

SHORT CIRCUIT PROTECTION OF HIGH SPEED, HIGH POWER IGBT MODULES*

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Abstract

At SLAC, research and development for the Next Linear Collider (NLC) is progressing. The 8-Pack project is a test stand in which key NLC components will be developed. Presently the setup is such that an Induction Modulator [1] will generate 400kV, 1200A, and 1.6 μ s flattop pulse to drive four XL4 X-band klystrons. This requires the use of 76 high power IGBT modules operating in parallel at 3600A and up to 2200V each. IGBT switching speeds and short circuit protection from klystron arcs are major concerns. This paper describes a gate drive circuit with a new method to protect IGBT modules under short circuit conditions. Using a dI/dt control technique, the gate drive circuit enabled the Mitsubishi module CM600HB-90H to switch 4000A at speeds up to 10kA/ μ s in normal operation, while holding the short circuit peak-current to about 8000A. Results from the single IGBT test and the 8-Pack Modulator prototype will be presented.

I. INTRODUCTION

During the first phase of the NLC Induction Modulator project, an IGBT gate driver [2] was developed to drive the Eupec IGBT module FZ800R33, rated at 3.3kV and 800A. Each module was tested on the test bench for normal operation at 2000A, 3 μ s, and shorted circuit at 2200V. A total of 152 of these modules were installed on the modulator prototype, and ran first into a water load and later into two conventional SLAC 5045 klystrons. The modulator output fall-time was consistent with the design goal of 250ns for 500kV. However, over 25% of these IGBT modules had failed after one of the klystron arced at 420kV. This incident has led to further investigation and testing of various types of IGBT modules from different manufactures, in search of an ideal IGBT that will not only support high current for normal operation, but also self-limit it under different types of short circuit conditions.

New challenges have arisen as the NLC modulator program develops into the 8-Pack project. The large stray capacitance, due to the unique cathode terminations of the XL4 klystrons and the three-turn coaxial output of the modulator, has required each IGBT module to drive a much higher peak current than originally thought. While

the exact cause of Eupec module destruction has not been definitely determined, severe unsymmetrical layout in the internal bus structure eliminated its use for this modulator setup. The module can support neither the peak current at the required dI/dt nor the type of short circuit following a klystron arc. The Mitsubishi IGBT module CM600HB-90H, rated at 4.5kV and 600A, with its uniform current-distribution structures and large IGBT dies has been chosen instead for the 8-Pack modulator prototype. The manufacturer's test data has shown that its module can support 10kA at a turn-on dI/dt of 10kA/ μ s. Detailed analyses of a new type of IGBT module failures [3], and of these two types of IGBT geometries along with a SLAC proposed IGBT design [4] have been discussed. The following section describes the gate drive circuit, focusing on IGBT protection and the limiting of short circuit currents, for the Mitsubishi module.

II. GATE DRIVE CIRCUIT

Table 1 lists the switching component requirements of the 8-Pack modulator.

Table 1. 8-Pack Modulator switching requirements.

| Parameter | Value |
|---------------------------|-----------|
| Collector-Emitter Voltage | 2200V |
| Collector Current - Flat | 3600A |
| Collector Current - Peak | 4800A |
| Pulse Width | 3 μ s |
| Pulse Repetition Rate | 60Hz |

The Mitsubishi CM600HB-90H is comprised of 12 parallel IGBT chips with a series gate resistance of 30 Ω on each chip and 12 diode chips. It is optimized for train and traction applications: slow switching speeds, relatively low current with high average power. In order to utilize this module for the NLC modulator, some unique gate drive conditions must be considered:

- IGBT large internal gate resistance requires much higher gate drive voltage for fast turn-on.
- High current and short pulse-width result in high V_{ce} (sat), which requires high-voltage detection of the IGBT de-saturation voltage.
- Short-circuit current level must be limited to protect the IGBT and more importantly the klystron load.

* Work support by the Department of Energy under contract No. DE-AC02-76SF00515.

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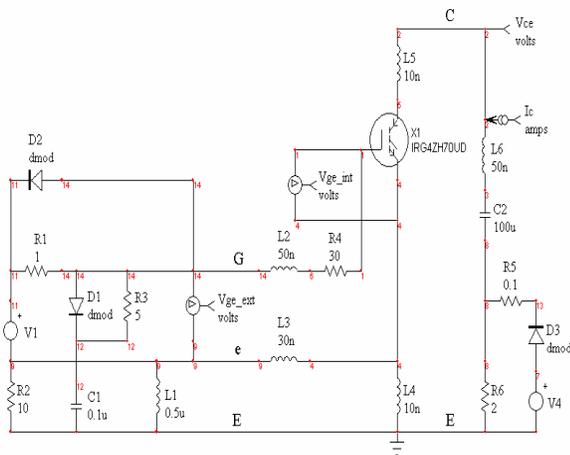


Figure 1. Spice simulation circuit for one IGBT chip.

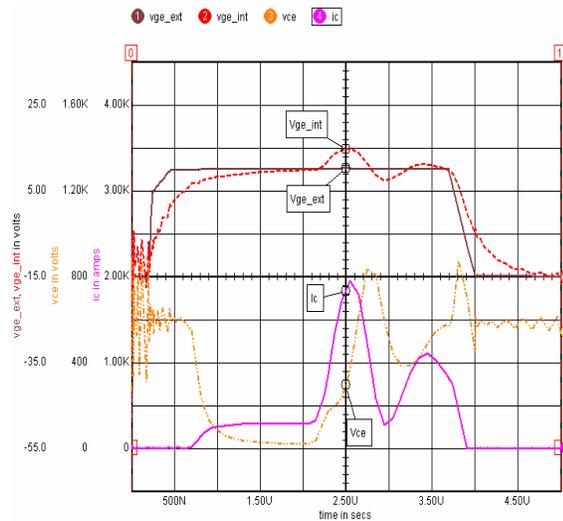


Figure 2. Short circuit without the protection.

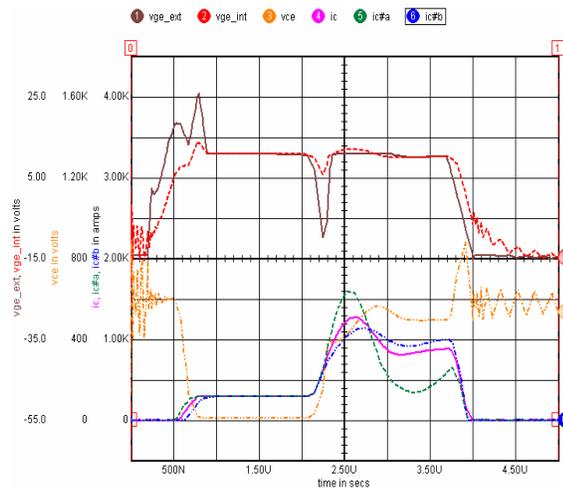


Figure 3. With the protection. Ic is shown for different values of the gate capacitor C1.

The gate driver consists of a standard gate drive from Concept Technology Ltd. Model IGD-515, a gate booster, a delayed gate voltage-clamping circuit, and a de-saturation voltage detector. The Concept gate driver provides a gate-emitter bias voltage of -15V . Upon triggering, a 15V pulse is boosted to a higher voltage for fast gate charging. Then as the IGBT fully conducts, the clamping circuit pulls the gate-emitter voltage (V_{ge}) down to 13V level. The high voltage de-saturation circuit monitors the collector-emitter saturation voltage, V_{ce} (sat), for fault conditions to turn off the trigger.

In soft short-circuit operation as in the case of a klystron arc, the fault current rises rapidly due to the extremely low stray inductance ($<30\text{nH}$) of the core driver circuit. As the IGBT comes out of saturation, the fast rising dV/dt coupled with the Miller capacitance, adds more voltage on the internal V_{ge} . This effect causes the fault current to rise even higher. Clamping V_{ge} from the external terminal does not alleviate the problem because of the module's internal gate resistance and inductance. Dynamic sensing of V_{ce} (sat) to shut off the trigger pulse cannot stop the rising current due to the required detection delay. After reaching its peak, the fault current comes down with a much higher dI/dt than the normal turn-off. This adds a large overshoot on the collector DC-link voltage. In order to control the short circuit current, the internal V_{ge} must be prevented from rising during the fault.

A simple method using dI/dt to limit the fault current has been devised. As shown in Figure 1, by connecting capacitor $C1$ in series with resistor $R3$ and diode $D1$ between the gate and the power emitter terminals, the IGBT turn-on and turn-off dI/dt can be independently controlled. The circuit works by using voltage developed by dI/dt from the IGBT module's intrinsic emitter-inductance to provide a negative voltage-feedback on the gate drive. At the same time, the dI/dt also reduces the gate-emitter voltage by the way of inductor $L1$, connected between the Kelvin and the power emitter terminals. This voltage reduction is due to the lower ratio of inductance associated with internal emitter inductance $L3$. The Spice simulation helps to visualize the effect of this type of dI/dt feedback method. The IGBT model is from the Intusoft ICAP/4 library [5]. The module emitter-inductance $L4$ is a calculated value based on measured dI/dt and V_e . $L1$, $L2$ and $L3$ inductances are estimated from the internal structure. As a short circuit occurs after the IGBT is fully on, the rising dI/dt generates a proportional negative V_{ge} that turns the IGBT off, thus reducing the fault current level. Falling dI/dt does the opposite. It turns the IGBT back on by raising V_{ge} , thus preventing fast turn-off dI/dt . Limiting dI/dt during IGBT turn-off is critical in two aspects. First, it protects the IGBT from over-voltage due to the external stray inductance. Secondly, it prevents the gate from high-voltage breakdown due to the internal emitter inductance. Figures 2 and 3 show the simulation results of the IGBT short circuit operation without and with the dI/dt feedback respectively.

This control method responds immediately to limit dI/dt and the fault current without any additional detection. The feedback circuit reacts to rising and falling dI/dt regardless of whether the IGBT turns on in normal or fault conditions. Fast turn-on in normal operation, however, is achieved by boosting the initial gate drive voltage.

III. SINGLE IGBT TEST

Figure 4 shows the gate drive circuit with the dI/dt feedback implemented. A test bench has been built to evaluate the IGBT module and its gate drive. It utilizes the same core driver board to drive a single-turn Metglas core 2605SA1 as in the modulator prototype. The secondary has one-turn, and connects to a set of high-power disc resistors. A pulsed current of 120A is used to reset the core for normal operation. When it is removed, the core will saturate and produce a short circuit condition. Figure 5 shows a tested IGBT running in normal operation at 2200V, and 4200A at $10\text{kA}/\mu\text{s}$. The effect of the short-circuit protection circuit can be readily seen by the opposite relationship of dI/dt and V_{ge} . IGBT power losses are small in comparison with its handling of the peak power. Most of the losses are due to turn-off switching and the long-tail characteristic of the IGBT PT-structure.

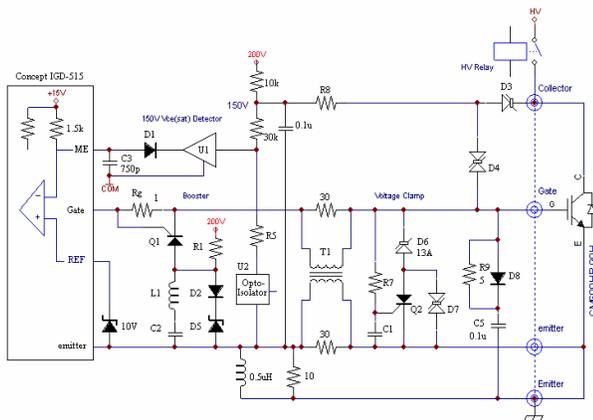


Figure 4. Gate drive schematic diagram.

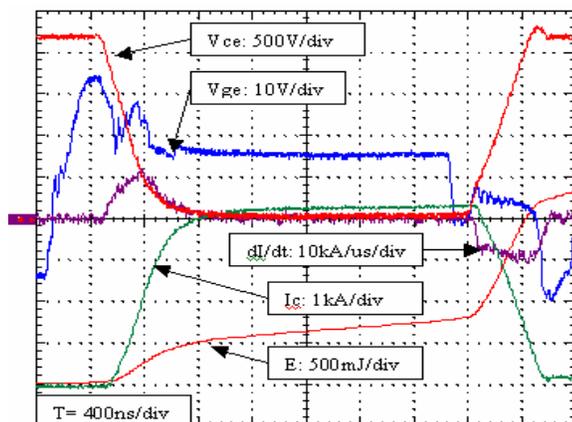


Figure 5. Typical IGBT waveforms in normal operation.

Figures 6 and 7 compare the measured waveforms in short circuit conditions without and with the protection. Without dI/dt feedback, the short circuit current and its dI/dt rise with the applied V_{ce} . At 1500V, the current peaks at 12kA and turns off at speeds of $32\text{kA}/\mu\text{s}$, generating 700V overshoot. With the dI/dt feedback, the fault current is limited at 8000A for a wide range of V_{ce} up to the required operating level of 2200V. The turn-off dI/dt is steady at about $12\text{kA}/\mu\text{s}$ with less than 300V of overshoot voltages.

It should be noted that since the Miller capacitance falls off at higher voltages, allowing the IGBT module to operate at a higher V_{ce} (sat) would also reduce the fault current at the expense of slightly increased conduction losses.

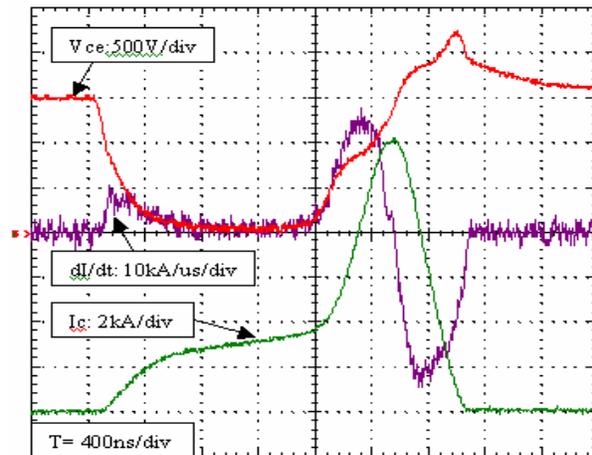


Figure 6. IGBT short circuit without the protection. High turn-off dI/dt is the main cause of Mitsubishi CM600HB-90H module failures.

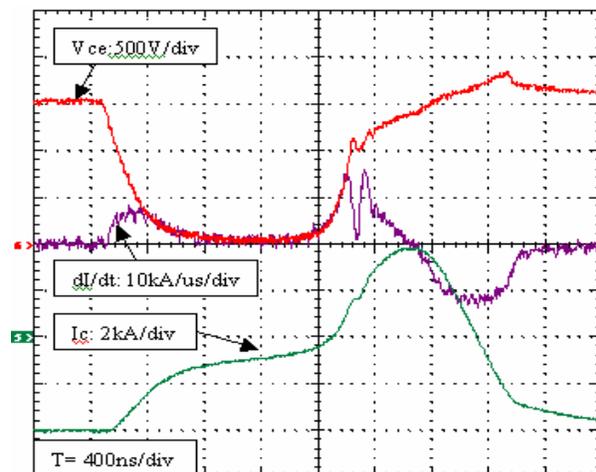


Figure 7. With the protection.

IV. MULTIPLE-IGBT TEST RESULTS

Proceeding cautiously, the IGBT module and gate drive were assembled and tested first on the Short-Stack

Modulator prototype [6]. This modulator setup consists of 11 Metglas cores driven by 11 parallel IGBT modules. The core secondary has one-turn connected to a resistive load in series with a diode. A triggered spark gap is placed across the output to simulate an arc. Figure 8 shows the Vce of an IGBT, the modulator output voltage, and the modulator current of a spark test. None of the IGBT modules failed despite being repeatedly sparked down.

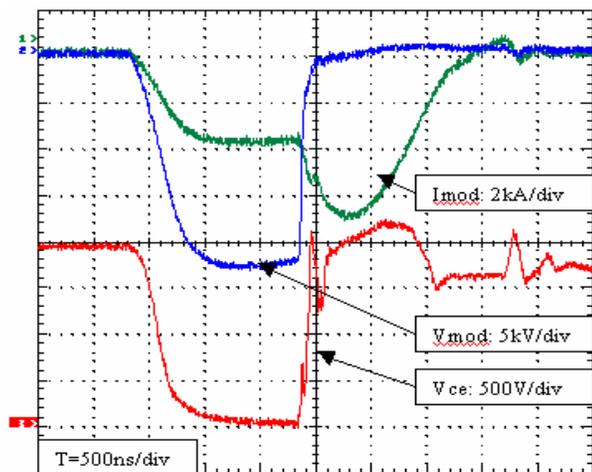


Figure 8. Short-Stack Modulator spark-down test.

Full installation of 76 IGBT modules and gate drivers were then implemented on the 8-Pack modulator driving a water load. Oil spark-down tests at 400kV were successfully performed, again without any IGBT failures. After the connection of four XL4 klystrons, several actual breakdowns were later captured. Figure 9 shows one of the klystron arc waveforms. At 420kV, the modulator normal peak-current is 1700A, which is equivalent to 5100A on the IGBTs. During the arc, the modulator current just rises to 2400A or 7200A on the IGBTs. A photograph of the gate driver is shown in Figure 10.

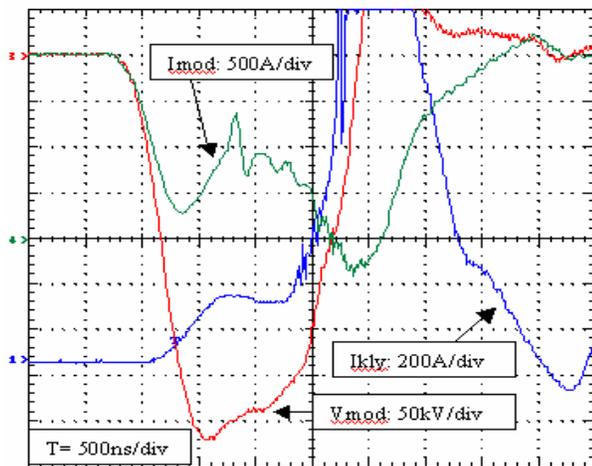


Figure 9. 8-Pack Modulator klystron arc waveforms.



Figure 10. IGBT module and gate driver.

V. CONCLUSIONS

The 8-Pack Modulator application has pushed the current generation of IGBT modules to their limit. With the new devised method to protect the IGBT under short circuit conditions, the Mitsubishi CM600HB-90H is able to safely switch currents of more than six times its rating. Long-term testing to determine the reliability of these modules is currently under way.

VI. ACKNOWLEDGMENT

The NLC Solid State Induction Modulator is a large multi-laboratory project led by R. Cassel at SLAC, E. Cook at LLNL and C. Brooksby at Bechtel-Nevada. The author would like to thank R. Larsen for his unrelenting support, J. de Lamare for his help in checking the manuscript, M. Larrus and D. Moreno for their tireless efforts toward commissioning of the 8-Pack modulator.

VII. REFERENCES

- [1] R. L. Cassel *et al.*, "The Prototype Solid State Induction Modulator for SLAC NLC", Proc. of the 2001 IEEE Particle Accelerator Conf., Chicago, IL.
- [2] M. N. Nguyen *et al.*, "Gate Drive for High Speed, High Power IGBTs", Proc. of the 2001 Pulsed Power Plasma Science, Las Vegas, Nevada.
- [3] R. L. Cassel *et al.*, "A New Type Short Circuit Failures of High Power IGBTs", Proc. of the 2001 Pulsed Power Plasma Science, Las Vegas, Nevada.
- [4] G. E. Leyh, "A Critical Analysis of IGBT Geometries with the Intention of Mitigating Undesirable Destruction Caused by Fault Scenarios of an Adverse Nature", Proc. of the 2003 IEEE Particle Accelerator Conf., Portland, Oregon.
- [5] Intusoft, San Pedro, California, www.intusoft.com
- [6] J. E. de Lamare *et al.*, "A Solid State Modulator for Driving SLAC 5045 Klystrons", Proc. of the 2001 Pulsed Power Plasma Science, Las Vegas, Nevada.