Influence of Stray Inductance on High-Efficiency IGBT Based Inverter Designs

Loss reduction for better energy efficiency is one of the major aspects in advanced inverter designs. Development engineers are striving for technically best performing and cost effective solutions. State of the art power semiconductors, like the Infineon 1200V IGBT4, are one of the key elements to fulfill these requirements. Another important factor for loss reduction and high efficiency designs is the switching speed of power semiconductors which is influenced by the stray inductance of the different inverter solutions.
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IGBT technologies can not drop back from these application requirements. As a consequence the latest IGBT chip generation from Infineon is offered in several versions to address specific application needs. Driving force for these different optimizations is the switching speed and the softness requirements related to the application power or respectively to the rated current level in today's existing inverter designs. The versions are the T4 chip with its fast switching behavior, the P4 chip with its soft switching behavior and the E4 chip with a switching speed between T4 and P4. In Table 1, an overview of the three trade-off points of the IGBT4 is given and indicates a hint to the addressed current ranges.

	IGBT^4 T4	IGBT^4 E4	IGBT^4 P4
V_{CEsat} @ T_{vj}=125°C	2.05V	2.00V	2.00V
R_{th} for a 300A device	100%	100%	100%
typical current range	up to 450A	200A - 1400A	400A - 3600A

Table 1: Infineon 1200V IGBT4 overview

Dynamic loss consideration of the IGBT and the diode

In order to investigate and to compare the switching losses and the softness of the three different chips at stray inductances from 23nH to 100nH a module type has been chosen which is just close to the limits of being reasonable for using the T4 chip optimization. Hence, a 300A half-bridge configuration in the well known 62mm package has been chosen as a platform and modules have been built with the three IGBT4 versions. The same Emitter Controlled (Emcon) diode is used in all three modules as well as the same gate drive set-up. In Figure 1 the experimental set-up is shown. Figure 2 visualizes the effect of two different stray inductances on the turn-on waveforms of a 300A half-bridge equipped with the IGBT4-T4.

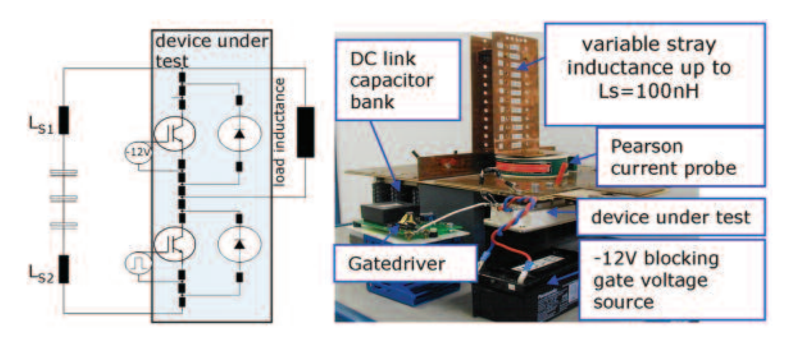

Figure1: Test set-up, for recovery measurement of the free wheeling diode the high side IGBT was switched and the load inductance was changed to be parallel to the low side diode

A higher stray inductance (L_s) not only increases the inductive voltage drop, $\Delta u=-L*di/dt$, at the device terminals after onset of the current rise but also affects the current rise speed di/dt itself. Even though the turn-on speed is slowed down by the parasitic inductance, the turn-on losses are significantly reduced.

In the shown example the losses in this initial switching phase, indicated by the time stamp a in Figure 2, are reduced by the increased stray inductance from 30.4mWs to 12mWs. The second phase of the switching event is characterized by the occurrence of the reverse recovery current peak of the diode and further voltage drop at the IGBT. An increased parasitic inductance leads to a delayed reverse recovery current peak and to increased switching losses during that second phase. Regarding the whole switching event, an increased parasitic inductance therefore may significantly reduce the turn-on losses. In this case the reduction from 40mWs to 23.2mWs.

The di/dt reduces the voltage at the IGBT during turn-on but it increases the over voltage shoot at the IGBT during turn-off. This is well known and therefore a growing of turn-off losses with increased DC link inductance is expected. The turn-off switching event may be divided into two phases as sketched in Figure 3.

At the time stamp b the current waveforms of low and high inductance set-up intersect. In the first switching phase, until the crossing point b is reached the increased over-voltage with the high

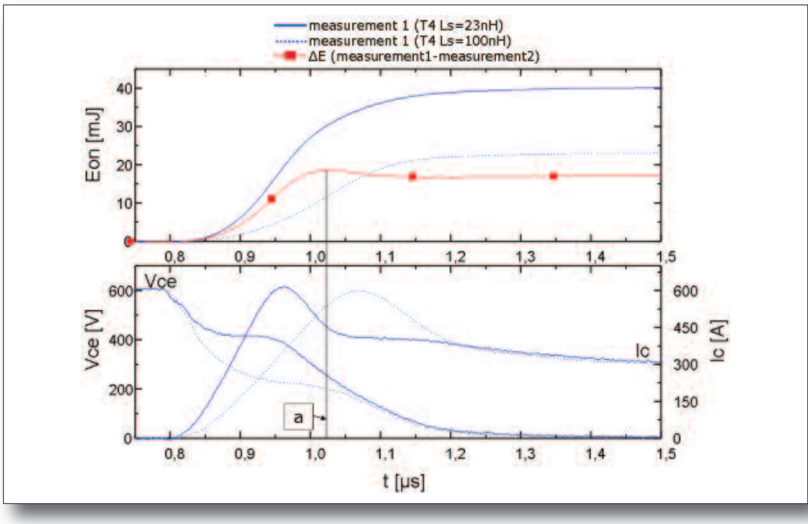

Figure 2: **Turn-on behavior of a T4; the diagram on the top shows the losses versus the time for two inductances, L_s=23nH and L_s=100nH; the bottom diagram shows the voltage and the current curves**

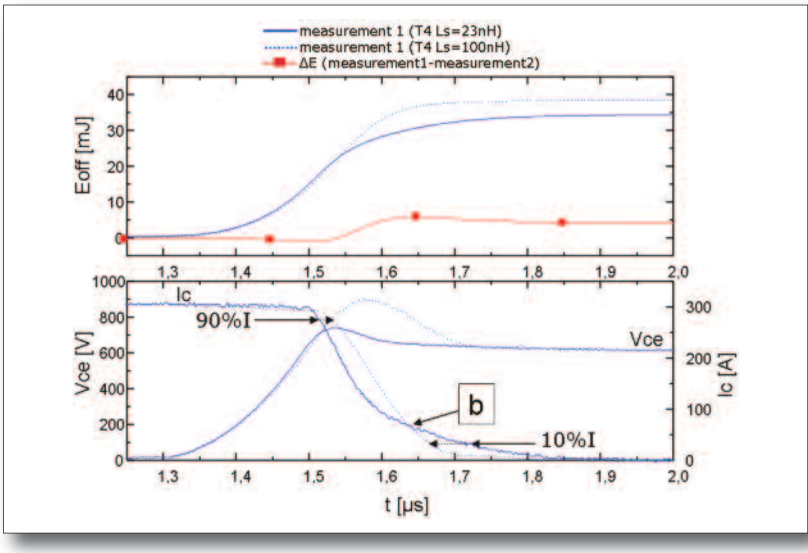

Figure 3: **Turn-off behavior of a Low Power IGBT; the diagram on the top shows the losses versus the time for two inductances (solid: L_s=23nH, dotted: L_s=100nH); the bottom diagram shows the voltage and the current curves**

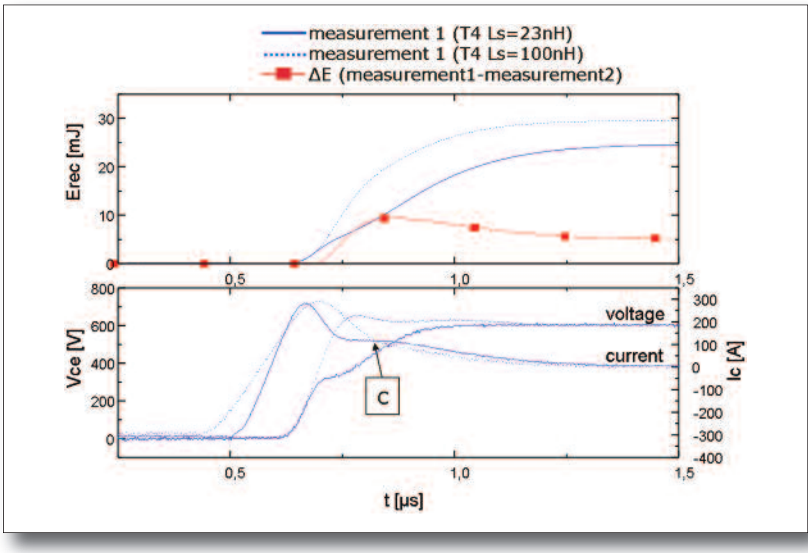

Figure 4: **Recovery of the diode: the diagram on the top shows the losses versus the time for two inductances (solid: L_s=23nH, dotted: L_s=100nH); the bottom diagram shows the voltage and the current curves**

inductance set-up results in increased losses of 36.3mJ as compared to 30.8mJ in the low inductance set-up. After point b the high inductance setup results in a shorter current tail, however the losses during this phase are about 1.8mJ lower than in case of the low inductance set-up. This result is dominated by the reduction of the current tail, i.e. a faster achievement of the 10% value.

It has been shown that the IGBT turn-on losses decrease with increased stray inductance, the diode losses increase as can be seen in Figure 4. A comparison of the diode recovery at low- and high inductances is also presented in Figure 4.

It becomes clear that the reduced di/dt of the IGBT has hardly any effect on losses at the beginning of the diode commutation since the diode voltage is still about zero. After the reverse recovery peak current the effect of the diode voltage increase by higher stray inductance dominates and induces additional losses. A higher over-voltage results in a loss increase from 10.1mJ to 19.6mJ before point c. As in case of the IGBT an increased dynamic over-voltage results in a reduction of the current tail after point c and the loss balance improves by 4.4mJ in favor of the high inductance setup. In total the first switching phase dominates and the diode losses increase with higher inductance from 24.6mJ to 29.7mJ by 20%.

Total dynamic loss consideration of the experimental results

The di/dt in combination with the stray inductance reduces the voltage at the IGBT during turn-on but it enlarges the over-voltage shoot at the IGBT during turn-off. A left-right comparison shows that the decrease of turn-on losses at a higher inductance is much more pronounced than the increase of turn-off losses.

This general trend is easily understood if one takes into account that the turn-off di/dt of modern trench field stop IGBT is intrinsically limited by the device dynamics to a value that is at about half of the turn-on di/dt. In Figure 5 IGBT turn-on losses, diode commutation losses and the turn-off losses are plotted against the parasitic DC link stray inductance for all three IGBT versions.

Softness and snap-off behavior

The preceding chapters have shown that parasitic inductances may be beneficial for the overall loss balance. But stray inductances may also lead to oscillations, e.g. as a consequence of current snap-off, which may limit the use of a device due to EMI or over-voltage limitations. All measurements presented so far have been performed at a junction temperature of T_{vj}=150°C which is most crucial for loss

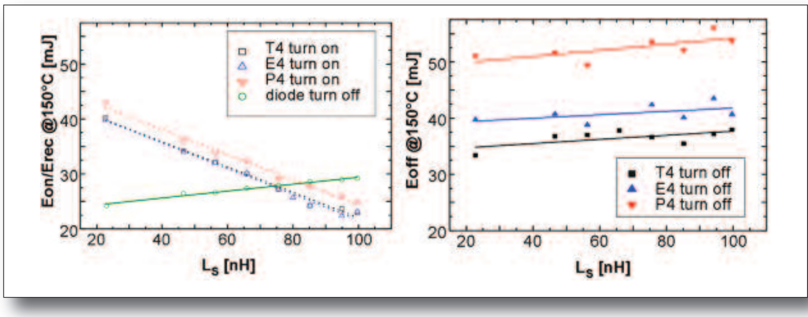

Figure 5: **Switching losses as function of the stray inductance L_s, the turn-on losses of the IGBT (left) will be reduced by increasing the inductance and the turn-off losses of the IGBT, right, and the freewheeling diode rise with the inductance**

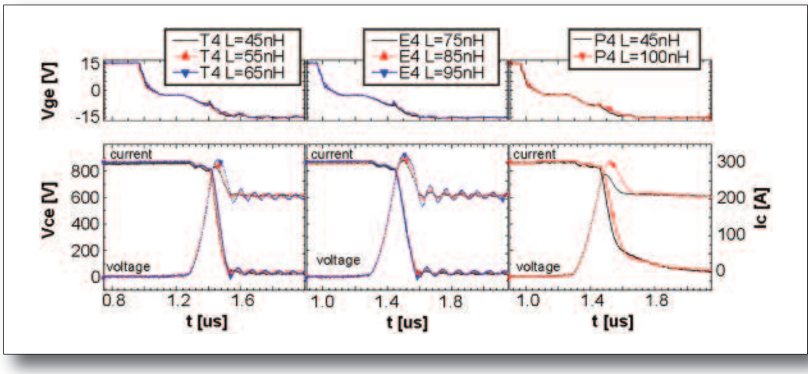

Figure 6: **Switching curves as function of the stray inductance L_s of three IGBT versions; T4 (left), E4 (middle), P4 (right); the diagrams on the top show the gate voltage; the diagrams on the bottom show the current and voltage curves**

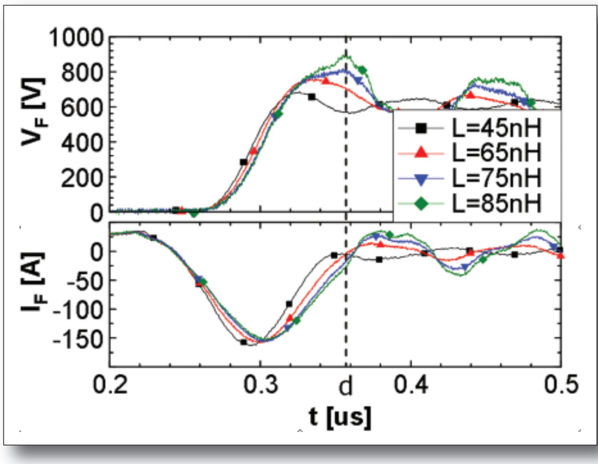

Figure 7: **Diode recovery at room temperature and 1/10 $I_{nominal}$; curves for different stray inductances**

considerations.

Snap-off is more critical at low temperatures since the carrier injection into the device decreases with temperature and pronounces the reduction of charge available for a smooth current tail. Therefore, in Figure 6 IGBT turn-off at rated current is compared between the three chip versions at a temperature of 25°C and a DC link voltage of 600V. As a parameter the DC link inductance is used.

In the given example, the T4 IGBT version gets snappy at a stray inductance of about 55nH and oscillations start to occur. The E4 version stays soft under the same conditions up to a DC link inductance of about 80nH. In case of the high power optimization the P4 chip remains soft in the inductance range observed (20nH...100nH). This observation is not surprising at all since this IGBT is designed to be used in high power modules up to 3600A current rating.

While snap-off tendencies of an IGBT are usually most pronounced at low temperatures and high currents, free wheeling diode softness usually is most critical at low temperature and low current. This is due to a couple of facts. As the diode is a carrier lifetime optimized device, the plasma density is lowest at low currents and therefore the tail charge is reduced with decreasing current level. Furthermore, the switching IGBT forcing the diode to commutate usually switches faster at low current levels. Finally, the diode over-voltage is not related to the switched current but results from the negative slope of the reverse recovery current peak of the diode. This also is steepest at low currents and low temperatures.

As a consequence of fast switching transients, du/dt and reverse recovery di/dt, DC link oscillations may easily be triggered at low current levels even without a diode snap-off. In Figure 7 the diodes reverse recovery at different stray inductances is presented.

Here, low stray inductances lead to higher resonance frequencies and may help to suppress such oscillations. Of course, the situation gets worse if large stray inductances lead to a real snap-off of the diode. This will give limitations for the use of higher stray inductances from EMI considerations.

Conclusions

IGBT optimizations designed for enhanced softness requirements pay for this feature by increased switching losses if operated under the same conditions. Besides of the switching losses, the turn-on and turn-off speed, the occurrence of snap-off and oscillation (EMI) are coming more and more into the focus. Parasitic stray inductances play an important role for DC link resonance frequencies and diode snap-off, as well. From EMI considerations at least diode snap-off will draw a simple limit to the reduction of turn-on losses by increased stray inductance or IGBT turn-on speed. Therefore different IGBT optimizations may be expected in future as well. On the other hand, recognizing the DC link inductance as a free parameter of inverter design may create a path for further loss optimizations.

The important aspect is that the further optimization of the DC link design in order to be able to use fast switching devices, i.e. as the T4, must be considered. For the inductance the lower the better is a simple rule for high efficiency designs (see Table 2).

	IGBT4 T4	IGBT4 E4	IGBT4 P4
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typical current range	up to 450A	200A - 1400A	400A - 3600A

Table 2: **Turn-off losses at the same stray inductance and softness**