IGBT and Diode Loss Measurements in Pulsed Power Operating Conditions

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Abstract

High voltage IGBTs and Series Diodes are used in Cymer's solid-state pulsed power commutator module. The IGBTs and Series Diode losses in the module affect the cooling system design and the energy transfer efficiency. It is difficult to estimate the IGBT and Diode losses in the pulsed power operating condition. We have previously tried to measure the IGBT losses by measuring the voltage across the IGBT (using a high voltage differential probe) and the current through the IGBT. Since the voltage across the IGBT changes from the kilo-volt level to several volts, it is very difficult to measure the small on-state voltage accurately. Also very small internal package inductance can obscure the voltage measurement due to the high dI/dt level in the circuit.

In this work, the IGBT and Series Diode losses were measured with a commutator module directly by measuring the water flow rate going through a cold-plate attached to the IGBT or Diode and the temperature difference of the inlet and outlet water. Heat transfer through other means, such as free convection, was minimized by sealing the IGBT/Diode inside a thermal isolation blanket and polyurethane foam. The loss measurement results on the dual package IGBT and dual package Diode are presented in the paper.

I. INTRODUCTION

In the pulsed power modules of Cymer's laser system [1], high voltage IGBTs and Diodes are used. The simplified Commutator schematic diagram is shown in Figure 1. Only one IGBT Gate Driver was used to drive the dual package IGBTs in parallel. C0 is negatively charged by a resonant charger, and discharged to C1 by closing the IGBT switch. Then C1 discharges through a magnetic switch LS and a high voltage pulse transformer to the compression head and the laser chamber.

The losses of IGBTs and Series Diodes in the commutator module affect the cooling system design and the energy transfer efficiency from C0 to C1. We have tried to measure the IGBT and Diode losses by measuring the voltage across the IGBT or Diode, and the current through the devices. The typical waveforms are shown in Figure 2.

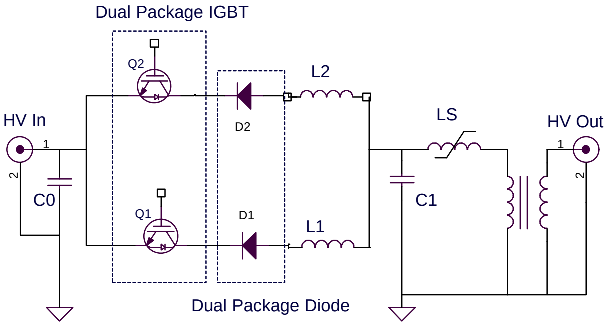

Figure 1. Simplified schematic diagram of Commutator.

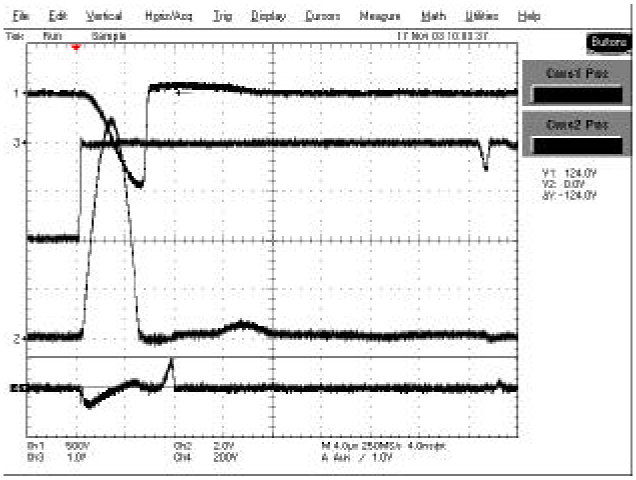

Figure 2. Typical waveforms.
{Ch1—V_{C1} signal (500V/Div)
Ch2—current signal through IGBT Q1 and Diode D1, by Pearson current monitor (200A/Div)
Ch3—V_{EG} signal across Q1, by Tek P5200 high voltage differential probe (500V/Div)
Ch4—V_{D1} signal across D1, by Tek P5210 high voltage differential probe (200V/Div) }

One can see from Figure 2 that the voltage across the IGBT changes from the kilo-volt level to several volts. It is very difficult to measure the small on-state voltage accurately together with the kilo-volt voltage level. Also the voltage signal across the IGBT or Diode is affected by the small internal package inductance and the voltage probe inductance due to the high dI/dt level in the circuit.

The IGBT losses are usually broken up into several time segments such as turn-on loss, conducting loss, and turn-off loss. The turn-off loss can be ignored here since the IGBT is turned off with almost no current about 35µs after it is turned on.

Here the dual package IGBT and dual package Diode losses were measured directly by measuring the water flow rate going through a cold-plate attached to the IGBT or Diode and the temperature difference of the inlet and outlet water. The test results are presented below. The accuracy of the measurement is also analyzed.

II. TEST SETUP

Figure 3 is an illustration of loss measurement test setup, including water flow meter, flow control valve, thermistor probes, IGBT or Diode, cold plate and thermal insulation.

Flow meter: high accuracy rotameter with the accuracy of ±2% of reading.

Thermometer: thermistor thermometer with accuracy of ±0.05% of reading.

Thermistor probes: with accuracy of ±0.1°C from 0 to 70°C.

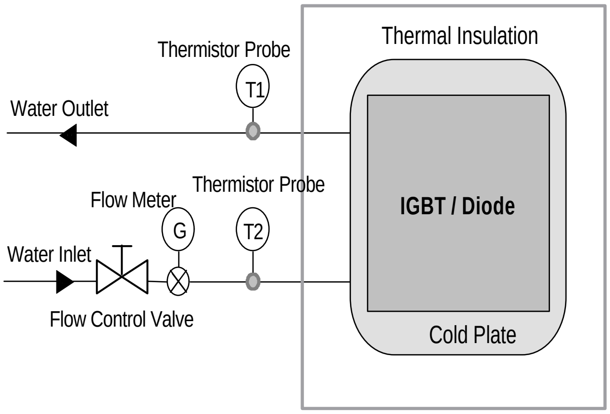

Figure 3. Illustration of IGBT or Diode loss measurement test setup

Figure 4 is a photo of the IGBT under test with thermal insulation in the Commutator module of the pulsed power system. The IGBT is fixed on an aluminum cold plate with water inlet and outlet. Two thermistor probes measured the water inlet and outlet temperatures respectively. There were two layers of thermal insulation blanket between the cold plate and the outside plastic box. The thermal blanket is 1/4 inch thick with thermal conductivity of 0.0519W/m-K. The polyurethane foam was used to cover the IGBT as thermal insulation material. It is also electric insulation foam. We applied the foam about 2 inches thick. It expanded to form a skin that contains closed air cells, which provided an effective thermal barrier against thermal energy loss to the outside environment.

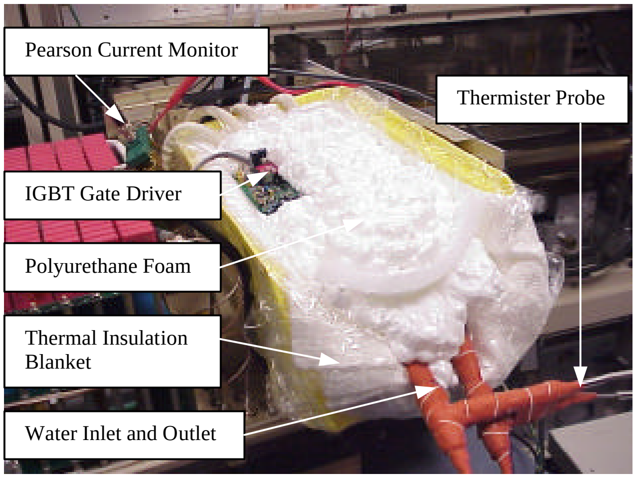

Figure 4. Photo of IGBT under test with thermal insulation in Commutator module.

The same thermal insulation fixture was used for Series Diode loss measurements.

III. TEST RESULTS

Tests have been done at different voltages on V_{C0} from 800 V to 1400V at certain pulse repetition rates. A Tektronix TDS7104 Oscilloscope was used to monitor the waveforms and collect the current data as shown in Figure 2. It usually took about one hour or so for the water outlet and inlet temperature difference to reach the steady-state level (thermal equilibrium condition) at each voltage. The following formula was used to calculate the energy loss (Joule) per pulse on the IGBT or Diode.

$$\begin{aligned}\text{Loss/Pulse} &= (\text{Flow}-\text{rate})(\text{ml}/\text{min.})\times 4.187(\text{J}/\text{g}\cdot\text{K}) \\ &\quad \times 1.0(\text{g}/\text{ml})\times \Delta T({}^\circ\text{F})\times 5/9({}^\circ\text{C}/{}^\circ\text{F})/[60(\text{s}/\text{min.})\times(\text{Rep}-\text{rate})(1/\text{s})] \\ &= 3.87685\times 10^{-2}\times(\text{Flow}-\text{rate})(\text{ml}/\text{min.})\times\Delta T({}^\circ\text{F})/(\text{Rep}-\text{rate})(\text{Hz})\end{aligned} \quad \text{------(1)}$$

Where 4.187(J/g•K) is the Specific Heat Capacity of water. ΔT is the temperature difference of the water outlet and inlet.

A. IGBT Loss Measurement

Table 1 summarizes the IGBT loss measurement results at equilibrium conditions with different voltages.

The relationship between peak current (I_{peak}) and V_{C0} is shown in Figure 5 and formula (2). It is a linear line through origin (0,0). The correlation coefficient R is 0.99995.

$$\mathrm{Ipeak} = 1.71158 \times \mathrm{VC0} \qquad \text{------(2)}$$

Table 1. IGBT loss measurement results
(At Ambient temperature of 71°F)

VC0 (V)	800	900	1000	1100
Ipeak (A)	1370	1542	1717	1886
Rep-rate (Hz)	1000	1000	1000	1000
Flow-rate (ml/min.)	134.3	134.3	134.3	134.3
Water-inlet (°F)	68.4	68.4	68.5	68.5
Water-outlet (°F)	73.5	74.3	75.5	77.1
ΔT (°F)	5.1	5.9	7.0	8.6
Loss/Pulse (mJ)	26.55	30.72	36.45	44.78

VC0 (V)	1150	1200	1300	1400
Ipeak (A)	1971	2056	2220	2389
Rep-rate (Hz)	1000	1000	1000	1000
Flow-rate (ml/min.)	134.3	134.3	134.3	134.3
Water-inlet (°F)	68.5	68.6	68.6	68.6
Water-outlet (°F)	77.7	78.5	79.3	80.7
ΔT (°F)	9.2	9.9	10.7	12.1
Loss/Pulse (mJ)	47.90	51.55	55.71	63.00

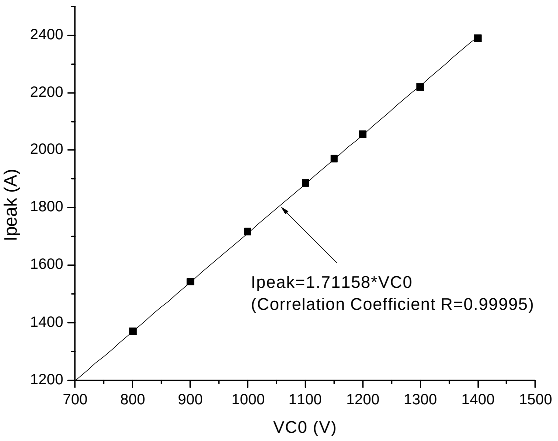

Figure 5. Relationship between (I_{peak}) and V_{C0} .

The relationship between IGBT Loss/Pulse and I_{peak} is shown in Figure 6. The relationship can be expressed with a linear line and formula (3). The correlation coefficient R is 0.9967.

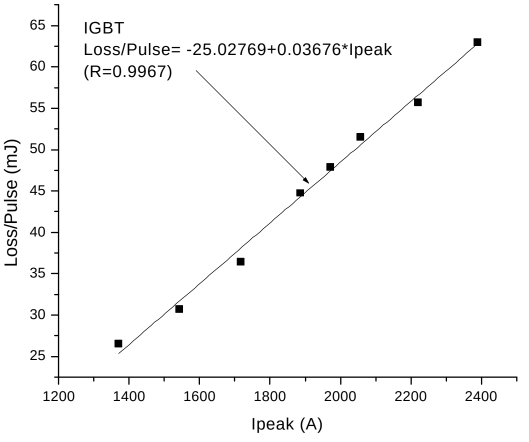

Figure 6. Relationship between IGBT Loss/Pulse and peak current (I_{peak}).

$$\mathrm{Loss/Pulse} = -25.02769 + 0.03676 \times \mathrm{Ipeak} \qquad \text{------(3)}$$

B. Diode Loss Measurement

Table 2 summarized the Diode loss measurement results at equilibrium conditions with different voltages. One may notice the current difference in Table 1 and Table 2 at same VC0 voltage. It was due to the small difference of circuit inductance of the two loss measurement setups.

Table 2. Diode loss measurement results
(At Ambient temperature of 71°F)

VC0 (V)	800	900	1000	1100
Ipeak (A)	1329	1497	1662	1825
Rep-rate (Hz)	500	500	500	500
Flow-rate (ml/min.)	134.3	134.3	134.3	134.3
Water-inlet (°F)	68.5	68.7	68.7	68.7
Water-outlet (°F)	73.0	73.8	74.6	75.6
ΔT (°F)	4.5	5.1	5.9	6.9
Loss/Pulse (mJ)	46.86	53.11	61.44	71.85

VC0 (V)	1150	1200	1300	1400
Ipeak (A)	1908	1992	2154	2312
Rep-rate (Hz)	500	500	500	500
Flow-rate (ml/min.)	134.3	134.3	134.3	134.3
Water-inlet (°F)	68.8	68.9	68.9	69.2
Water-outlet (°F)	76.3	77.0	79.0	81.9
ΔT (°F)	7.5	8.1	10.1	12.7
Loss/Pulse (mJ)	78.10	84.35	105.17	132.25

The relationship between Diode Loss/Pulse and I_{peak} is shown in Figure 7. The relationship can be expressed with formula (4). The correlation coefficient R is 0.9993.

$$\mathrm{Loss/Pulse} = 33.38892 + 1.02301 \times \mathrm{EXP}(\mathrm{Ipeak}/506.20348) \qquad \text{------(4)}$$

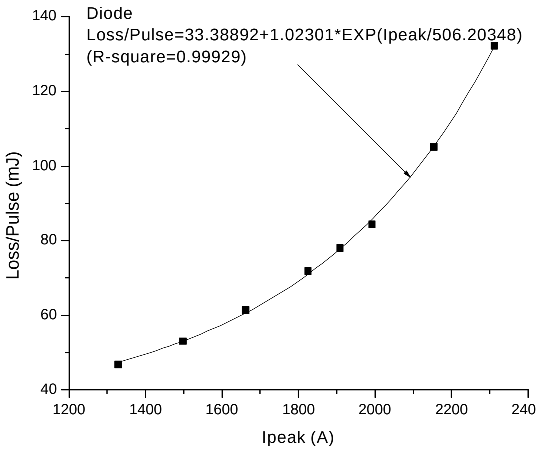

Figure 7. Relationship between Diode Loss/Pulse and peak current (I_{peak}).

IV. TEST ANALYSIS

A. Loss Measurement Results

From the tests results, one can see that the relationship between circuit peak current and V_{C0} is linear through the origin point, which corresponds with the following theoretical formula (5).

$$\mathrm{Ipeak} = \mathrm{VC0} \times \sqrt{\mathrm{C/L}} \qquad \text{------(5)}$$

The IGBT Loss/Pulse and I_{peak} relationship can be expressed by formula (3). The IGBT Loss/Pulse growths linearly with I_{peak}.

The Series Diode Loss/Pulse and I_{peak} relationship can be expressed by formula (4). The Diode Loss/Pulse growths exponentially with I_{peak}.

We may put them together to compare their losses, shown in Figure 8. One can see that the Diode loss is much larger than IGBT loss with the same peak current. Their loss difference is larger with increasing I_{peak}.

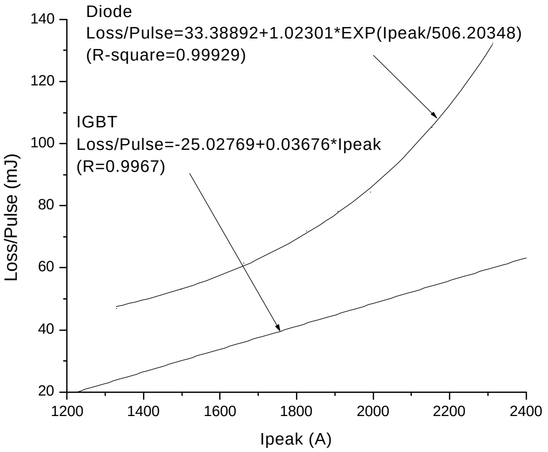

Figure 8. IGBT and Diode losses vs. peak current (I_{peak}).

B. Loss Measurement Accuracy

The loss measurement accuracy could be estimated in formula (6) based on formula (1). As it is not likely that the maximum uncertainty for each variable will co-exist for a given measurement, a reasonable level of uncertainty corresponds to the Pythagorean summation of the discrete uncertainties [2].

$$\begin{aligned}
&\frac{\Delta(\mathrm{Loss/Pulse})}{(\mathrm{Loss/Pulse})} \\
&= \sqrt{\left(\frac{\Delta(\mathrm{Flow-rate})}{(\mathrm{Flow-rate})}\right)^2 + \left(\frac{\Delta T_{outlet}}{T_{outlet} - T_{inlet}}\right)^2 + \left(\frac{\Delta T_{inlet}}{T_{outlet} - T_{inlet}}\right)^2} \\
&= \sqrt{(2\%)^2 + \left(\frac{0.2165}{4.5}\right)^2 + \left(\frac{0.21425}{4.5}\right)^2} \\
&= 7.06\%
\end{aligned}$$

------(6)

This is the worst-case at V_{C0}=800V of Diode loss measurement with (T_{outlet}-T_{inlet})=4.5°F shown in Table 2. The flow meter measurement accuracy is 2%.

Water inlet and outlet temperature measurement uncertainties are as follows.

$$\Delta T_{outlet} = 0.05\% \times 73.0°\mathrm{F} + 0.1 \times 9/5°\mathrm{F} = 0.2165°\mathrm{F}$$

$$\Delta T_{inlet} = 0.05\% \times 68.5°\mathrm{F} + 0.1 \times 9/5°\mathrm{F} = 0.21425°\mathrm{F}$$

Where 0.05% of reading is the thermometer accuracy, and 0.1°C is the thermistor probe accuracy.

So, the Loss/Pulse measurement accuracy at the worst case is ±7.1%. It is mainly determined by the thermistor probe accuracy and the flow meter accuracy.

C. Thermal Insulation Energy Leakage

We may also estimate the thermal energy leakage through the thermal insulation material.

$$(\mathrm{Thermal-leakage}) = \frac{0.0519 \times 0.06}{0.5 \times 25.4 \times 10^{-3}} \times (81.9 - 71) \times 5/9 = 1.485\ (\mathrm{W})$$

The total area covered by the insulation material (with IGBT or Diode) is estimated at about 0.06m^2. We use the insulation blanket parameter here with thermal conductivity of 0.0519 W/m-K, and insulation material thickness of 0.5 inch for thermal leakage calculation.

This is the worst-case estimation at VC0=1400V of Diode loss measurement with water outlet temperature of 81.9°F, and ambient temperature of 71°F.

The total measured loss in this case is about 66.125W.

$$\mathrm{Loss} = (\mathrm{Rep-rate}) \times (\mathrm{Loss/Pulse}) = 500 \times 132.25 \times 10^{-3} = 66.125\ (\mathrm{W})$$

So the thermal leakage is about 2.25% of total measured loss, without considering the thermal energy going into the system due to lower inlet water temperature than ambient temperature. The thermal energy leakage could therefore be neglected.

V. SUMMARY

We can draw the following conclusions through the IGBT and Diode loss measurement practice in the pulsed power operating conditions.

- The IGBT Loss/Pulse grows linearly with peak current (Ipeak). The relationship can be expressed by formula (3).
- The Series Diode Loss/Pulse grows exponentially with peak current (Ipeak). The relationship can be expressed by formula (4).
- The loss measurement accuracy is estimated at about ±7.1%
- The energy leakage through the thermal insulation materials could be neglected.

VI. REFERENCES

[1] R.M. Ness, P.C. Melcher, and R.B. Saethre, “Timing and Synchronization of Solid State Pulsed Power Modules (SSPPM) for Excimer Laser Applications”, presented at 2002 International Power Modulator Conference, June 30 to July 3, Hollywood, California.

[2] Thomas G. Beckwith, Roy D. Marangoni and John H. Lienhard V, “Mechanical Measurements”, 1995.