PV INVERTER PERFORMANCE AND RELIABILITY: WHAT IS THE ROLE OF THE IGBT?

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ABSTRACT

The inverter is still considered the weakest link in modern photovoltaic systems. Inverter failure can be classified into three major categories: manufacturing and quality control problems, inadequate design, and electrical component failure. It is often difficult to deconvolve the latter two of these, as electrical components can fail due to inadequate design or as a result of intrinsic defects. The aim of the current work is to utilize the extensive background in both inverter performance testing and component reliability found at Sandia National Laboratories to assess the role of component failures in PV performance and reliability. Although there is no consensus on the least reliable component in a modern inverter system, the IGBT is often blamed for failures and hence this was the first component we studied. A commercially available 600V, 60A, silicon IGBT found in common residential inverters was evaluated under normal and extreme operating conditions with DC and pulsed biasing schemes. Although most of the sample devices were robust even under extreme conditions, a few of the samples failed during operation well within the manufacturer-specified limits. Additionally, we have begun *in situ* monitoring of IGBTs as well as other components within an operating 700 W, single-phase inverter. The *in situ* testing will guide future device-level work since it allows us to understand the conditions that are experienced by inverter components in a realistic operating environment.

INTRODUCTION

Photovoltaic inverters continue to enjoy a skyrocketing market growth and it is predicted that the yearly market will reach $8.5 billion by 2014 [1]. However, the inverter is still considered the weakest link in photovoltaic systems, and is believed to be the leading cause of lost energy and power outages [2].

The Sandia National Laboratories Distributed Energy Technology Laboratory (DETL) has an inverter performance evaluation setup that has been used to demonstrate and extensively model inverter performance degradation [3]-[5]. Thus far, this effort has focused on the evaluation of inverter performance and reliability at the system level, without detailed examination of the components. A logical extension of this work is to examine the reliability and performance of components which make up the inverter system.

Inverter failures can generally be traced to three categories of defects: manufacturing quality, inadequate design, and defective electronic components. Problems with manufacturing include defects such as loose terminals and screws, broken wires, and loose connectors. Very simple components (such as cooling fans) can also be considered a manufacturing quality problem, since these are a very common, mature technology. These problems must be addressed by manufacturing or supply chain quality control and are not addressed in the present research. Examples of design problems include insufficient wire gauges, inadequate cooling, or incorrect capacitor sizes. However, failures caused by inadequate design and component failure are often difficult to deconvolve. For example, IGBTs are often blamed for the failure of inverters, whereas it is later found that the IGBT was operating in extreme conditions, such as high voltage, current, or temperature, which exceed the normal operating conditions specified by the manufacturer [6]-[7]. However, there are also situations where the failure is caused by the IGBT itself. It is a major goal of this research project to evaluate these electronic components and to determine the underlying causes of inverter failures.

The typical PV inverter contains several major electronic components: the IGBTs or intelligent power module (IPM), bus-link capacitors, transformer, control circuit board(s), and electrical contactor relays. There does not appear to be sufficient data to say which electrical component is the most common cause of failure. The most common component failure also may be a function of the size of the inverter, since utility-scale inverters may use different classes of components than residential scale inverters (i.e. film vs. electrolytic capacitors). However, since anecdotal [6]-[7] and some preliminary statistical [8] evidence points to the IGBT as a common cause of inverter failure, this was the first electronic component we chose to study. As this research progresses the intent is to assess the reliability of all problematic inverter components.

EXPERIMENTAL DETAILS

The Sandia Microsystems and Engineering Sciences Applications (MESA) center has a long history of semiconductor reliability evaluation. To make measurements on power IGBTs, a test setup was established for high voltage, high current, and high temperature measurements. A Keithley 2410 was used to characterize standard current-voltage (I-V) curves and to provide emitter-collector stress voltages (V_{CE}) up to 1100 V. The Agilent N8731A was used to provide high-current stress and is able to supply currents up to 400 A. Device heat sinks were affixed to a custom test fixture which allows temperature control from 25 to 150°C. A single common silicon IGBT model was chosen for this initial research. It is found in common residential inverters, and is rated for 600 V and 60 A at 25°C and 30 A at 90°C.

IGBT DC RELIABILITY EVAULATION

To begin, several IGBTs were stressed at approximately the maximum rated current ($I_C \approx 61$ A) for 45 minutes at 25°C. A majority of the devices showed no signs of degradation under room temperature stress at high voltages, and they showed excellent immunity to high thermal stress conditions. Fig. 1 shows a typical collector current (I_C) versus collector-emitter voltage (V_{CE}) curve with the full 15 V gate drive (V_G = 15 V) before and after this stress. The change in on-current for these typical devices is negligible.

However, the more significant aspect of the thermal stability of the devices was a large immunity to over-current operation at high temperatures. In order to investigate device behavior when stressed beyond their rated limits at high temperature (30 A at 90°C), the IGBTs were subjected to a sequence of 45 min. stress periods at $I_C \approx 61$ A at 70°C and 100°C, respectively, along with an initial control test at 25°C. Fig. 2 gives the I_C-V_{CE} curves resulting from each of these measurements for a typical device. There is almost no perceptible change in output characteristics.

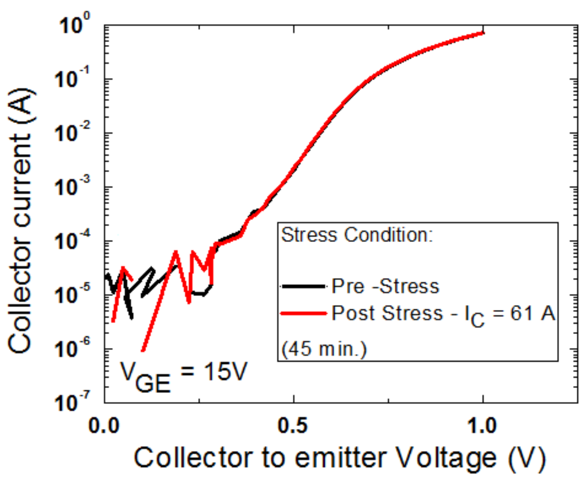

Figure 1. Pre and post-stress I_C-V_{CE} curves for typical IGBTs, after 45 min stress at $I_C \approx 61$ A.

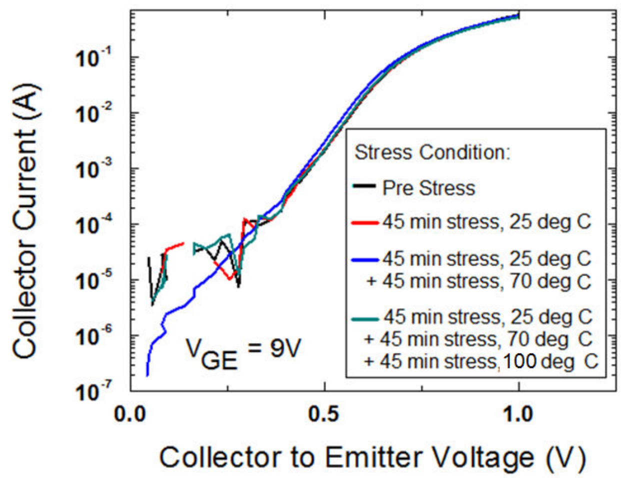

Figure 2. Pre- and post-stress I_C-V_{CE} curves for a typical IGBT with stress temperatures of 25, 70 and 100°C for 45 min. each.

Although the majority of these IGBTs showed negligible degradation even when operated outside of their rated limits, a few devices significantly degraded even when used well within their specified operating conditions. For example, an IGBT was found that when stressed at V_{GE} = 20 V, V_{CE} = 2 V, giving IC ≈ 36 – 39 A at 25°C (significantly less than the rated 60 A) for 60 s, the output characteristics were significantly altered. To further study this behavior, I_C-V_{GE} measurements were made at several time intervals as recorded in Fig. 3. Between the first (t = 0) and second (t = 60 s) measurements, there is a significant increase in the leakage current. Subsequent measurements show a marked increase in leakage current without any significant effect on the threshold voltage. This IGBT degradation would most likely not cause the failure of an inverter, but could degrade performance. Furthermore, it is highly questionable if a device exhibiting significant instability would operate for the expected lifetime of an inverter (i.e. 5 to 20 years).

An example of a different failure mechanism was observed in a fresh device stressed under the same bias conditions at 100°C. In this case, the gate oxide leakage current increased as a result of the electric field across the gate, as plotted in Fig. 4. After 1740 s under stress, the gate current is already several mA at V_G = 5 V, indicating a serious oxide defect. In this case, the gate no longer controls the device current and a PV inverter would not be capable of operating correctly with this device.

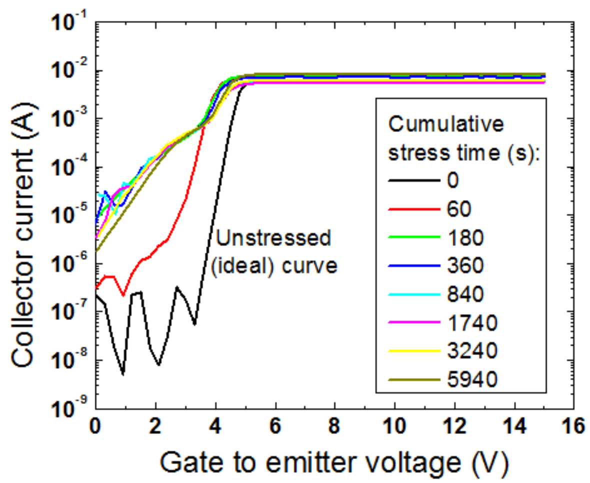

Figure 3. I_C-V_{CE} curves resulting from stressing an IGBT at V_{GE} = 20V, V_{CE} = 2 V ($I_C \approx$ 38 A), corresponding to a condition of high electric field in the gate oxide and moderate thermal stress.

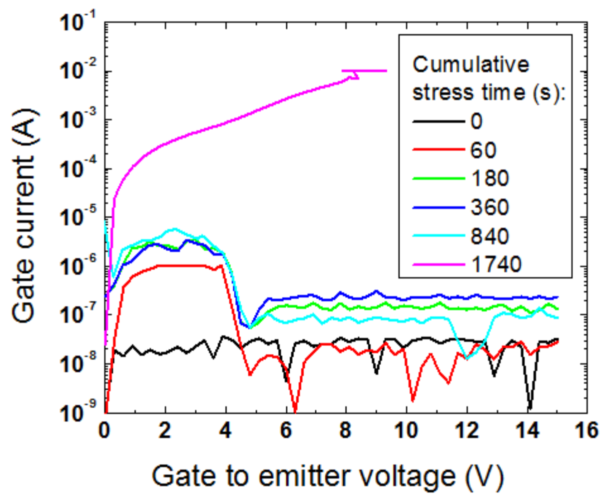

Figure 4. I_G-V_{CE} curves resulting from stressing an IGBT at V_{GE} = 20 V, V_{CE} = 2 V ($I_C \approx$ 38 A), corresponding to a condition of high electric field in the gate oxide and moderate thermal stress.

IGBT PULSED RELIABILITY EVAULATION

During operation inside a PV inverter, IGBTs are subject to AC stress conditions as opposed to DC stress conditions. This typically consists of a 60 Hz on-off cycle, with a Pulse-Width-Modulated (PWM) signal on the order of 10 – 15 kHz superimposed on the lower-frequency cycle. The result is that the IGBT, which is typically part of an H-bridge circuit, is alternately subjected to a low-voltage, high-current on-state, followed by a high-voltage-low-current off-state.

An initial attempt was made to ascertain the impact on the IGBT of pulse stress conditions using the same laboratory test setup as was used for the DC stress experiments. For these tests, the high-current power supply was connected across the collector and emitter terminals of the IGBT, and a function generator was connected to the gate. The function generator available was only capable of providing pulses of 10 V amplitude maximum, so this pulse amplitude was used. The power supply was set to a constant voltage (5 – 10 V as would be typical for an IGBT in the on-state) and the pulse out of the function generator momentarily turned the gate on. Thus, the IGBT was not subjected to high voltage during the off-state, as would be the case in a realistic application; we are currently working to build an experimental switching set-up to mimic this more realistic condition. During our experiments, the voltage across the cable leading to the IGBT collector was measured using an oscilloscope. Since the resistance of the cable between the voltage measurement points is known (approximately 2.2 mΩ), the measured voltage transient could be converted to the collector current. An example of the results of such an experiment for V_{CE} = 7 V are shown in Fig. 5. In this case, a square wave of 1 ms period and a 24% duty cycle was used as the gate control.

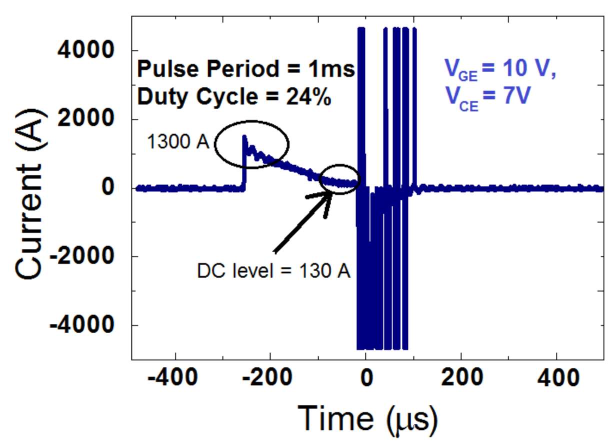

Figure 5. IGBT collector current resulting from pulsed gate input. Measurement is made at room temperature.

It is very interesting to note that the initial level of the collector current (approximately 1300 A) immediately following the application of the gate pulse is much larger than the DC value (approximately 130 A). Clearly, the IGBT is subjected to a current level far in excess of its rated value, albeit for a very short period of time. However, damage resulting from this over-current condition could potentially be cumulative, as the device is subjected to numerous on-off cycles. Note also the extremely large oscillations following the termination of the gate voltage pulse; while we believe that large turn-off oscillations represent a real effect, the very large magnitude present in Fig. 5 may be an artifact of our experimental set-up, which is not optimized in terms of impedance-matching.

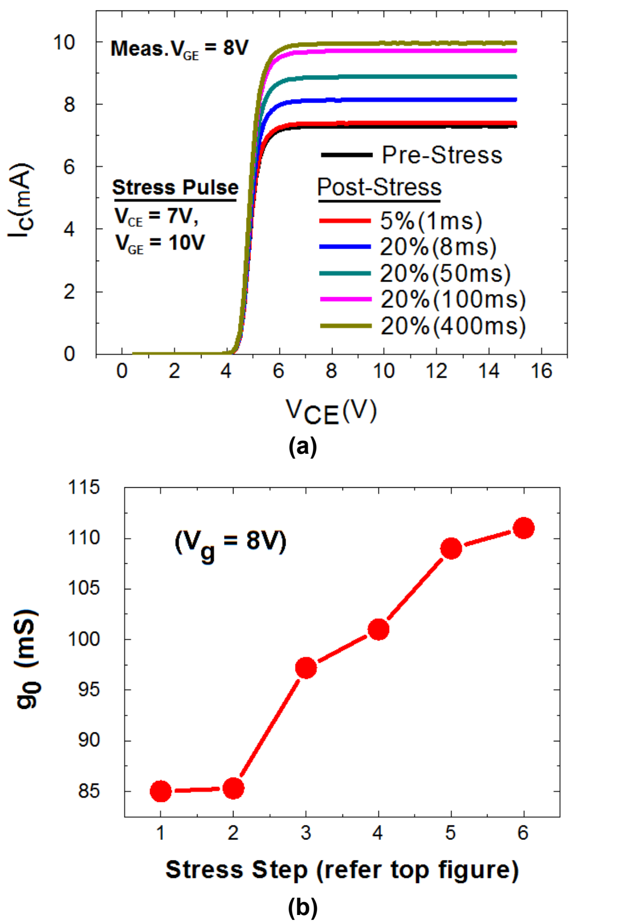

Figure 6. (a) DC I_C-V_{CE} curves for an IGBT subjected to increasing increments of AC stress. (b) The output conductance (g_0) measured at the end-point of each of the curves in the top portion of the figure (V_{GE} = 8 V, V_{CE} = 15 V) for each of the steps in the sequence.

An additional set of experiments was performed in which the DC characteristics of the IGBT were evaluated following AC stress. An example of the results of such an experiment are shown in Fig. 6. In this experiment, the IGBT was set up as described above, and was subjected to a sequence of gate pulses (V_{GE} = 10 V, V_{CE} = 7 V) of increasing duration (from a 1ms pulse with 5% duty cycle to a 400 ms pulse with 20% duty cycle – each pulse being repeated for 150 cycles), as indicated in the top part of Fig. 6. The I_C-V_{CE} curve was measured following each step of the gate pulse sequence and, as is evident in the top part of Fig. 6, the pulse stress causes a monotonic increase in saturated collector current for the IGBT. While such a shift will not result in inverter failure, it will cause a change in the operating characteristics (i.e. efficiency) of the inverter, similar to the situation that was discussed regarding the DC degradation observed in Fig. 3. The bottom portion of Fig. 6 shows the output conductance (g_0) at the fixed bias point V_{GE} = 8 V, V_{CE} = 5 V (where the output characteristics show good linearity) to illustrate more clearly the progressively increasing collector current. Note that unlike the situation for the DC stress shown in Fig. 3, the present increase in collector current occurs in the saturated portion of the curve as well, not just the sub-threshold region.

IN SITU IGBT RELIABILITY EVAULATION

In order to better ascertain the true operating conditions of IGBTs and other devices inside a working inverter, and to correlate the characteristics of the inverter as a whole with the device characteristics, a commercially available, 700 W, single-phase inverter was obtained and was set up at DETL [3]. Thus, inverter characteristics such as input power, output power, power factor, and voltage and current waveforms on both the DC and AC sides of the inverter have been monitored. Four temperature probes were set up to record the following temperatures: (1) Ambient, (2) IGBT case, (3) Bus capacitor, and (4) Heat sink. Additionally, wires were soldered to the leads of one of the IGBTs, which were connected to high-impedance, high-voltage, high-speed probes (voltage attenuation factors of 50:1 and 500:1 are available). Thus, we were able to record the gate-emitter and collector-emitter voltages on an oscilloscope.

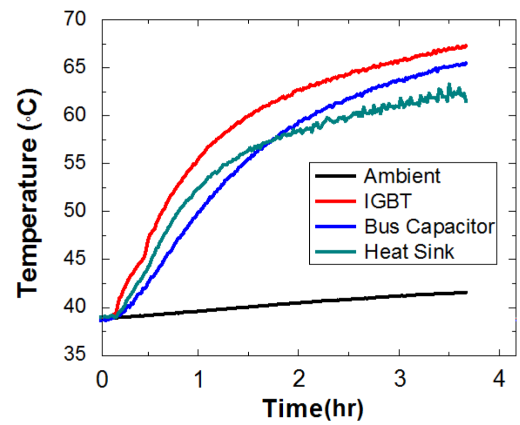

Figure 7. Temperature traces for (1) Ambient, (2) IGBT, (3) Bus capacitor, and (4) Heat sink for an operating, 700 W, single-phase inverter.

Fig. 7 plots the recorded temperatures mentioned above vs. time, following the turn-on of the inverter at t = 0. Notably, the IGBT is the hottest component, reaching a temperature in excess of 65°C, and still increasing at the end of the period over which data were recorded. The heat sink is the next hottest component at early times, but is surpassed by the bus capacitor (which is an electrolytic capacitor) after roughly two hours of operation. Note that the greatest temperature fluctuations are apparent in the trace of heat sink temperature. Each of the internal component temperatures measured are considerably higher than the ambient temperature, by 20 to 25°C. Future work will correlate the recorded temperatures of the internal components with their electrical performance, as well as the performance of the entire inverter.

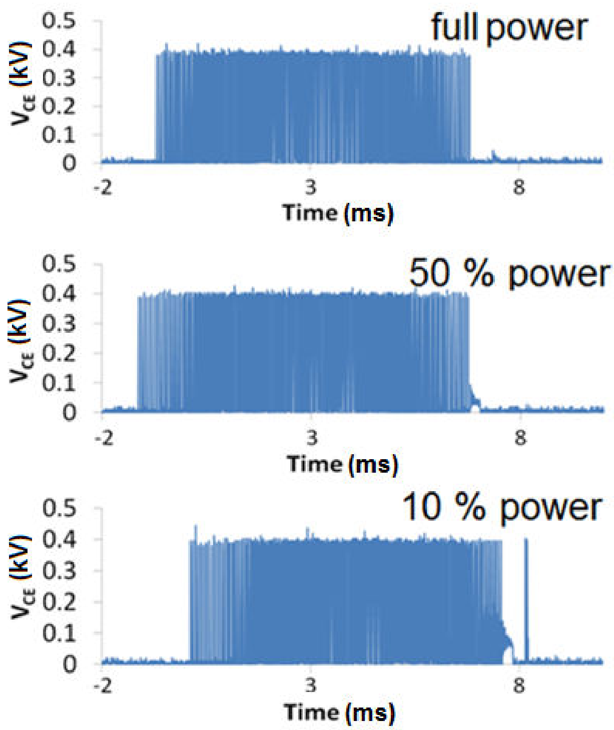

Figure 8. Collector-emitter waveforms for an IGBT monitored *in situ* for an inverter operating at (1) 100% of rated power, (2) 50% of rated power, and (3) 10% of rated power.

Fig. 8 shows the collector-emitter waveforms for the measured IGBT for various inverter output levels: (1) 100% of rated power (700 W), (2) 50% of rated power (350 W), and (3) 10% of rated power (70 W). The time scale shows roughly half of one 60 Hz cycle; the oscillations observed are the PWM (note how the duty cycle is higher near the center of the waveform). When the collector-emitter voltage is high, the IGBT is in the blocking state, and the other IGBT in the leg of the H-bridge is passing the current to the load. Observations of the inverter output waveforms showed a clear degradation as the inverter power was reduced, especially in the current waveform, resulting in a significant degradation of the power factor and an increase in the total harmonic distortion. This degradation is mirrored in the IGBT waveforms of Fig. 8, which clearly show degradation due to the introduction of spurious signals as the output power is reduced. At 50% power, a small "hump" becomes apparent at the end of the pulse train. At 10% power, the hump is still present, and additionally, spurious pulses are now observed well after the termination of the main PWM signal. Note also that the overall timing of the signals changes significantly relative to the IGBT gate signal (the oscilloscope was triggered off of the latter) as the inverter power is reduced.

Future experiments will involve the measurement of the other IGBTs in the H-bridge circuit, and will attempt to stress the inverter though high-temperature operation (the inverter is set up inside an environmental chamber) and other stressful environments such as high humidity. Additionally, at DETL it is possible to simulate grid events such as voltage transients, and we will examine the effects of such stresses on the operation of the IGBTs. This *in situ* monitoring will give us a good idea of what types of stresses we need to study in order to create accelerated reliability models of inverter components.

CONCLUSIONS AND FUTURE WORK

The majority of the IGBTs tested showed the device to be highly reliable under both normal and extreme operating conditions. This was true for both high temperatures and excessive currents. However, in a few cases there was significant degradation even under normal operating conditions – one of these cases was severe enough that inverter operation would be terminated. This suggests that there may be some cases where the IGBT is the root cause of the inverter failure, even when the inverter design does not subject the IGBT to conditions outside of those specified by the IGBT manufacturer. AC stress (gate pulse with constant collector-emitter voltage) on IGBTs showed transient collector currents many times in excess of rated DC values, although for a short period of time only. Nevertheless, the effects of damage due to such stress may be cumulative. The DC characteristics of IGBTs were shown to change following AC stress. *In situ* monitoring of IGBTs demonstrate that the IGBT is the hottest component inside the inverter, although all monitored components were significantly hotter than ambient. Spurious signals in the IGBT collector-emitter voltage correlated to degraded inverter output waveforms as power was reduced. *In situ* monitoring will help us understand the realistic operating environment of IGBTs and other inverter components, and will guide future device-level accelerated testing to create inverter reliability models.

ACKNOWLEDGEMENTS

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