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ADVANCED GATE DRIVE FOR THE SNS HIGH VOLTAGE CONVERTER MODULATOR*

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Abstract

SLAC National Accelerator Laboratory is developing a next generation H-bridge switch plate [1], a critical component of the SNS High Voltage Converter Modulator [2]. As part of that effort, a new IGBT gate driver has been developed. The drivers are an integral part of the switch plate, which are essential to ensuring fault-tolerant, high-performance operation of the modulator. The redesigned driver improves upon the existing gate drive in several ways. The new gate driver has improved fault detection and suppression capabilities; suppression of shoot-through and over-voltage conditions, monitoring of dI/dt and Vce(sat) for fast over-current detection and suppression, and redundant power isolation are some of the added features. In addition, triggering insertion delay is reduced by a factor of four compared to the existing driver. This paper details the design and performance of the new IGBT gate driver. A simplified schematic and description of the construction are included. The operation of the fast over-current detection circuits, active IGBT over-voltage protection circuit, shoot-through prevention circuitry, and control power isolation breakdown detection circuit are discussed.

INTRODUCTION

The High Voltage Converter Modulator is a versatile klystron power supply delivering from 75kV to 140kV at an average power of 1MW for the Spallation Neutron Source (SNS). It is a three-phase H-bridge converter utilizing a resonant topology. High power IGBTs switch between the ±1100V rails at about 2200A peak current. Since inception, the modulators have suffered numerous IGBT failures. Some faults are attributed to the power rail de-coupling capacitors reaching end–of-life. However, other failures have been speculated to be attributed to a control system, which failed to protect the IGBTs during a fault event. The existing gate drive, constructed during the early stage of modulator development, does not provide sufficient protection for the IGBT; its function was to provide gate drive power. Shortcomings include; a lack of over-current or over-voltage protection, a long propagation delay time, and large power transformer coupling.

In collaboration with the SNS, SLAC has developed a new H-bridge switch plate that employs recently available high power press-pack IGBTs. These new IGBTs offer higher collector-emitter breakdown voltages (4.5kV vs. 3.3kV), improved characteristics for pulsed-power, and better cooling access than the existing flat-pack design. A parallel effort to develop a new gate drive is a part of this project. The new gate drive is designed to integrate with both the existing and the redesigned switch plate. This paper describes the new H-bridge gate drive system, including IGBT protection and shoot-through prevention features, and test results with various IGBT modules.

H-BRIDGE GATE DRIVE

The H-bridge gate drive system consists of an isolated AC/DC power source and four fully isolated gate drivers as shown in Figure 1. The power source provides 24V control power to the gate drive. The integrity of the voltage isolation is continuously monitored by a bipolar absolute value circuit. Excessive leakage will induce an over-voltage condition that will shut down the control power if it exceeds a pre-determined level. This redundant, double insulated system ensures modulator reliability should isolation barriers on any of the gate drives break down.

Gate Drive Description

The H-bridge gate drive includes a commercial gate driver, a high voltage isolated DC/DC converter, fiber optic transmitters and receivers, and IGBT protection circuitries. The commercial driver can sink/source 15 A of drive current at ±15 V. It provides over-current detection using a standard de-saturation technique. Advanced fault detection functions are added to protect the IGBT under the fault conditions typically encountered in an H-bridge circuit such as transformer core saturation, transformer primary arcs, and shoot-through.

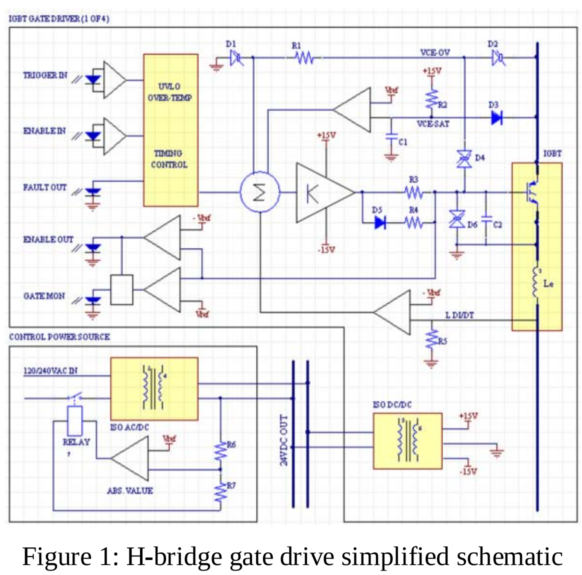

Figure 1: H-bridge gate drive simplified schematic

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IGBT Protection

The gate drive circuitry protects the IGBT in five critical areas; over-current, collector-emitter over-voltage, gate-emitter under-voltage, over-temperature, and controller-induced shoot-through gating.

Detection of an IGBT over-current condition by monitoring for de-saturation is often used for relatively slow circuits. However, in a high-speed circuit, detection delays associated with this technique can allow the fault current to rise to a dangerously high level. Hence, a fast over-current detection circuit is added to complement the de-saturation measurement. It is based on measurement of dI/dt, the fastest way to detect the onset of an over-current condition. It uses a novel approach for sensing dI/dt, by measuring the voltage produced across the intrinsic IGBT emitter inductance[3]. The method is simple and requires no external current sensor. Nevertheless, an external Rogowski coil can be used when device packaging does not present measurable emitter inductance. After an initial blanking of dI/dt during turn-on, the inductive voltage is compared to a preset reference and as soon as it exceedes this threshold the IGBT is gated off. Due to the very fast detection, the resulting fault current is significantly reduced.

IGBT over-voltage protection is achieved using redundant active clamping. During an over-voltage condition the CE voltage exceeds transzorb voltage D2. This drives charge directly into the IGBT gate through D4. It also drives charge into the driver input through R1. Both temporarily turn the IGBT back on, quickly eliminating the over-voltage condition.

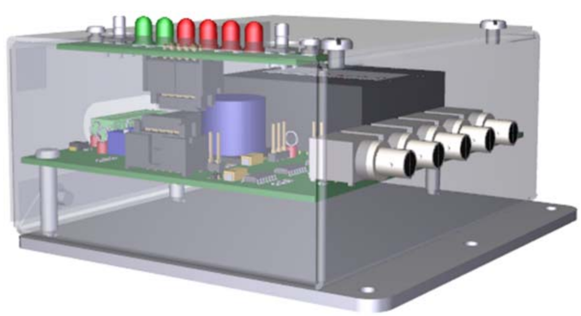

Figure 2: IGBT gate driver

Figure 3: Control power source

To prevent excessive IGBT loss due to low gate drive voltage, a microprocessor voltage monitor, MAX8216, is used to track all internal supplies for under-voltage conditions. In addition, thermal sensors attached to the IGBT latch triggers off if the temperature rises above a set limit.

Fault Prevention

The extremely low inductance between the de-coupling capacitors on the power rails and the H-bridge makes short circuit protection of IGBTs on the same phase leg particularly challenging. DI/dt of several thousand A/µS would likely destroy the IGBT in a direct shoot-through scenario. To mitigate this problem, a unique hand-shaking technique is applied between IGBTs on the same phase leg. The gate-emitter voltage of each IGBT is monitored and fed to the gate drive of the IGBT in the shoot-through path. One IGBT has to be biased off to enable the trigger of the other. Thus, even if spurious triggers are present, the two opposite IGBTs are prevented from creating a shoot-through condition by switching on at the same time.

Other fault prevention features are incorporated such as the use of a high isolation, low coupling capacitance DC/DC converter, a bi-level G-E voltage sensor for remote monitoring, and a large supply capacitance to retain control of the IGBT in the event power is lost during a fault.

Construction

The complete driver, shown in Figure 2, is built on a four-layer PC board, and housed in a compact, low cost, off-the-shelf aluminum enclosure. The external dimensions are 4”W x 5”L x 2”H. Pluggable terminal blocks are used for connection to the IGBT and the 24V control power. Threaded ST fiber optic connectors link signals between the drivers and the control system. External LEDs are provided to indicate driver status. The control power source, as shown in Figure 3, is constructed in a similar manner and can provide up to 60W of power for the four drivers.

TEST RESULTS

The driver propagation delay time, defined as trigger input to the onset of gate drive output, is less than 200nS. The RMS jitter of the delay is about 2nS as measured by an SRS620 universal time interval counter.

The new gate drive has been tested with three IGBT models, FZ1200R33KL2, CM1200HB66H, and the press-pack T1200EA45E. Figure 4 shows the single IGBT test circuit, and figure 5 is a photograph of the single IGBT test stand. Each IGBT was subjected to core saturation and triggered spark-gap arc-down conditions. Typical over-current test waveforms of the T1200EA45E are shown in Figure 6. Of note is the peak fault current, which is only about three times the device rated current of 1200A.

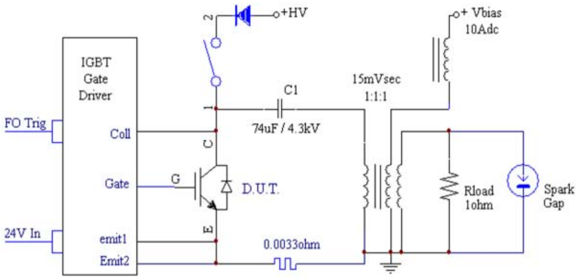

Figure 4: Single IGBT test circuit

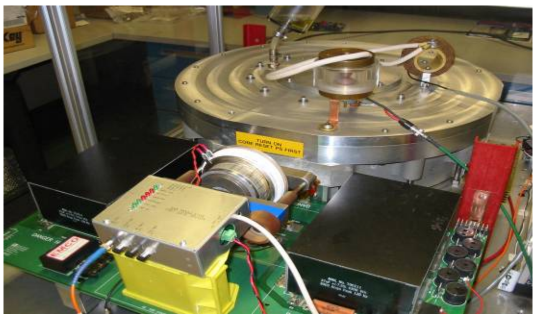
Figure 5: Single IGBT test stand

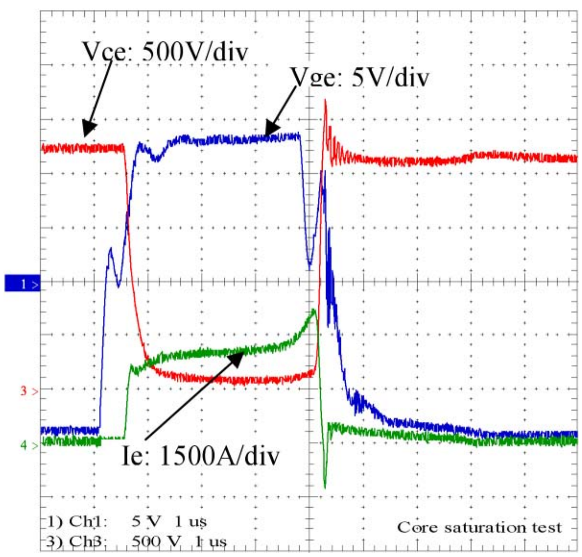

Figure 6: Over-current test waveforms on the single-device test stand.

In order to evaluate the redesigned H-bridge switch plate and the new IGBT gate drive at full peak power, SLAC built a single-phase H-bridge test stand, shown in Figure 7. The load resistance is configured to simulate the switching waveforms of the SNS modulator. Testing was conducted with a 2200V, 2200A peak, and 1.6mS long at 20 kHz burst. The gate drive successfully controlled the H-bridge both in normal and fault modes. IGBTs were safely commutated off in tests of transformer saturation and primary arcs, which were simulated with a self-triggered spark gap. Figure 8 shows waveforms of a core saturation test, where the transformer is forced into saturation by switching on only one leg of the H-bridge.


Figure 7: Single-phase H-bridge test stand

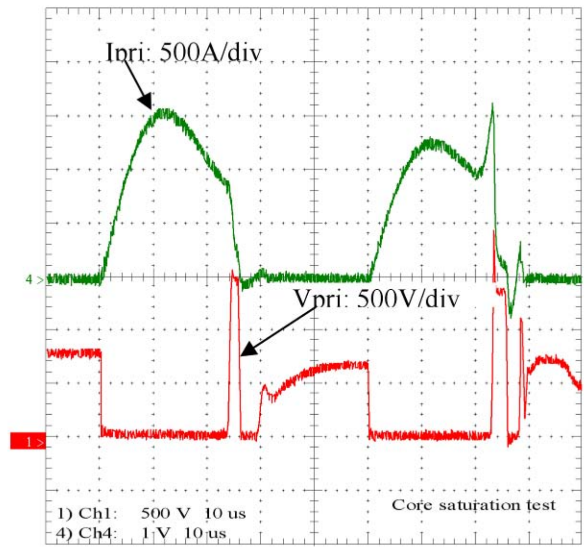

Figure 8: H-bridge fault test. The transformer saturates on the second pulse; dI/dt detection circuit detects the rising current and turns IGBT off when its peak current is still less than the normal current

CONCLUSION

An H-bridge gate drive system for the SNS High Voltage Converter Modulator has been developed to replace the existing driver. The new gate drive has successfully controlled different models of high power IGBT modules in normal operation, as well as safely protected them in various fault conditions.

REFERENCES

[1] W. A. Reass, et al., “Design, Status, and First Operations of the Spallation Neutron Source Polyphase Resonant Converter Modulators”, Particle Accelerator Conference, 2003

[2] M.A. Kemp, et al., “Next Generation IGBT Switch Plate Development for the SNS High Voltage Converter Modulator” LINAC, 2008.

[3] M. N. Nguyen, “Short Circuit Protection of High Speed High Power IGBT Modules” Pulsed Power Conference, 2003