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IGBT Testing: a revised approach from a metrological perspective

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Abstract: The usage of IGBTs in power electronics field is increasing day by day and drawing the attention of researchers to characterize its application in different fields. One of the most important parameters for the designers is to determine the energy losses introduced by these devices. The manufacturers of IGBT do not always provide this parameter in the same way and very often at comparable values of the parameter may correspond different behaviors. Moreover, in the tests carried out by manufacturers, some aspects that are responsible for a significant measurement uncertainty are neglected or underestimated. With the development of two new measurement system, this paper investigates about some particular sources of uncertainty that can affect static and dynamic loss of IGBT measurements. In particular, evaluation on the effect of self-heating process in the measurement of voltage drop Vce across the collector emitter terminal. In addition, this paper presents the effect of socket that holds the DUT in the measurement of Vce. Finally, the result of investigation on the effect of stray inductance in the switching characteristic measured with the developed measurement system is compared to the switching characteristics given by the manufactures in the data sheet.

I. INTRODUCTION

The growing demand of low carbon emission power system and deployment of smart grid is boosting the usage of Insulated Gate Bipolar junction Transistor (IGBT) that combines the high-speed switching and voltage drive characteristics of MOSET with the low on state resistance (low saturation voltage) characteristic of a bipolar power transistor. IGBTs seizing the power electronic industries attention in numerous field of applications like power system, renewable energy, rail traction, UPS, automotive, motor drive, consumer electronics, and others. A report states that the market size of IGBTs expected to reach more than $8 billion by 2020 at a compound annual growth rate of 9.5% from 2015 to 2020 [1]. The increasing demand of IGBT as an ideal switch is due its high speed and low saturation voltage characteristics and the improving cost-performance ratio.

In designing circuits for power control in switching applications, the usual way to select the best device is by ensuring two important parameters. One is the on-state voltage at rated current that depicts the conduction loss that is responsible for the heat dissipation and the second is the switching time that determines the energy loss per transition in order to determine the operating frequency of the IGBT.

Despite the manufacturers always declare these parameters in their datasheets, very often the adopted test condition differs. In particular, not only the test circuits may vary, but also the definition and the parameters considered for the evaluation may vary among the different manufacturers. Hence, in order to have comparative tests between different types of IGBTs, a proper measurement system has to permit a high level of flexibility in implementing and changing the definition of the quantities to measure in an easy way. Moreover, another mandatory task of the measurement system is to have a good measurement accuracy that permits a reliable analysis of the characteristics of an IGBT and a reliable comparison with other similar devices [2, 3 and 4]. Taking into account these requirements, the use of a virtual instrument approach may prove to be an efficient solution in developing a measurement system for IGBT testing.

The solution adopted in this paper is based on the combined use of DAQ boards and traditional instruments managed in LabView environment. Despite being simple and low-cost structure, the developed system permits to point out some very relevant measurement aspects that usually are not considered properly in IGBT testing and that may represent a relevant source of measurement uncertainty in the evaluation of some critical parameters.

The organization of the paper is as follows. Section I describes the main parameters of interest of the IGBTs, discussing the different possible conditions adopted by the manufacturers in their evaluation. Section II presents the hardware and software solutions implemented in the developed measurement system. Section III and Section IV dedicated to the discussion about some particular measurement uncertainties that affects the static and dynamic characteristics measurements, which are very often underestimated.

II. MAIN IGBT LOSSES: DEFINITIONS

One of the main parameter considered in the design process is the energy losses caused by the IGBT during its two working states on and off. There are two types of losses: the conduction loss and switching loss. The conduction loss occurs when the device is in on-state and conducts a current that produces a voltage drop between the collector and emitter terminals and the related power dissipation can be expressed as:

$$P_{st} = \int_{o}^{t0} I_{ce}(t) \times V_{ce}(t) dt \quad (1)$$

where t_0 is the time interval of the conducting phase, $I_{ce}(t)$ and $V_{ce}(t)$ are the current and the voltage between collector and emitter respectively.

Despite the current and voltage are time-dependent and can vary during the time interval t_0. Very often, for the sake of simplicity, the evaluation of static losses considers both the current I_{ce} and the voltage Vce as constants. This first order approximation requires the value of the V_{ce_sat}, which represents the value of the V_{ce} voltage for a given constant current. Hence, the IGBT manufacturers provide many values of V_{ce_sat} for different values of I_{ce} and at different temperature conditions.

In addition to the static losses, another important phenomenon is the switching losses that occur during the state transition of the device i.e. from on state to off state or vice versa. During the state transition, there is a voltage drop between the collector and emitter terminals when the current is still flowing through the same terminals and this causes an instantaneous power loss and is very important for the reliability of the device. Since this power loss may heavily affect the junction temperature of the IGBT, one prefers to evaluate this loss in terms of energy instead of instantaneous power represented by two different quantities: E_{on} and E_{off} for the any state transition, and expressed as:

$$E_{on} = \int_{t_{on}} V_{ce}(t) \times I_{ce}(t) dt \quad (2)$$

$$E_{off} = \int_{t_{off}} V_{ce}(t) \times I_{ce}(t) dt \quad (3)$$

Where, t_{on} and t_{off} characterize the time intervals with significant energy losses and it is clear that their definition is very important since different choices can lead to different evaluations of the same quantities. There is no common definition for the parameters t_{on} and t_{off} among different IGBT manufactures. For instance, some of them define t_{on} as the elapsed time between the time corresponding to that at which the current reaches a given percentage of the rated value and those in which the V_{ce} fallen to a given percentage of supply voltage. The percentage values can vary according to the manufacturers. Others manufacturers prefer to refer the starting time of the t_{on} interval to a given value of the gate voltage. Actually, every measurement system devoted to this kind of measurements should be characterized by a proper flexibility and configurability as this becomes mandatory, if the target is to compare the performance of IGBTs from different manufacturers, as it is in our research activity.

III. DEVELOPED MEASUREMENT SYSTEM

The testing of IGBT for the static and dynamic characteristics are performed with two different measurement systems: one dedicated to measure the conduction loss and the other for the switching losses.

The measurement system for static measurements comprises a Printed circuit board (PCB) jig with a socket to hosts the device under test, a commercial gate pulse drive and a shunt to measure the current through the device. A DC voltage generator, a DAQ board and a PC with LabView environment are connected to form the complete measurement system as represented in Fig. 1.

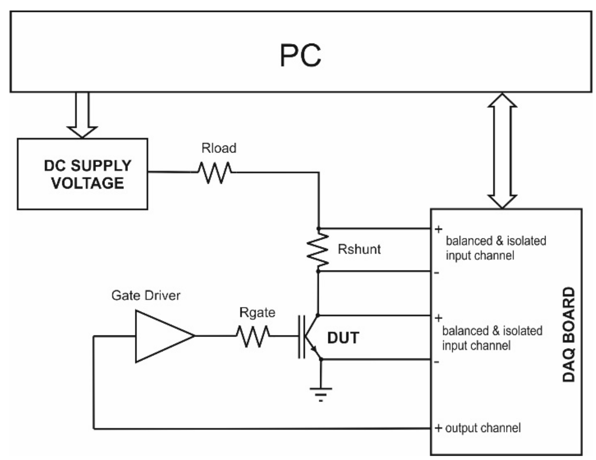

Fig. 1. Measurement system for static characteristics.

A pulse of width 0.5ms defined in the LabView program is applied to the IGBT through a gate driver that boosts the signal and drives the gate terminal through a resistor. The DC voltage generator also controlled by the LabView program sets the voltage level that permits to have the required current flow in the IGBT. A 16-bit resolution DAQ board with a sampling rate of 100 kS/s acquires the voltage between collector and emitter and the current signal (namely the voltage drop on the resistive shunt). When setting up the voltage generator for the rated current, even in the case of a fine-tuning of the DC voltage generator, it is not possible to guarantee the precise target current value. In fact, the current depends also on the specific V_{ce_sat} of the device under test. Hence, the measurement is performed for current value as close as possible to the rated one and post-processing the measured data permits to interpolate the V_{ce_sat} at the rated current value.

The measurement system for dynamic characteristic uses the traditional double pulse test [5, 6 and 7] and a clamped inductive load as shown in Fig. 2. A PCB jig hosts a capacitor capable to deliver the energy needed for the test and a socket hosts the device under the test.

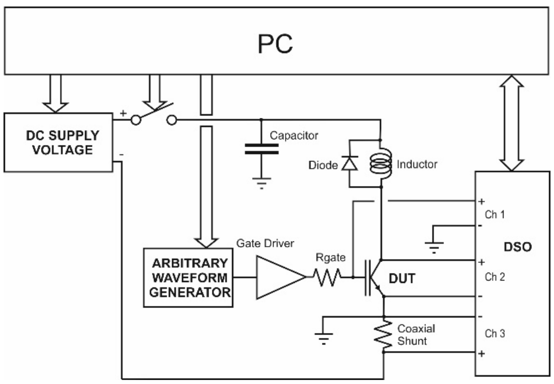

Fig. 2. Measurement system for dynamic characteristics.

The DC generator charges the capacitor at the rated voltage and is isolated before triggering the gate pulse. A high voltage probe is connected between the collector and emitter while a wide bandwidth coaxial shunt permits to convert the current pulses into correspondent voltage pulses. Since the edges of these pulses have to be sampled with a proper time resolution, an 8-bit digital scope with four isolated channels is used as data acquisition system, working at a minimum sampling rate of 1 GB/s per channel. A PC with LabView environment sets up the arbitrary waveform generator with the defined pulse width, the voltage level of the DC voltage generator and all the control of the digital oscilloscope. A user-friendly front panel of the LabView program allows changing the acquisition parameters for obtaining an accurate signal. Waveforms are stored in files as well as the computed energy.

IV. STATIC MEASUREMENT METHODS AND RELATED SOURCES OF UNCERTAINTIES

The measurement of V_{ce_sat} is a very simple task from a conceptual point of view, as it only requires measuring the voltage drop at the terminals of the device when a constant current is flowing through them. However, the duration of the test at which the measurement is performed may be a critical parameter. Since the device is tested usually without the aid of any heat sink, it is mandatory to verify that the self-heating of the device does not significantly vary the temperature of the device during the test. This is especially true when the test is performed keeping the case of the IGBT at high temperature, i.e. 100°C or 150°C.

Usually, this test is based on a single current pulse, such that the subsequent energy stored in the device under test (that can be assumed as an adiabatic process) can be estimated as:

$$E_{se} = I_{ce} \times V_{ce\_sat} \times t_{pulse} \quad (4)$$

where, I_{ce} represents the amplitude of the current pulse, V_{ce_sat} is the voltage drop between collector and emitter due to current I_{ce} and t_{pulse} is the pulse width. It is clear that for longer measurement time the energy stored inside the device is higher with the corresponding increase in the junction temperature and this possibly introduces uncertainty in the V_{ce_sat} measurement. This effect has been investigated for different kinds of IGBT by measuring the increase of V_{ce_sat} as a function of t_{pulse}. For an IGBT series having a TO220 package and 20A of rated I_{ce}, the average variation of the V_{ce_sat} is represented in Fig. 3.

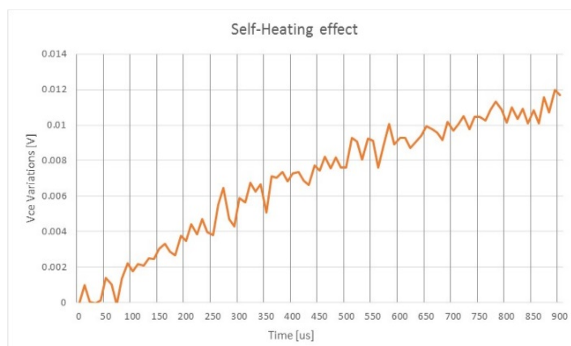

Fig. 3. V_{ce_sat} variation versus time during the static test.

The pulse width has been extended up to 900 μs, even if in some industrial test this kind of test is based on the use of multimeters and it may requires more time (up to some milliseconds). Anyway, it is clear from Fig.3 that, also with the adopted measurement time, there is a self-heating effect and the voltage drop of the junction increases over time. For a pulse of 900 μs, the variation is about 12 mV, which is about 1% of the typical value of the V_{ce_sat}. Usually, this value is negligible considering the possible dispersion of the parameter V_{ce_sat} that characterizes the usual industrial production of IGBT. Therefore, we can conclude that the self-heating effect can be neglected, if the pulse duration of the measurement parameters is below 1ms.

Another aspect that plays a more important role in the V_{ce_sat} measurements is the method used to pick up the voltage signals at the level of device pins. Very often, in the automatic procedures of test, a socket is employed to insert the IGBT in the PCB jig in order to save time when testing a large number of devices.

The socket must withstand the rated current values of the IGBT under test for the time required by the measurement process assuring a high reliability even at the higher temperature and most importantly, their contact resistances should not introduce a significant error in the V_{ce_sat} measurement. Therefore, in the market some specific sockets are available for transistors testing specially designed with a double contact and terminal to support any type of IGBT pin. Practically, the IGBT pin is inserted between two separated spring contacts that work on the top and the bottom surface of the pin. This type of contact is also called as "kelvin" contact, because it should work following the principle of the separation between the electrodes carrying the current from those of sensing the voltage. Unfortunately, it is not completely achieved in the case of the V_{ce_sat} measurement. Typical structure of this type of sockets is shown in Fig. 4 and it is clear that the current injection is at the same position but on different surface of the point where the voltage is measured and is not at a proper distance as required for a correct kelvin insertion.

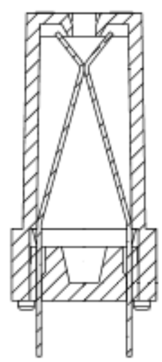

Fig. 4 Internal structure of a "kelvin contact" socket.

As a matter of fact, the effect of the contact resistance cannot be excluded as usually happens in an accurate kelvin insertion, especially when the current value is high, because the voltage drop due to the contact resistance is localized in the same position where the voltage signal is picked up. These effects can be evaluated directly by comparing results obtained by measuring the voltage drop at the terminals of the socket and that obtained placing the voltage probes directly on the IGBT pins (in the free part between the contact and its body), by means of two clips. Two different commercial sockets have been used, especially designed for the testing the in-line devices with three leads. Socket 1 has gold plated on nickel boron contacts, while the socket 2 presents gold plated on beryllium copper contacts. The continuous rated current of the first socket is three times that of the second one (3 A).

The measurement results are reported in Table 1. As expected, the first socket presents better performance, but even in this case the voltage drop is relevant even at the lower current values. At the rated current value of the IGBT under test (20A), the socket may be responsible for a very large error in the V_{ce_sat} measurement. It is clear that despite these kind of sockets are defined as having "kelvin contacts" by the manufactures their use has to be limited only for testing activities involving current with much reduced amplitudes.

Table 1. Effect of socket in Vce_sat measurement.

Current [A]	Socket 1 Voltage drop [V]	Socket 2 Voltage drop [V]
5	0.13	0.234
10	0.27	0.42
15	0.41	0.66
20	0.55	0.89

V. SWITCHING TEST: EFFECT OF STRAY INDUCTANCE

Switching tests requires the DUT to close and open in the circuit at its rated current and voltage. For most of the interesting families of IGBT, the value of current is in the order of some tenth of amps, and the voltage supply is in the order of some hundreds of volts. The simplified circuit shown in Fig. 5 is usually employed for this test.

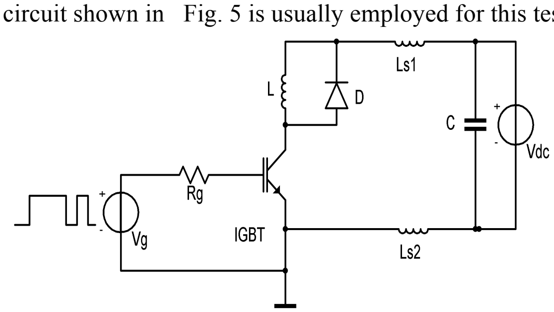

Fig. 5 Simplified circuit for switching test of the IGBT

The DUT is driven with a double pulse, where the first pulse has a longer time duration that permits to charge the inductor linearly with time to the rated current value. When the current value is equal to the target value, the DUT turns off and the current continues to flow in the mesh represented by the inductor and the freewheeling diode. The voltage between collector and emitter goes back to the level imposed by the DC voltage supply (V_{dc}). When the second pulse triggers the gate of the IGBT successively, the device turns on and the current again flows through the IGBT. In the ideal model, the amplitude of the current becomes instantaneously equal to that flowing before in the diode and inductor mesh. The time duration of the second pulse has to be shorter enough in order to avoid an excess of energy storage in the IGBT that can damage it.

The most critical evaluation in the switching test is that referred to the E_{on} energy. In particular, this value can be influenced heavily by the presence of stray inductances in the mesh including the device, the inductor and the power supply. These inductances are due to wires, PCB tracks and socket leads that are necessary to connect different devices. However, they are responsible for a voltage drop during the turn-on phase. The current increases with an almost constant slope that depends on the specific DUT. Hence considering a single equivalent stray inductance L_s, the voltage drop is:

$$V_s = L_s \frac{di(t)}{dt} = kL_s \qquad (5)$$

This voltage drop reduces the voltage across the DUT, so that E_{on} is evaluated at $(V_{cc} - V_s)$ value instead of V_{cc}, thus producing an underestimation of the energy required by the device for its commutation. A higher V_{dc} increases the error in E_{on} measurement. Unfortunately, in the setup used by the manufacturers for their device testing, very often the stray inductances have no negligible values, because of the requirements to have flexible and universal test bed. In the datasheets of the manufacturer, typical values of this parasitic element may range from 30 nH to 200 nH. Since derivative of the current may assume values of about 1×10^3 A/µs, the voltage drop can result more than one hundred volts and hence heavily affects the E_{on} measurement. Unfortunately not always this effect is properly considered even if it can be recognized easily in some waveforms that are reported in commercial datasheets [8] as depicted in Fig. 6. The equivalent stray inductances on the two cases are about 94 nH and 200 nH respectively

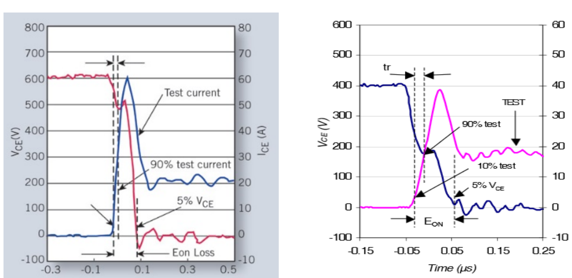

Fig 6. Turn-on Loss Waveform for two different commercial IGBT.

On the contrary, with a careful design, in our setup the stray inductances are limited and well controlled. This has been obtained using a reservoir capacitor closed to the socket of the IGBT and carefully designing the PCB. Practically, the capacitor provides all the energy required by the test and its capacitance is selected in order to store an energy that is at least one thousand times the energy loss during the turn-on phase. In this way, the voltage variation at its terminals is negligible also during the overall t_{on} phase and then the test is performed at a constant voltage.

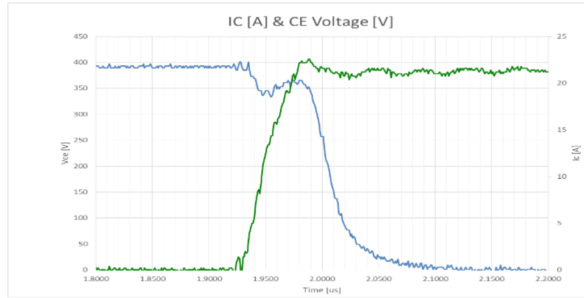

Fig. 7. Turn on waveforms collected with the developed measurement setup

Fig.7 represents the turn-on waveforms collected with our measurement systems for the same device whose waveform is shown in Fig 6. The voltage drop due to the stray inductances is about 35V in 17ns, which correspond a current slope of 0.73 A/ns. The resulting value of the equivalent stray inductance is about 42 nH.

VI. CONCLUSION

The low switching losses make IGBTs the preferred technology for high voltage applications in the electrical systems. Manufacturers continuously present new technologies and designs, able to extend and increase the performance of IGBTs, in terms of static and dynamic losses. This growing availability not always becomes an immediate simplification of the work for the designers and users. In fact, different approaches in the definitions and measurements of the main energetic parameters of the IGBT followed by the manufacturers do not permit a real and easy comparison between different devices, having similar rated characteristics. In a practical point of view, this problem can be easily overcome by means of simple and direct comparative tests that do not require complex instrumentation.

However, this apparent simplicity of the measurement process can hide some very critical measurement aspects. In this paper, three of these sources on measurement uncertainties are highlighted and analyzed. The first one is represented by the effect of the self-heating process that affects the device in the static test and then the error introduced by the socket that is more critical in the measurements of the junction voltage drop in the static test. Since the use of a socket cannot be avoided for practical reasons, it has been pointed out that their effects in terms of increment on voltage drop have to be carefully considered and compensated. Finally, the problem related to the stray inductance has been investigated, pointing out that in some commercial reports, it is clear that the measurements have been performed in presence of a large stray inductance and hence the declared values of energy losses can be affected by a relevant underestimation.

VII. REFERENCES

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