A SOLID-STATE OPENING SWITCH FOR CROWBAR REPLACEMENT

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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 [1] (see Figure 2). If klystron faults clear within this time, no beam restart will be required.
- Crowbars often use mercury-containing ignitrons. When 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). [2]. Solid-state opening switches use no mercury.

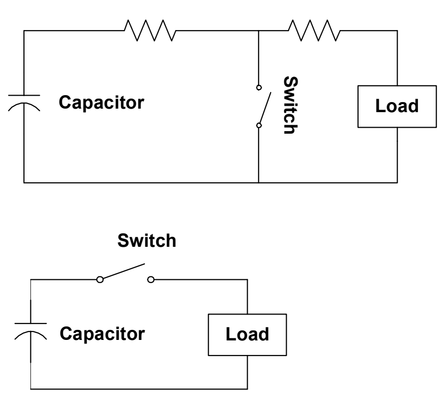

Figure 1. Circuit diagrams for crowbar (upper) and opening switch (lower).

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 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 opening switch voltage. Opening switches have been in service for several years without failures.

An additional benefit of the series-array opening switch is redundancy. Switches are made with excess voltage capability, so the 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.

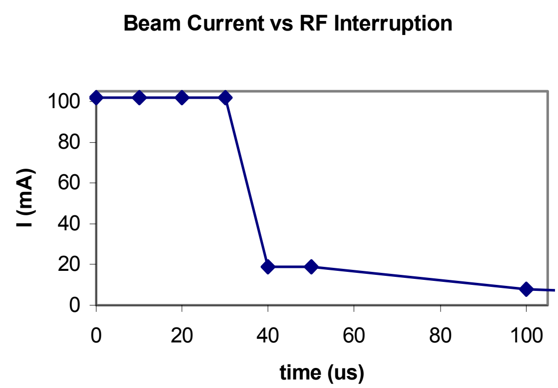

Figure 2. Beam current vs. RF interruption. An interruption of up to 30 µs can be sustained without beam loss.

2. OPENING SWITCH OPERATION

An example of an operational opening switch, which carries 500A and opens 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. Waveforms of a deliberate short are shown in the right panel of Figure. 3. The lower trace shows the current. After the current passes the arc-detection threshold of 200A, it rises for an additional 700ns before being interrupted. The peak interrupted current is 700A.

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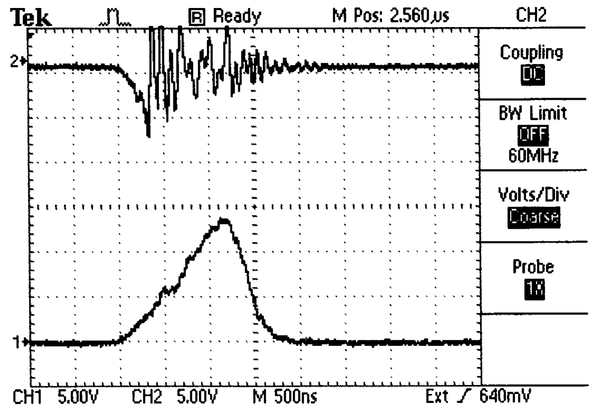

Figure. 3. Left: Opening switch delivered to CPI. Right: Waveforms of a deliberate short. Upper trace, voltage, 50kV/division; lower trace, current, 250 A/division.

3. OPENING SWITCH DEVELOPMENT

DTI builds two basic types of solid-state switches, a high-current switch, and a low-cost switch (Figure 4). The high-current switch, which uses IGBT modules, carries DC currents up to 65A, and pulsed currents up to 750A. The low-cost switch, based on discrete IGBTs, will carry currents of up to 25A DC, and 200A pulsed. DTI is presently improving these switches under a Phase-II SBIR grant from the DOE.

Both switches require an output current monitor that will give a trip signal during a fault. 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 operates with a DC current, and has a pulse response that is fast enough for fault detection.

We have further developed the control circuitry for the high-current switch to decrease the system response time to an over-current fault. 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. DTI systems presently take 700ns from the over-current signal to the turn-off of the switch.

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. Finally, we have reduced the number of fiber-optic cables per switch plate from three to two by multiplexing diagnostic signals.

As well as making improvements to the controls and triggering, we are increasing the DC capability of the low-cost switch from 5 to 25A. This will permit using this switch for the klystron power supply for the Advanced Photon Source, which operates at 20A DC. To do this, we

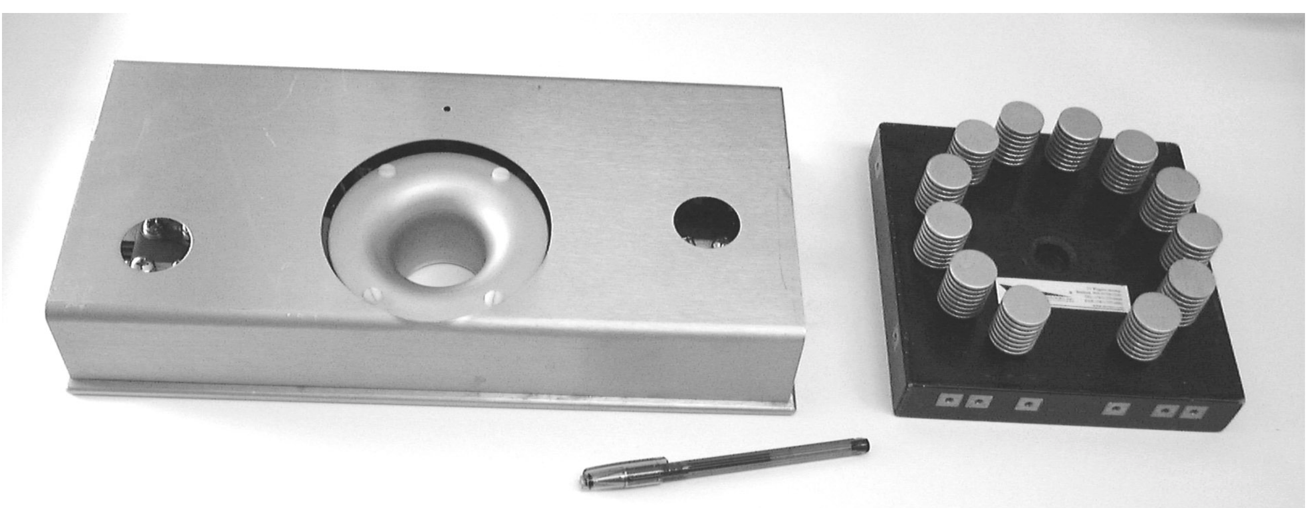

Figure 4. Switch modules. Left: 3kV high-current (65A DC, 750A pulsed). Right: 6kV low-cost (25A DC, 250A pulsed).

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

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

The opening switch built under the SBIR will be incorporated into the klystron power-supply for the Advanced Photon Source (APS) at Argonne National Lab.

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 system are listed in Table 1.

In addition to the opening switch, the other major component is the buck regulator. It uses the same switch technology as the opening switch, and the required performance has already been demonstrated: Figure 5 shows a buck regulator that is installed at CPI. This buck regulator gives a power output of 140kV and 20A, 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, which is scheduled for 2002.

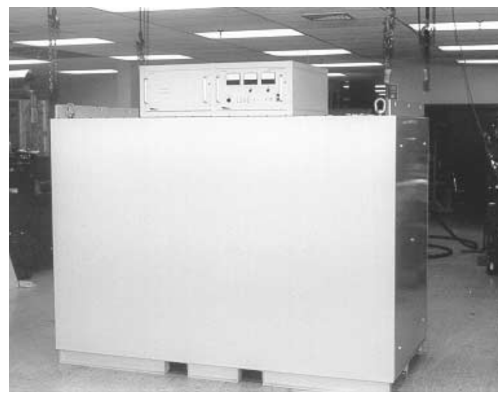

Figure 5. 140-kV, 20 A buck regulator installed at CPI.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] D. Horan, Argonne National Laboratory, private communication.
[2] G. Pile, Argonne National Laboratory; private communication