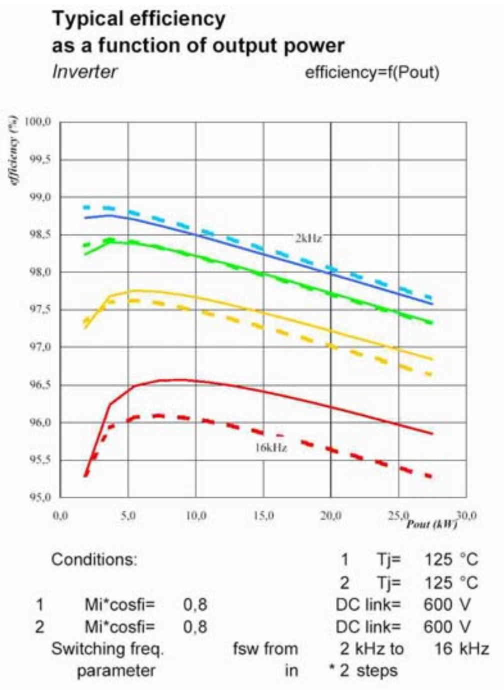
The picture shows the comparison of the available electrical output power for components based on following technologies:
- Trench FS: dotted lines
- PLANAR CELL FS: solid lines



Results:
The maximum electrical output power for the PLANAR CELL FS IGBT at a PWM frequency of 16 kHz and heatsink temperature of 80°C is 11kW. In comparison the Trench FS only achieves 5,5kW.
The reduced chip size increases the thermal resistance of the component. Therefore, the chip requires at the same heatsink temperature a higher efficiency to achieve the same chip temperature at the equal output power.

The picture shows the comparison of the efficiency for components based on following technologies:

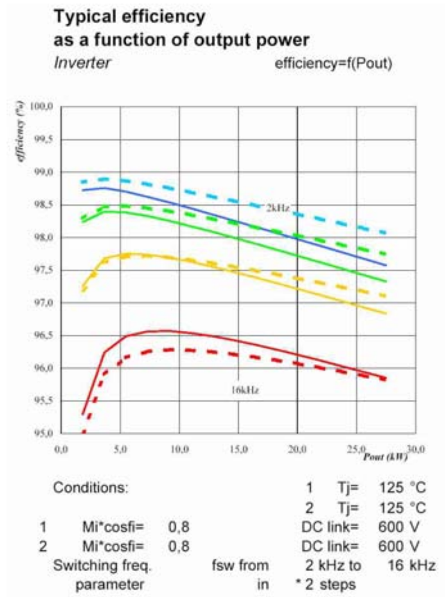
- Trench FS: dotted lines
- PLANAR CELL FS: solid lines



But the higher switching losses are dominating. The Trench FS IGBTs are already at PWM frequencies of 4 kHz worse than IGBTs using the PLANAR CELL FS technology.

For a benchmark of the chip technology a comparison based on the same chip size is made. The comparison of the efficiency for components based on following technologies is shown:

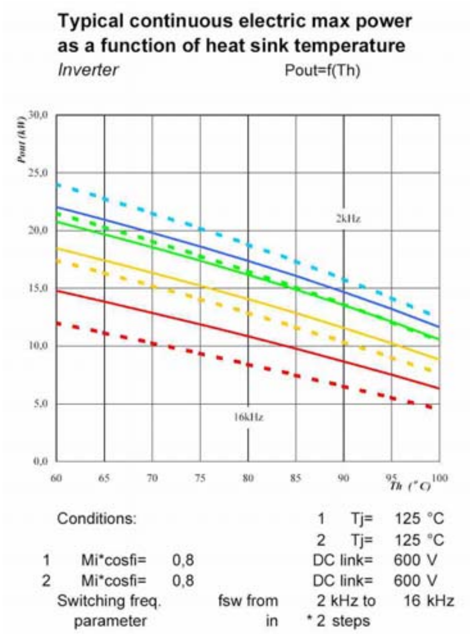
- Trench FS: dotted lines
- PLANAR CELL FS: solid lines



Results:
The thermal conditions for the IGBTs are now identical due to the same chip size. The crossover is at ca. 8kHz. At higher frequencies the PLANAR CELL FS is more efficient than an Trench FS IGBT.

The picture shows the comparison of the available electrical output power for following chip technologies:

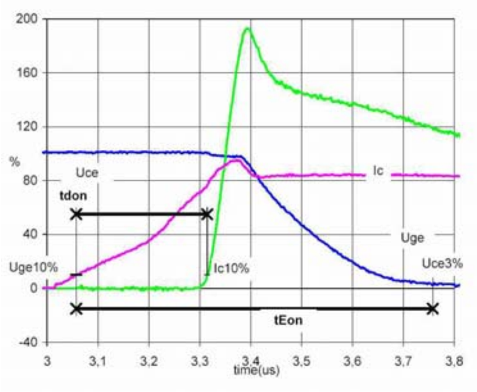
- Trench FS: dotted lines
- PLANAR CELL FS: solid lines



Results:
At 16 kHz the maximum output power is approx. 8kW compared with the 11kW of the PLANAR CELL FS IGBT!

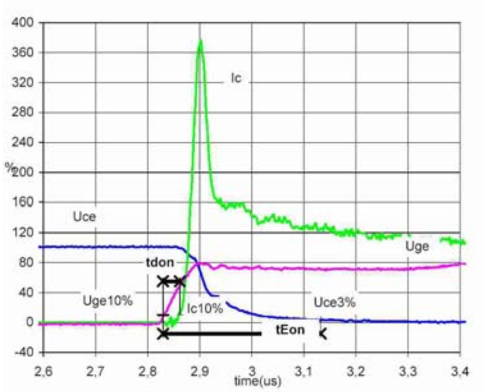
In parallel the higher switching speed does increase also the requirements on the switching behavior of the freewheeling diode. This test is done with the same EMCON-H Diode for both IGBTs.

Below the switching definition of the Trench FS IGBT are shown:



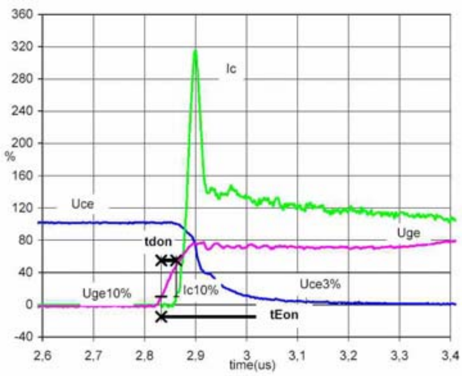
The used diode fits to the Trench-FS IGBT.

The following figure shows the switching definition for the PLANAR CELL FS IGBT:



In this case the relative high Qrr in conjunction with the PLANAR CELL FS IGBT causes a current peak, which is approximately double as high during turn on as with Trench FS. Therefore, a faster diode would improve the efficiency of the IGBT significantly.

Below the improvement is shown, the current peak has been reduced from ca. 375% down to 315% by using a faster diode.



But a performance benchmark for diodes is not the key issue for this paper.

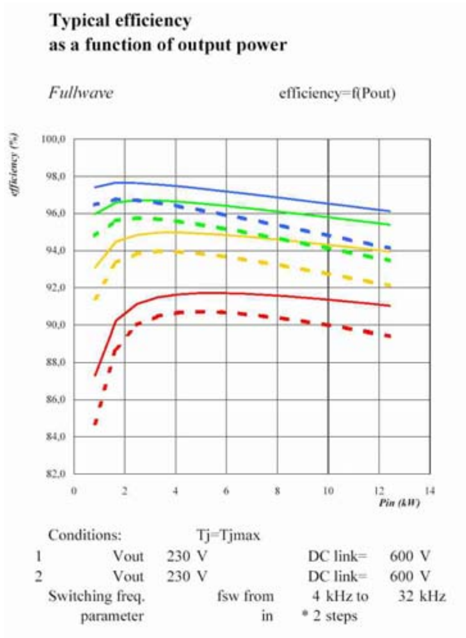
Performance Comparison – Generator / UPS

In Generator / UPS applications typically also a hard switching topology is used. The fixed frequency and the fact that there is no regenerative power will make it easier for the components. The power rating for the corresponding diode is much lower and there are no requirements regarding short circuit capability. For the performance comparison we expect here similar results as in motor drive applications.

Comparison NPT (UPS / Generator) NPT vs. Planar Cell Field Stop

Below picture shows the comparison of the efficiency for following semiconductor technologies:

- Fast-NPT: dotted lines
- PLANAR CELL FS: solid lines



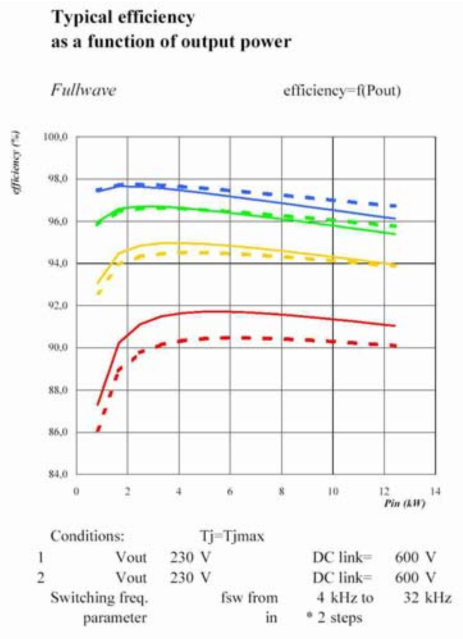
Results:
The curves show that there is no crossover. The PLANAR CELL FS is the more efficient component over the whole usable range.

Comparison NPT (UPS / Generator) Field Stop vs. Trench Field Stop IGBT

Here again the same chip size is benchmarked, meaning a PLANAR CELL FS IGBT with 25A nominal current and a 35A Trench-FS IGBT are compared.

The diagram below shows the comparison of the efficiency of following IGBT technologies:

- Trench FS: dotted lines
- PLANAR CELL FS: solid lines



Result:
The crossover is already at ca. 8kHz. For higher PWM frequency the PLANAR CELL FS IGBT is the more efficient device!

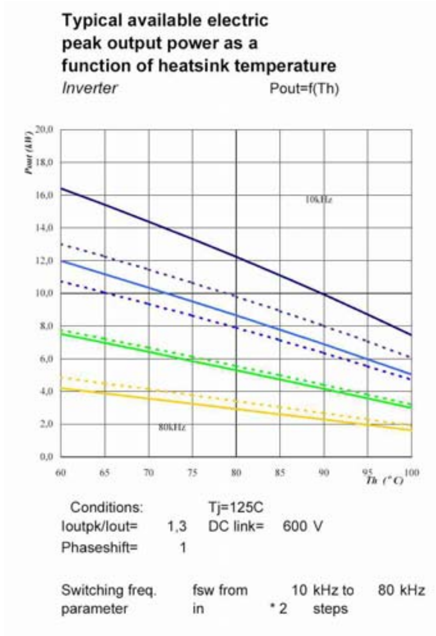
Comparison – ZVS

In Zero Voltage Switching applications unlike hard switching applications the losses of the IGBT and the corresponding diode are nearly independent. The switch-on at zero voltage causes only negligible losses. Switching losses in ZVS applications are mainly switch-off losses. Often additional snubber capacitors are used. These capacitors reduce the losses but on the other side also increases the minimum achievable duty cycle and the capacitor influences the switching behavior of the IGBT. Due to this it is not possible anymore to predict the switch-off losses without actually measuring them.

Comparison (ZVS) NPT vs. Planar Cell FS

Below is the comparison of the available output power of following IGBT technologies:

- Fast-NPT: dotted lines
- PLANAR CELL FS: solid lines



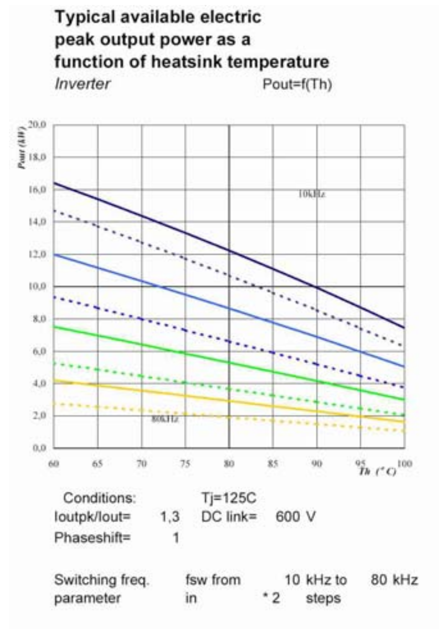
Result:
The fast NPT IGBT is slightly faster. At ca. 40 kHz the available power is identical. For higher frequencies the PLANAR CELL FS is somewhat worse, but the difference also at 80 kHz is not significant. More important is the advantage of the PLANAR CELL FS IGBT at frequencies below 30 KHz. At 10 kHz the available output power is for the PLANAR CELL FS IGBT approx. 12,2kW and only 8,8kW for the fast NPT chip.

Comparison (ZVS) Planar Cell FS vs. Trench FS IGBT

Here again the same chip size is benchmarked. Meaning a PLANAR CELL FS with 25A nominal current and a 35A Trench FS is evaluated.

The comparison of the available output power for following chip technologies is shown below:

- Trench FS: dotted lines
- PLANAR CELL FS: solid lines



Result:
The crossover is below 10 kHz. The used Trench-FS IGBT is definitely not the right component for ZVS applications and switching frequencies higher than 10 kHz. At 20 kHz the available output power at 80°C heatsink temperature is 5,5kW for the PLANAR CELL FS IGBT and only 3,8kW for the Trench-FS component.

Performance overview

In the following table the ideal devices for the different applications are listed (based on same chip size):

Component:	Motor Drive	Generator / UPS	ZVS
Fast NPT			> 30kHz
PLANAR CELL FS	> 8kHz	> 8kHz	> 8kHz < 30kHz
Trench FS (low loss)	< 8kHz	< 8kHz	< 8kHz

The next table provides an overview of the optimal component for the different applications and PWM frequencies (based on same chip size):

Component:	Fast NPT	PLANAR CELL FS	Trench FS (low loss)
Motor Drive			
< 8kHz	+	++	+++
8..16kHz	++	+++	+
16..30kHz	++	+++	0
Generator / UPS			
< 8kHz	+	++	+++
8..16kHz	+	+++	+
16..30kHz	++	+++	0
ZVS			
< 8kHz	+	++	+++
8..40kHz	++	+++	+
40..80kHz	+++	++	+

+++	best relative performance
++	good
+	acceptable
0	not usable

Conclusion

The Trench Field Stop IGBT is designed for motor drive application with a typical switching frequency up to 4 kHz. At higher frequencies the Planar Cell Field Stop component is the optimal choice. A further improvement of the PLANAR CELL FS solution is clearly visible by using faster diodes. This IGBT is the favorite for nearly all applications except the traditional 4 kHz motor drive inverters. The fast-NPT IGBT is still an alternative for high frequency ZVS applications.

But the advantage is not that significant anymore.

Efficiency and available output power are the key parameters to benchmark components. For a final selection, additional requirements have to be met by the components. For example, the PLANAR CELL FS IGBT is more sensitive for parasitic inductance that can cause problems in the switch-off behavior. In this case this is solved with a conclusive, low inductive module design.

References

[1] Infineon Technologies 2002
[2] IGBT Fundamentals Siemens, May 1997
[3] New Power Module Structure for Efficiency Improvement in Fast Switching Power Applications (>50kHz, >1kW) Temesi, Zsadany, Frisch Mar. 2005, Vincotech