# Accurate Measurement of on-State Losses of Power Semiconductors


Alex Pokryvailo and Costel Carp
Spellman High Voltage Electronics Corporation
475 Wireless Boulevard
Hauppauge, NY 11788



*Presented at 28th Int. Power Modulators Symp.*, Las Vegas, 27-31 May, 2008, pp. 374-377.



***Abstract*— For safe design, the junction temperature should be kept within the specified range. Three methods are used most often for determining the power losses:**

1. **Calorimetric method;**
2. **Using calibrated heatsinks;**
3. **Electrical measurements of the device voltage and current, and finding the losses by integrating these variables.**

**The paper concentrates on the third method with the emphasis given to the accurate measurement of the on-state voltage. The techniques of using non-linear dividers with deep voltage clamping are discussed. Novel circuits allowing faithful measurements of the on-state voltage along with good timing resolution of the switching transitions are proposed. Results of circuit simulations are borne out by extensive testing. Examples of measurement of the on-state voltage of large IGBT modules and free wheeling diodes (FWD) are presented. The obtained results are applicable for characterizing various power switches, e.g., gas discharge devices.**


## I. Introduction

For safe design of switch-mode power conversion systems, the junction temperature, $T_j$, of power semiconductors should be kept within the specified range. A practical method of calculating this parameter is using the following formulae:

$$T_j = T_c + \Delta T_j,\ \Delta T_j = QR_{th(j-c)}, \tag{1}$$

where $T_c$ is the case temperature, $\Delta T_j$ is the junction temperature rise over the device case, $Q$ is the component power loss, and $R_{th(j-c)}$ is the thermal resistance, junction to case, specified by the manufacturer. All the indicated temperatures can be readily measured; determining the power losses, involves more effort. Three methods are commonly used:

4. Calorimetric method (see, e.g., [1]);
5. Using calibrated heatsinks;
6. Electrical measurements of the device voltage $v$ and current $i$, and then finding the losses $E$ by integrating:

$$E = \int_0^T vi dt, \tag{2}$$

where $T$ is the period. The power loss is found as $Q = Ef$, where $f=1/T$.

The first method provides accurate and most reliable results, but is difficult to implement, especially in air-cooled setups. The second method is simpler but inconvenient for the breadboard setups with ever-changing cooling schemes. We will discuss in more depth the third method as most flexible and understandable for electrical engineers.

Eq. (1) works out well only if the current and voltage measurement are correct. In view of a very large dynamic range of the voltages in the on- and off states, it is difficult to devise a one-stop setup, although there are recommendations how to circumvent this problem [2]. One needs high-quality probes and a good scope; this alone does not guarantee faithful measurements. Ensuring safety is realized with differential probes, at a price of compromising the measurement accuracy in view of their limited bandwidth and capacitive effects.

In determining the switching losses, good time resolution is of prime importance, whereas the dynamic range is less important. For hard switching topologies, these losses may be estimated using the datasheets. In soft switching circuits, the conduction losses dominate, and switching losses may be often neglected. Here the accurate measurement of the on-state voltage comes to the front plan. The following discussion concentrates on this problem.

Basic technique of narrowing the dynamic range is voltage clamping using non-linear dividers (see, e.g., [3]). Fig. 1 shows two examples of such dividers. Implementation *a* uses $N$ low-voltage diodes connected in series, so when the applied voltage drops below $NV_{df}$, where $V_{df}$ is the diode forward conduction threshold, there is no current flowing through R1, and the voltage at the scope input equals $HV_m$. Circuit *b* functions similarly.

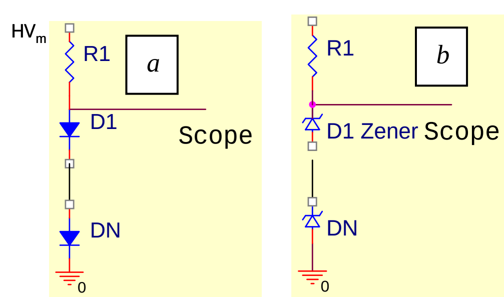



Fig. 1. Schematics of basic nonlinear voltage dividers.

Experimental techniques and measurement means are described further in the body of the text.

## II. SHORTCOMINGS AND LIMITATIONS OF BASIC CIRCUITS

Circuits Fig. 1 depict idealized, and if realized, the ideal devices for measurement of low voltages in high dynamic range. In reality, there are several factors that limit the applicability of these schemes as given in Fig. 1. We skip here obvious component ratings constraints.

One limitation is the inertia introduced by the time constant $\tau = R_1 C_p$ of the measuring circuit, where $C_p$=$C_{pr}$+$C_{pd}$ is the capacitance of the scope input (including the probe), $C_{pr}$, in parallel with the dynamic capacitance of the diodes/Zener diodes, $C_{pd}$. Passive voltage probes have typical capacitance of 10 pF, so with $R_1$=10 kΩ, the time constant of the circuit *a* may be ~$10^{-7}$ s, i.e., quite small if the diodes' capacitance can be neglected. However, the diodes remain forward-biased for some time after the voltage $HV_m$ drops below the threshold value, since there is no reverse voltage applied to them. This time may be about 1 µs for diodes specified for $t_{rr}$ =75 ns recovery, such as BYM26E, as show experiments and PSpice simulations. It takes the diodes ~0.5 µs to come to a non-conducting state, because the reverse current is very small and unable to evacuate the stored charge fast.

Using signal diodes with $t_{rr}$ of the order of a few nanoseconds resolves the stored charge problem as show simulations with 1N4500 diodes having $t_{rr}$=6 ns. However, these and similar diodes (in experiments, we used MMBD914, $t_{rr}$=4 ns) have significant forward current of tens of µA at tenths of a volt, which translates to a voltage drop across R1 of the order of 1 V. Thus, large number of diodes should be connected in series to reduce this effect, with some uncertainty remaining.

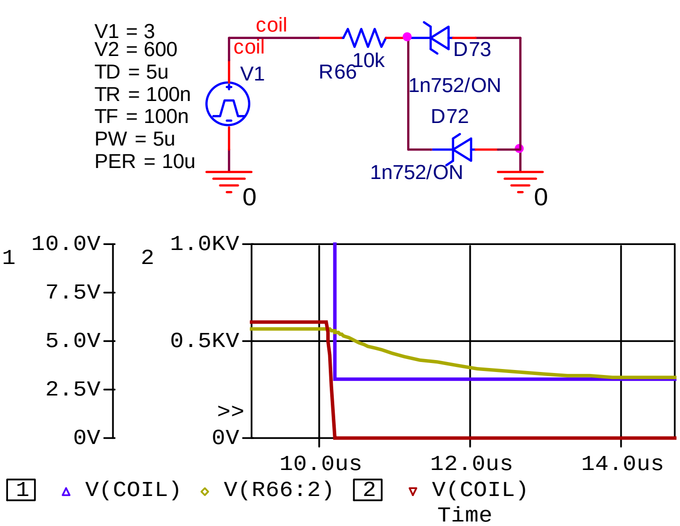



Fig. 2. PSpice simulation of circuit Fig. 1b with Zener diodes. Net aliases in this and following figures show connectivity (e.g., source V1 is connected to point "coil" of circuit Fig. 2).

The capacitance of Zener diodes, on the opposite of the diodes use, must be accounted for, and in this case, the time constant is on the order of a microsecond. This is larger than typical switching times and commensurable with the pulsewidth at high conversion frequency. Fig. 2, Fig. 3 illustrate this statement. The experiments were conducted with a half-bridge quasi-resonant inverter. A Rogowski coil CWT15 [4] was used for monitoring the components current. Since it is an essentially AC probe, the current traces are usually biased. In Fig. 3, the bias in the emitter current, *Ie*, was removed numerically.

## III. IMPROVED PRACTICAL CIRCUITS

The detrimental action of the Zener capacitance can be rectified using a fast diode connected in series as shown in Fig. 4 that simulates the actual circuit (except the Zener diodes were 1N751A, and the diode was MMBD914). Simulations Fig. 4 correspond to the measurements of Fig. 5. It is seen that the on-state transition is faster and less noisy compared to Fig. 3. This is important for the loss calculation using (2). We note that a circuit similar to that of Fig. 4 is described in [3], but the actual waveforms exhibit slow ~2 µs transitions, which might be related to the use of an unsuitable diode.

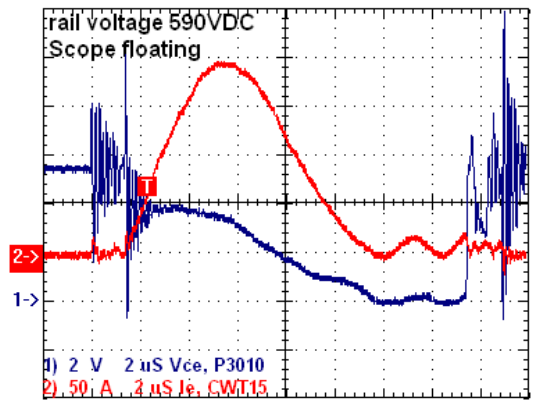



Fig. 3. Measurement of collector-emitter voltage $V_{ce}$ of CM300DC-24NFM Powerex IGBT using circuit Fig. 2. TDS 3024B scope is floating. In this and further plots, waveform notes carry scale information and types of probes used.

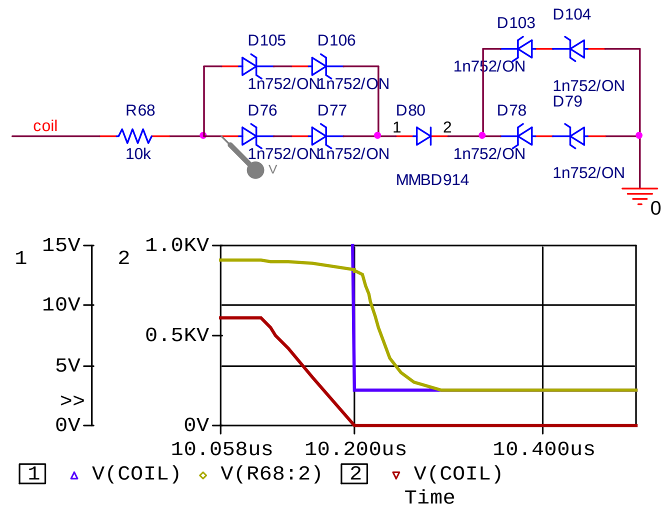



Fig. 4. Blocking Zener diode capacitance using a fast diode. Circuit excited by source V1 Fig. 2.

Although measurements Fig. 5 can be believed to be true in the sense that the voltage *between the measurement points* was recorded faithfully, the actual $V_{ce}$ voltage is different from it owing to the IGBT internal inductance $L_{IGBT}$. The inductive voltage drop $L_{IGBT}\, {di_e}/{dt}$ can be deducted from the measured voltage; a corrected waveform calculated for $L_{IGBT}$=20 nH is shown in Fig. 6.

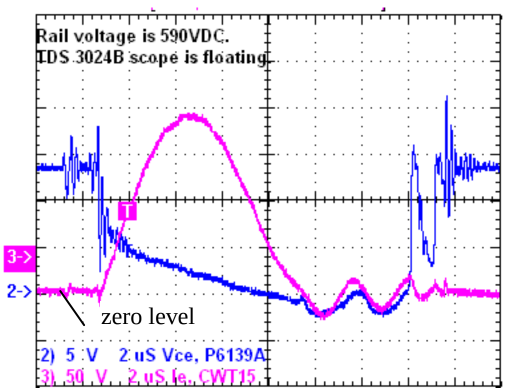



Fig. 5. Measurement of saturation voltage $V_{sat}$ (collector-emitter voltage $V_{ce}$,) of CM300DC-24NFM using circuit Fig. 4. Scope is floating.

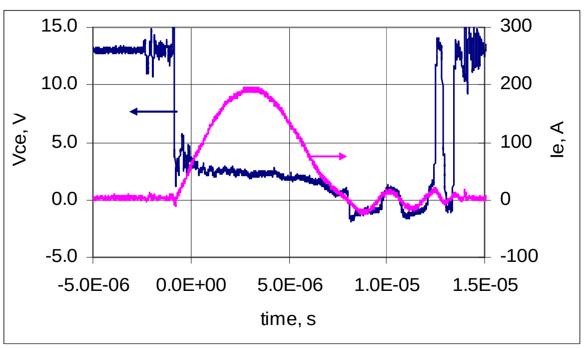



Fig. 6. $V_{ce}$ adjusted for inductive voltage drop (numerical filtering has been applied). It corresponds to CM300DC-24NFM datasheet.

Divider Fig. 4 (forward-biased Zener diodes are redundant) is adequate for $V_{sat}$ measurement of power transistors (and incidentally, many other types of switches, such as SCRs, GCTs and gas discharge devices), but cannot be used for the measurement of the forward voltage drop of free wheeling diodes (FWD) because it swings negative relative to the $HV_m$ point. (Without the cut-off diode, the divider is universal, but the transition to the on-state is slow as indicated in Fig. 2, Fig. 3.) In this case, a bridge formed by fast diodes around a Zener provides a solution (Fig. 7).

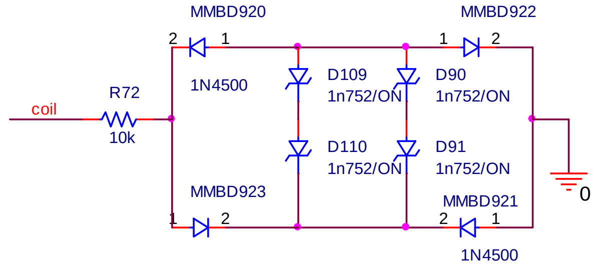



Fig. 7. Bridge formed by fast diodes around a Zener diode works equally well for measurement of positive and negative low voltages in wide dynamic range. Circuit excited by source V1 Fig. 2.

Fig. 8 shows the trace of an IXYS DSEI 2x61 FWD current (one module contains two diodes connected in parallel) together with the voltage trace taken with the divider Fig. 4 (fast diode removed) with the scope floating. The voltage trace has almost a sine wave form with a slow falltime, which is a measurement error caused by the inherent defect of this circuit (Zener diode capacitance).

Using a divider Fig. 7 provides a different picture and is believed to improve the measurement considerably as seen in Fig. 9 that shows also an adjusted waveform and loss curves. Again, the actual forward drop is lower by the inductive component.

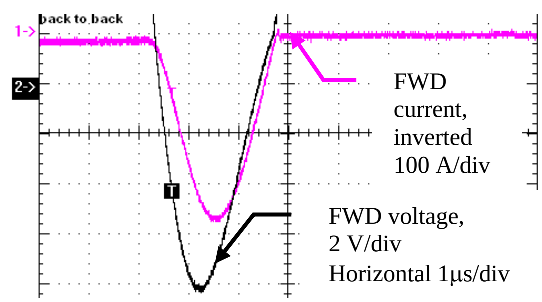
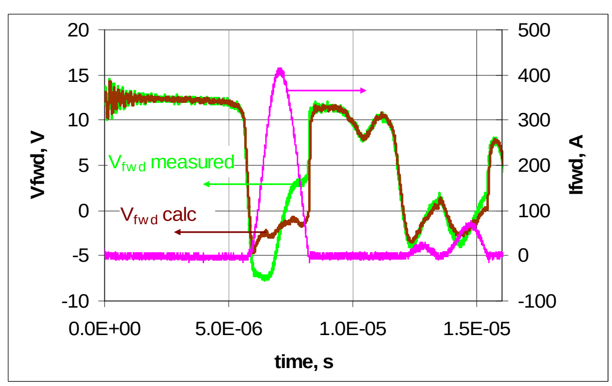
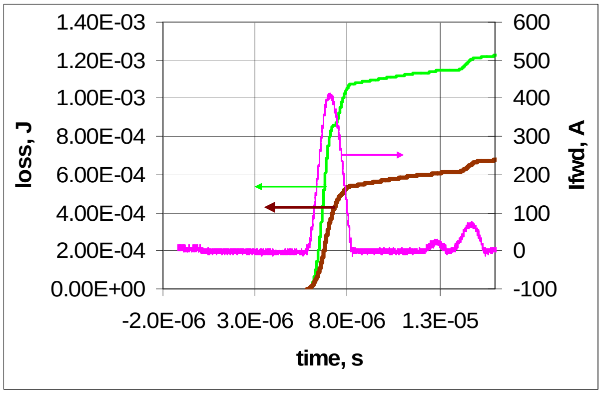



Fig. 8. Trace 2 - Forward drop of FWD IXYS DSEI 2x 61 (negative part). Clamped positive voltage (diode non-conducting) is off-scale. Zener diode capacitance (divider Fig. 4) affects the voltage fall time.




a




b

Fig. 9. FWD IXYS DSEI 2x61 losses. Plot a – green trace is measured signal; brown trace is $V_{fwd}$ adjusted for inductive drop $LdI_{fwd}/dt$ (diode assembly inductance *assessed* at 5 nH). Green and brown curves plot b match their counterparts in plot a. Divider Fig. 7, *Floating scope.*

## IV. Floating or Differential Measurements? Safety Issues

As a rule, the scope chassis is grounded for safety, and floating measurements are performed with differential probes as recommended by scope vendors (see, e.g., [2]). Our experience shows, however, that the quality is severely compromised compared to the case when the scope is floating together with the reference point, e.g., the transistor emitter or the FWD anode. Examples of using a differential probe P5200 for $V_{ce}$ and FWD forward drop measurement are shown in Fig. 10, Fig. 11, respectively.

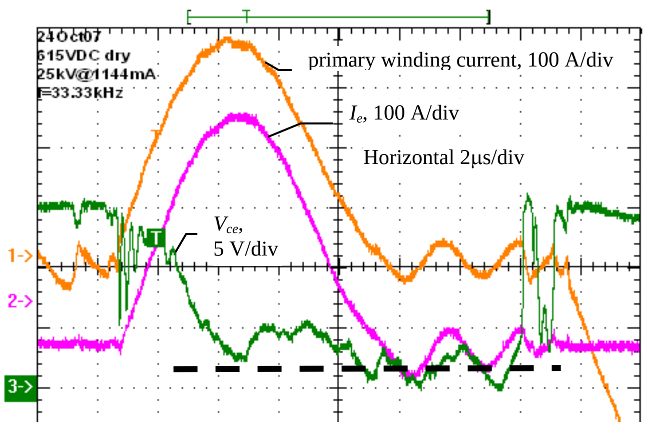



Fig. 10. Differential measurement of $V_{sat}$ (trace 3 Vce) of CM300DC-24NFM Powerex IGBT using circuit Fig. 4. Trace 3 may have some offset, likely zero is shown by dashed line.

They are less "trustworthy" in our opinion than their floating counterparts Fig. 5, Fig. 9 (see also the superposition of the differential and floating measurements Fig. 12), which can be explained by the probe limited bandwidth (25 MHz for P5200 compared to 500MHz for P6139A), leads' capacitance to ground in addition to a 7-pF capacitance of each input (estimated 30 pF total), and by the large voltage swings (~360 V at a rail voltage of 600 V) of the inputs relative to ground. Therefore, battery-fed scopes, such as Tektronix TPS series are preferential for this task. Even better, universal, and less expensive solution is using regular scopes fed from an uninterruptible power supply ***disconnected*** from mains. Usual safety precautions should be taken in floating measurements.

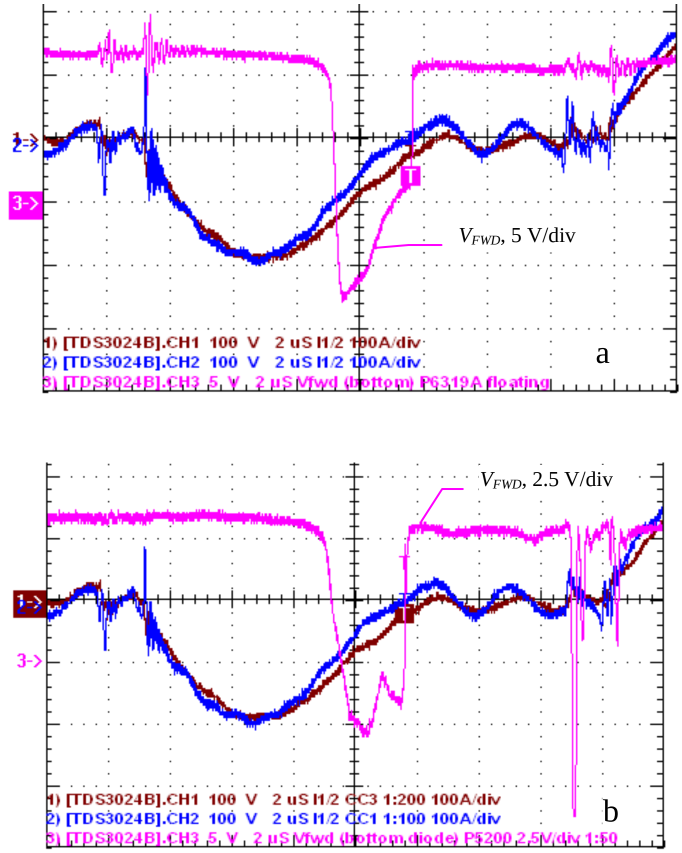



Fig. 11. Trace 3 - Forward drop of FWD IXYS DSEI 2x 61, two modules in parallel. a – *high-bandwidth P6139A probe*, b - *differential probe.* Both measurements taken with floating scope.

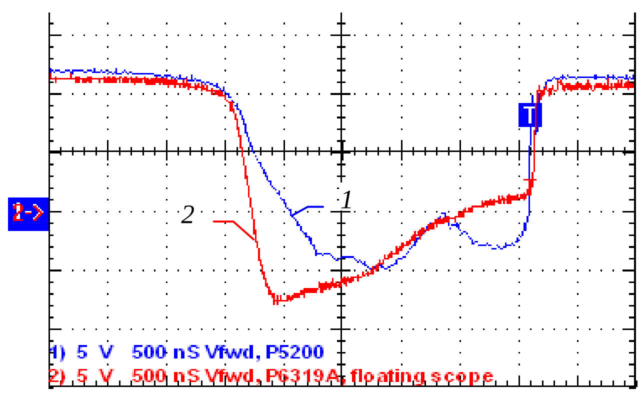



Fig. 12. Superposition of differential and floating measurements of Fig. 11a, b.

## V. Conclusion

Divider Fig. 4 is recommended for the measurement of the on-state voltage of large power switches. Clamping voltage should be adjusted to the expected on-state value using proper number of zener diodes. Floating measurements provide better accuracy, however, safety rules should be strictly observed.

## ACKNOWLEDGMENT

The authors acknowledge the support of this work given by Spellman High Voltage Electronics Corporation.

## REFERENCES

[1] C. Huang, P. Melcher, G. Ferguson and R. Ness, "IGBT and Diode Loss Measurements in Pulsed Power Operating Conditions", *Proc. Power Modulator Symposium*, 2004, pp. 170-173.

[2] S. Gupta, Power Measurements and Analysis: Challenges and Solutions, *Tektronix White Paper*.

[3] A. Calmels, "VDS(on), VCE(sat) Measurement in a High Voltage, High Frequency System", *Advanced Power Technology*, Application note APT0407, November 2004.

[4] http://www.pemuk.com/pdf/cwt_mini_0605.pdf