Power Device

Estimation of Switching Losses in IGBTs Operating with Resistive Load

In most of the applications where IGBTs are used the device switches an inductive load. Datasheets and simulation models are made with this kind of operation in mind. However, there's a growing interest in using IGBTs with resistive loads, mainly driven by the high-voltage (HV) heater market used in electric vehicles. They rely on IGBTs for regulating the heating power. For them, this translates into switching a predominantly resistive load on and off. A proper estimation of the losses during turn-on and turn-off is needed to avoid device failure, but common loss estimation methods cannot be applied to this case. In this note, a reliable method to estimate the switching losses and instantaneous junction temperature considering these operating conditions is presented.

Switching behavior of an ideal switch – Inductive and resistive loads

For an easier understanding of the differences between inductive and resistive loads, the switching behavior here only considers *ideal* switches and diodes. Thanking this into account, the voltage V and current I waveforms during an inductive turn-on switching transient can be seen in Figure 1a. The main characteristic of this operation mode is that the voltage V can only start to decrease once the load current I_L has been reached. Conversely, during turn-off the voltage V must reach the total dc-link voltage V_{dc} for the current to decrease. The instantaneous power peak in this case is $P_{max} = V_{dc} I_L$.

Resistive switching waveforms look significantly different, as shown in Figure 1b. Here the factor V/I must remain constant and equal to the load R. The maximum stress for the device will happen at the middle of the switching transient, $P_{max} = \frac{1}{4} V_{dc} I_L$. The total switching energy can be expressed analytically and amounts to

$$E_{id} = \frac{1}{6} V_{dc} I_L t_{sw} \quad (1)$$

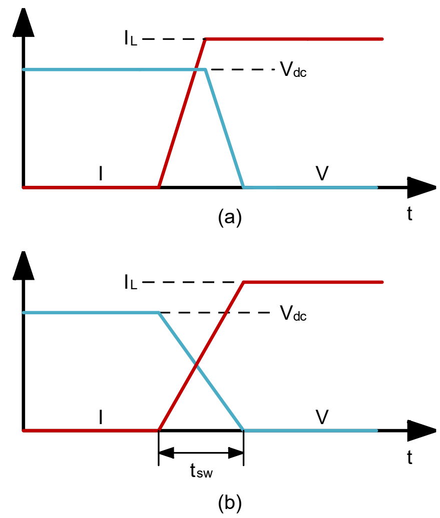


Figure 1. Ideal turn-on waveforms for (a) inductive and (b) resistive switching

Switching waveforms of an IGBT operating with resistive load

As we know, IGBTs do not behave as ideal switches. In the case of inductive switching, the "tail current" during IGBT turn-off is a good example of this. When the IGBTs are operated with a resistive load, their losses will be higher than in the ideal case:

$$E_{on} = E_{off} = \frac{1}{6} V_{dc} I_L t_{sw} + E_{cm} \quad (2)$$

where the term E_{cm} accounts for the losses due to the conductivity modulation process in the IGBT. In an IGBT, a carrier injection from collector into the drift region of the device improves the conductivity of the device when it is turned on. This is a dynamic process that happens each time the device is turned on. During this process, the device behaves as a time-dependent variable resistance. For a detailed explanation, please refer to [1].

Exemplary waveforms of an IGBT during turn-on have been sketched in Figure 2. The main difference between ideal and

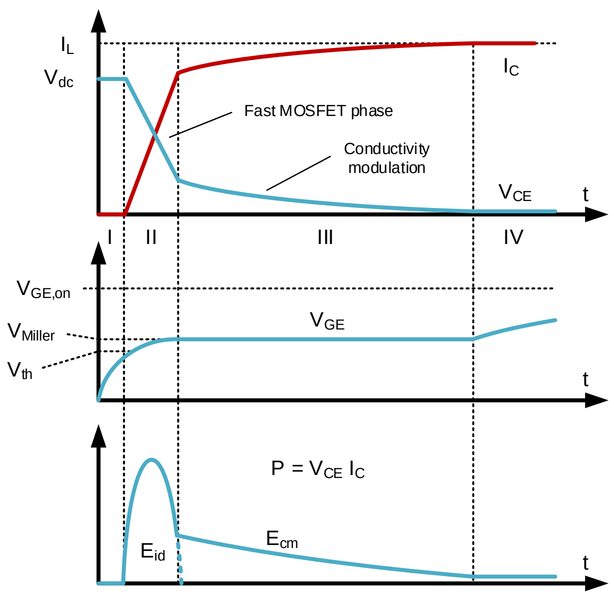


Figure 2. Resistive turn-on waveforms (simplified) in an IGBT.

real devices can be found during phase III, where the conductivity modulation takes place. This phase depends on the IGBT technology, and its duration is inversely proportional to the gate current.

Depending on the device selected and its operating conditions, the additional losses E_{cm} can be quite significant. For the case shown in Figure 3, the ideal losses E_{id} calculated according to (1) amount to 83 mJ, but the total losses E_{on} equal to 142 mJ. Hence, E_{cm} is equal to 59 mJ, only 20% less than E_{id}. It is important to note that this is an extreme example: a 1200-V IGBT is operated at a voltage of 470 V.

SPICE models: Are they good enough?

After understanding that ideal waveforms do not reflect the behavior of an IGBT accurately enough to estimate switching losses, it is necessary to assess how accurate is the SPICE-based IGBT model provided by ROHM. The first issue when trying to compare experimental with simulated waveforms is that for the same R_G value, the IGBT will switch faster in the simulation than in reality: 38 µs vs. 45 µs. Losses will be underestimated if nothing is done to compensate for this: 82 mJ (simulation, not shown here) vs. 142 mJ (experimental).

If the value of R_{G} in the simulation model is increased from 23 kΩ to 34 kΩ, both switching times (experimental and simulation) will match, see Figure 3. The conductivity modulation phase is not reproduced properly by the SPICE model, which results in 19% lower E_{on} losses. Although adjusting the

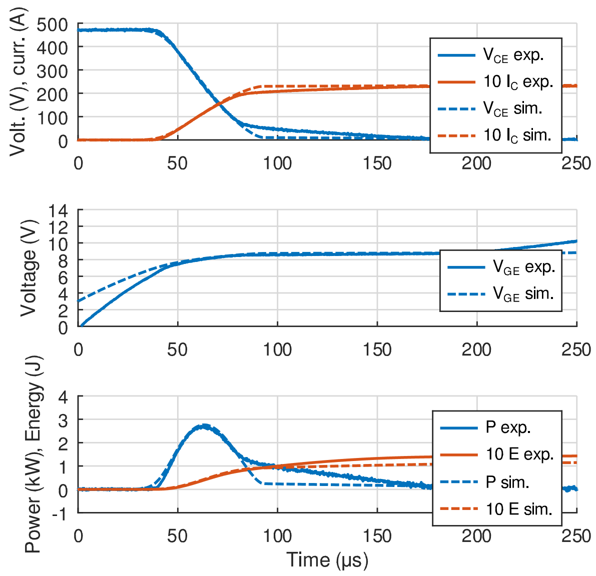


Figure 3. Turn-on of IGBT RGS80TSX2DHRC11 at 470 V, 23.5 A, and t_{sw} = 45 µs, based on measurements (exp.) with R_G = 23 kΩ and simulated (sim.) with R_G = 34 kΩ. Losses E_{on} = 142 mJ (exp.) vs. E_{on} = 115 mJ (sim.)

switching time is more accurate than considering ideal waveforms, it is still not accurate enough for a proper loss estimation. This inaccuracy of standard IGBT models is a known limitation and has been discussed in [1].

Proposed estimation method

Since both ideal and simulated waveforms do not properly reflect the behavior of the IGBT for an accurate estimation of the switching losses, a hybrid method is presented here, where the device losses are extracted from measurements and the temperature swing is reproduced based on the worst-case operating conditions using an equivalent RC thermal network.

Part 1: Experimental waveforms

A single pulse test of the IGBT driving a resistive load is carried out to capture V_{CE} and I_{C} waveforms during turn-on and turn-off, as in Figure 4. The IGBT should be heated up externally to reflect the temperature at which the device will be operating. Usually, a value between 100 and 150 °C should be selected. If the R_{G} value is high, setting a temperature close to the maximum junction temperature rating might result in destruction during the turn-on or turn-off phase due to the significant temperature swing.

The other important factor to consider here is the dc-link voltage V_{dc}, which must be chosen according to the worst conditions for the IGBT in the application. For HV heaters, some of

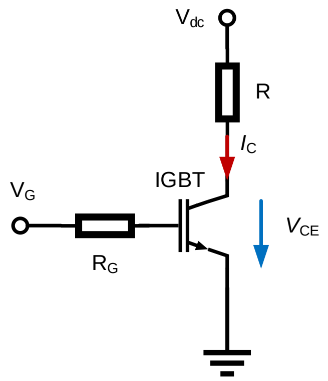


Figure 4. Circuit diagram for resistive load switching characterization.

the operating points that can yield the highest T_j temperature in the power/voltage plane of Figure 5 are:

1. Full power operation at the highest voltage allowed without de-rating, (P_{max}, $V_{max,FP}$).
2. Absolute maximum voltage and maximum power allowed at that voltage, (P_{max2}, V_{max}).
3. Absolute maximum voltage and minimum duty cycle, ($P \rightarrow 0$, V_{max}).

This means that at least two different voltages V_{dc} must be considered. Depending on the specific operating conditions of the IGBT, there might be other relevant voltages worth checking.

Part 2: Post-processing of the switching waveforms

It is recommended that the waveforms obtained experimentally are adjusted to reflect worst-case conditions and not the ones of a typical device. We recommend the following procedure:

1. Extract both turn-on and turn-off switching instances out

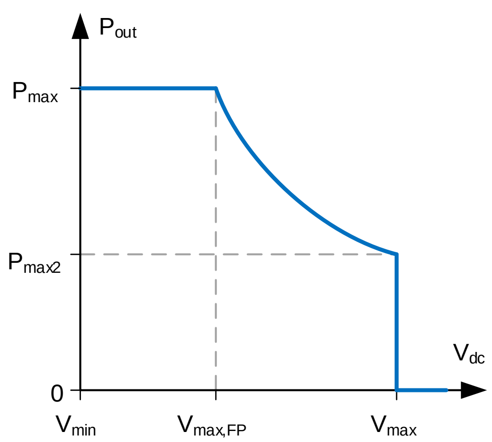


Figure 5. Exemplary output power P_{out} vs. voltage V_{dc} diagram, as used in HV heaters.

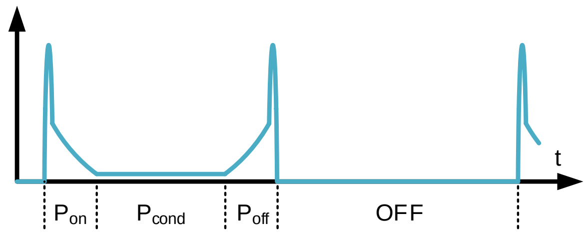


Figure 6. Instantaneous power waveform synthetized out of measured turn-on and turn-off transients and an estimation of the conduction losses.

of the captured waveforms.

2. Obtain the instantaneous power waveform by multiplying voltage and current:

$$P(t) = V_{CE}(t)\, I_C(t) \tag{3}$$

3. Add a safety margin of 20% to the duration of $P_{on}(t)$ and $P_{off}(t)$ to account for device outliers with higher switching losses.

Part 3: Synthesis of instantaneous power waveform under worst-case operating conditions

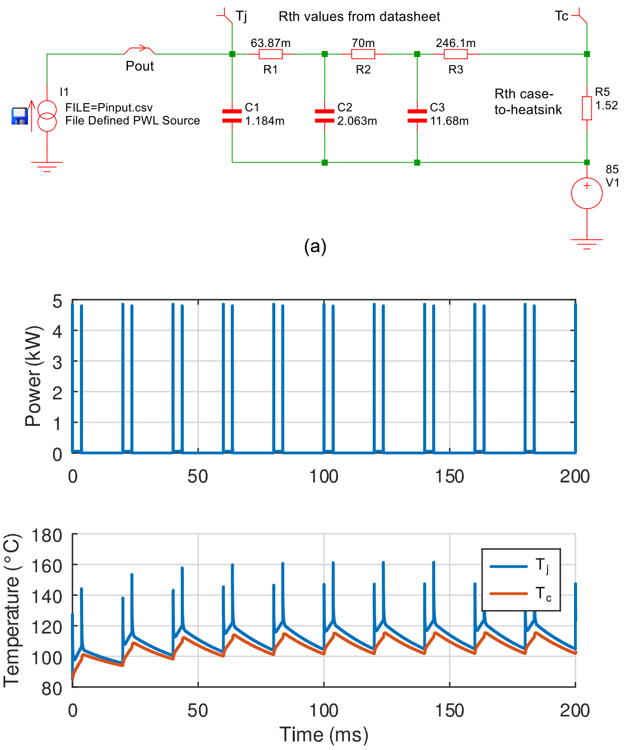
A usual way of estimating the maximum junction temperature of a device is by calculating the losses for turn-on, turn-off, and conduction, adding them up and calculating the junction temperature T_j based on the cooling conditions. This approach is, however, not suitable when the IGBT is switching with a very high gate resistance value in the kΩ-range, as commonly preferred in applications such as HV heaters. Using the total loss would yield the average T_j value, which neglects the temperature swing of the device. This swing is significant and shouldn't be neglected.

For this purpose, a better approach is to estimate the instantaneous T_j waveform by combining the power waveforms P_{on} and P_{off} obtained in the previous part with the conduction losses

$$P_{cond} = V_{CE,sat}\left(I_{max}, T_{j,cond}\right) \cdot I_{max} \tag{4}$$

where $V_{CE,sat}$ is the device C-E saturation voltage at the maximum expected load current I_{max} and at the maximum expected junction temperature $T_{j,cond}$ during conduction. To simplify this step, the $V_{CE,sat}$ value given in the datasheet for T_j = 175 °C can be used as a worst-case estimation.

The final step in the synthesis of the instantaneous power waveform is to concatenate P_{on}, P_{cond} and P_{off} to reflect the worst-case operating conditions for a device, such as the ones listed under Part 1 of this section.



(a)

(b)

Figure 7. Exemplary results for the proposed method: (a) simulation circuit for SIMetrix-SIMPLIS, (b) power P and temperature T_h and T_j waveforms (IGBT RGS50TSX2, R_G = 5.6 kΩ, V_{dc} = 865 V, R = 50 Ω, f_{sw} = 50 Hz, duty cycle D = 0.18, $R_{th,c\text{-}h}$ = 1.52 K/W, T_h = 85 °C)

The final $P(t)$ waveform should look like the one in Figure 6, which also considers the time the device is OFF until the cycle starts over again.

Part 4: Power waveform as an input to the RC thermal network

After generating the instantaneous power waveform $P(t)$, it can be applied cyclically to a thermal network representing the device plus the cooling conditions. An example of the simulation circuit used for this purpose and the resulting P and T_j waveforms are shown in Figure 7. It is made based on measurements of the IGBT RGS50TSX2DHRC11, the conditions have been detailed in the captions.

Part 5: Assessing the simulation output

Once the instantaneous temperature T_j has been plotted, it is easy to assess if the device is working within its specifications or not. The maximum T_j for the IGBTs from ROHM is 175 °C. This temperature limit should be respected at all times, including the switching transients. As a rule of thumb, keeping the peak value below 160 °C should give a good compromise between safety margin and device utilization.

Conclusion

This application note has shown that a correct estimation of the switching losses of an IGBT operating with a resistive load is not trivial. There are several obstacles that can lead to an underestimation of the losses or temperature. To overcome this, a method based on measurements has been proposed. This should help designers to choose the right IGBT and dimension the cooling circuit accordingly.

There are further documents from ROHM regarding thermal design of power devices that are worth checking and getting familiarized with. A summary of the most relevant documents can be found in [2].

References

[1] A. T. Bryant, L. Lu, E. Santi, J. L. Hudgins and P. R. Palmer, "Modeling of IGBT Resistive and Inductive Turn-On Behavior," in IEEE Transactions on Industry Applications, vol. 44, no. 3, pp. 904-914, May-june 2008, doi: 10.1109/TIA.2008.921384

[2] "4 Steps for Successful Thermal Designing of Power Devices", ROHM Co., Ltd., Kyoto, Japan, White paper 64WP010E. [Online]

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