A SOLID STATE OPENING SWITCH AND MOD ANODE SUPPLY FOR THE ADVANCED LIGHT SOURCE KLYSTRONS

Ian S. Roth, Jeffrey A. Casey, Marcel P.J. Gaudreau, Michael A. Kempkes, Timothy J. Hawkey, J. Michael Mulvaney
Diversified Technologies, Inc. Bedford, MA USA

Abstract

Series opening switches have substantial advantages over crowbars in protecting RF amplifiers such as klystrons, TWTs, and gyrotrons. Diversified Technologies, Inc. (DTI) has developed and delivered many solid-state opening switches using series arrays of insulated-gate bipolar transistors (IGBTs). The opening switch described here will be part of a complete klystron power-supply system for the Advanced Photon Source (APS) at Argonne National Laboratory.

1. INTRODUCTION

Crowbars are commonly used to protect klystrons from arc damage. When an arc occurs, the crowbar closes, and rapidly discharges the energy-storage capacitor. A typical crowbar circuit that shunts energy from the load is shown in Figure 1 (upper). An alternative way to protect a klystron is to use a switch that opens during an arc, as shown in Figure 1 (lower). Opening switches have substantial advantages over crowbars:

- No series resistor is required, so an opening-switch system has high circuit efficiency.
- Because the energy-storage capacitor does not discharge during an arc, high voltage (and RF) can be turned on again immediately after the arc clears. At APS, the accelerator beam continues 30μs without RF. If klystron faults clear within this time, no beam restart will be required.

Crowbars often use mercury-containing ignitrons. When

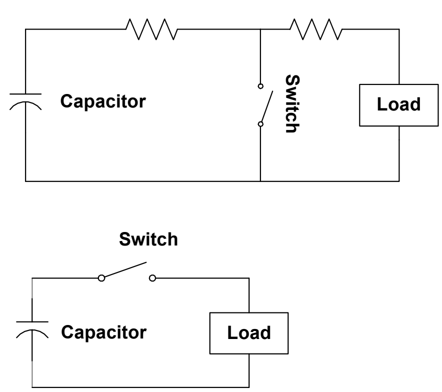

Figure 1. Circuit diagrams for crowbar (upper) and opening switch (lower).

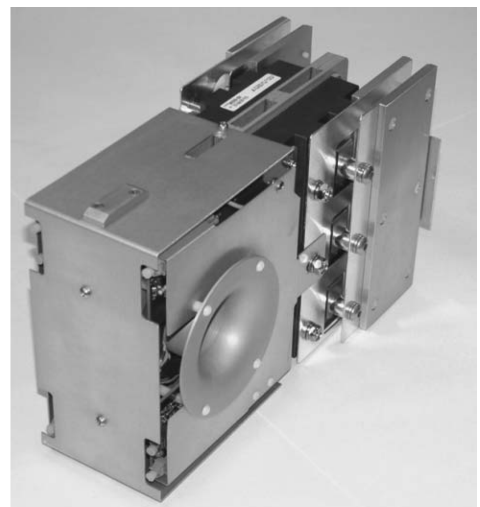

Figure 2. 3.5 kV, 5000 A peak solid state switch plate

an ignitron explodes, the required clean up is time-consuming and costly. As an example, the ignitron failure at the Joint European Tokamak in 1986 shut down the machine for three months. The total cost of the failure, including lost staff time, was £1 M ($1.9 M). Solid-state opening switches use no mercury.

Opening switches can be made using vacuum tubes, but these are expensive, have a forward voltage drop equivalent to 10-20% of the total switched voltage, and a limited lifetime. Diversified Technologies, Inc. (DTI) has developed opening switches made from a series array of solid-state IGBTs or FETs. These can be much less expensive than vacuum tubes, and have much longer lifetimes. The forward voltage drop of these opening switches is small, less than 0.5% of the rated switch voltage. DTI solid state, high voltage opening switches have been in service for multiple years without maintenance or failures.

An additional benefit of the series-array opening switch is redundancy. Solid State Switches are made with excess voltage capability, similar to high voltage rectifier stacks. A switch can continue operating even if several devices should fail. (IGBTs always fail shorted.) Diagnostics report any device failures, so repairs can be scheduled appropriately.

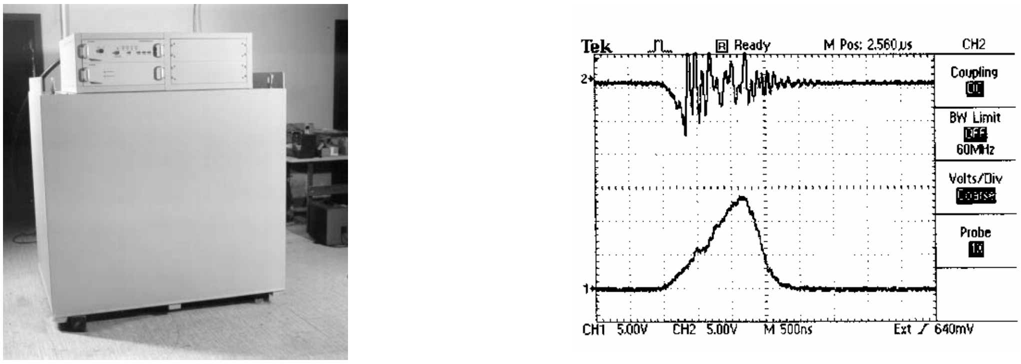

Figure 3. Left: Opening switch delivered to CPI. Right: Waveforms of a deliberate arc. Upper trace, voltage, 50kV/division; lower trace, current, 250 A/division.

2. OPENING SWITCH DEVELOPMENT

DTI builds three basic types of solid-state switches, a high-current switch, a medium current switch and a low-cost switch. The high-current switch, which uses IGBT modules, is rated up to 1000 A continuous, and up to 5000 A pulsed current (Figure 2). The medium current switch is used in the system shown in Figure 3, and is rated at 100 A DC and up to 750 A pulsed. The low-cost switch, (Figure 4) based on discrete IGBTs, will carry currents of up to 25A DC, and 100A pulsed. All of these switches require an output current monitor and fast logic that will provide a signal to the switch, commanding it to open when a fault is detected.

Figure 4. Solid-state switch modules and solid-state switch module assembly.

3. OPENING SWITCH OPERATION

An example of an operational opening switch, which carries 500A pulsed, and operates up to 140kV, is shown in the left panel of Figure 3. This switch is also used as a modulator, like most of the high-power opening switches built by DTI. It has been operating at CPI since 1998. A deliberate arc is shown in the right panel of Figure 3. After the current passes the arc-detection threshold of 200A, it rises for an additional 700ns before being interrupted, limited only by the circuit impedance. The peak interrupted current is limited to 700A.

For a pulsed system, where the same series switch provides both pulse modulation and arc protection (fast opening), a simple pulsed current transformer is used to detect the overcurrent resulting from a load fault. The typical fault sensing to switch opening time is approximately 400 – 800 ns (Figure 5), depending on the specific switch and controls configuration. This can be up to an order of magnitude faster than a conventional crowbar system, and represents several orders of magnitude less fault energy into the klystron (or other load). In a pulsed system, the switch will typically resume normal operation with the next commanded pulse – which can be of very high value in a military radar system, for example.

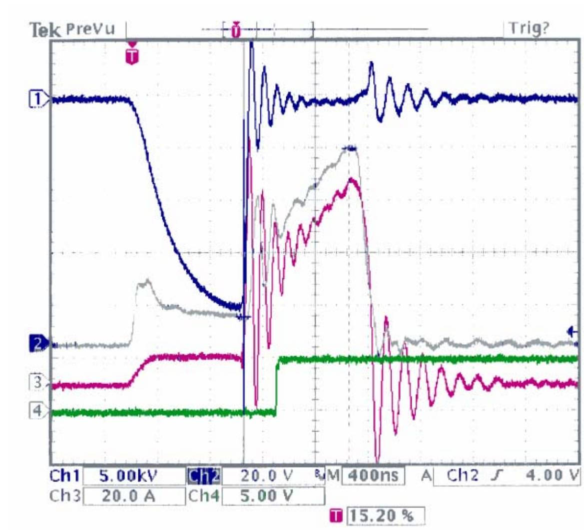

Figure 5. AN/SPS-49 Arc Response.

In a DC system (often used to drive klystrons) pulsed current transformers do not work well, because the ferrite in the transformer saturates. One of the improvements made is to use a Hall-effect current monitor, which both

Table 1. Specifications for the APS Klystron Power Supply at Argonne.

Component	Specification
Transformer	13.6 kV in, 110 kV out, 2.2 MW
Buck regulator	110 kV in, 0-100 kV out, 20 A out, ±0.5% regulation, >90% efficient
Filament heater	0-25 V, 0-25 A, ±1% current regulation
Mod anode power supply	0-90 kV with respect to cathode, 20 mA
Opening switch	100 kV, 20 A, 1 μs response to fault
Ion pump power supply	3.5 - 5.5 kV, 20 mA
Electromagnet power supplies	0-300 V, 0-12 A, 0.1% current regulation
Controls	interlocks, local/remote operation

operates with a DC current, and has a pulse response that is fast enough for fault detection.

Figure 6 shows the logical steps in detecting and responding to a load fault, such as an arc. The key to use of an opening switch is to perform all of these steps, from

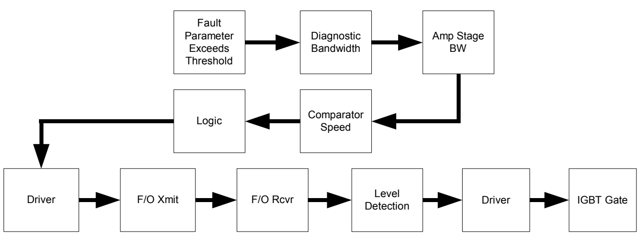

Figure 6. Opening switch fault action

detection to gate drive output, as quickly as possible (<<100nS). This time can be seen in the delay between the onset of the arc and the gate drive signal. The remaining time to switch opening is simply a function of the IGBT switching time.

Under a recent SBIR grant, we have further developed the control circuitry for the high-current switch to significantly decrease the system response time to an over-current fault, from 100 – 200 ns to below 50 ns. This has been done by using faster fiber optic receivers (fiber optic cables are used to trigger and diagnose the IGBTs), and increasing the slewing rate of the IGBT trigger.

We have also added fault latching, which displays the first fault signal, and locks out subsequent signals. This allows the operator to determine the cause of a fault, and make repairs if needed.

In addition to making improvements to the controls and triggering, we increased the DC capability of the low-cost switch from 5 to 25A. This allows the low cost to be utilized for the Advanced Photon Source, which operates at 20A DC. To do this, we first chose an appropriate IGBT. We selected a device that has a forward voltage drop of 1.8V at 20 A, and a maximum operating voltage of 1200V. An alternate device operates at 2500V instead of 1200V, but has a forward voltage drop and thermal resistance that are too large to permit operation at the required 20A DC.

We matched the IGBT to a heat sink that has a thermal resistance of 0.25°C/W in oil. The measured temperature rise at the heat sink is 10°C at 20A, which gives a junction temperature of 68°. This temperature is well below the 110°C maximum operating temperature of the device

4. ARGONNE KLYSTRON POWER-SUPPLY SYSTEM

The opening switch is the first part of a klystron power-supply system planned for APS. Specifications for the complete system are listed in Table 1.

The opening switch for APS is complete, and is currently under test at DTI. The unit contains both the switch and the mod anode voltage regulation, and is approximately the size and configuration of the modulator shown in Figure 3. It will be integrated into the klystron power-supply for the Advanced Photon Source (APS) at Argonne National Lab during the summer of 2002.

In addition to the opening switch, the other major component of the complete klystron power supply is the buck regulator. This unit acts as a DC-DC transformer, providing voltage control and regulation from an unregulated transformer-rectifier. The buck regulator uses the same switch technology as the opening switch. The required APS performance has already been demonstrated in multiple DTI systems: A buck regulator installed at CPI, for example, gives a power output of up to 3.2 MW continuous, at 80 - 140kV, with regulation to ±0.3%.

The remaining components in the system use conventional technology. We anticipate no difficulty in constructing the complete APS klystron power supply,

5. ACKNOWLEDGEMENTS

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