A SOLID-STATE TRANSMITTER FOR THE ARGONNE ADVANCED PHOTON SOURCE

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

Abstract

Diversified Technologies has constructed a solid-state transmitter for the Advanced Photon Source at Argonne National Laboratory. The transmitter includes a series opening switch that protects the klystron, a modulating-anode supply, and a filament heater. The opening switch has substantial advantages over a crowbar in protecting RF amplifiers. The mod-anode supply was newly developed for this transmitter.

1 INTRODUCTION

Diversified Technologies has delivered a fully solid-state transmitter to the Advanced Photon Source at Argonne National Laboratory. A photograph of the transmitter is shown in Figure 1.

The high-voltage portion of the transmitter, diagrammed in Figure 2, consists of three major units: an opening switch, a modulating-anode power supply, and a filament heater. The opening switch protects against short-circuit faults in the klystron. The modulating-anode supply corrects for variation in the accelerator current; it operates in linear mode. The filament heater provides DC, rather than AC, to minimize ripple on the beam.

The system also includes power supplies for the ion pump and klystron magnets, and a control system that monitors faults and sends data to the accelerator control room.

This paper discusses the opening switch and the mod-anode supply.

Figure 1. Transmitter for the Advanced Photon Source, with one of the authors (I.R.).

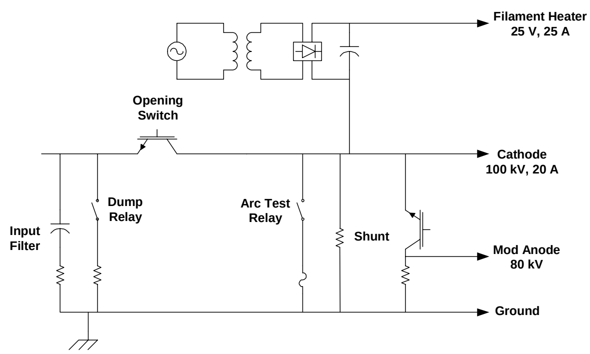

Figure 2. High voltage portion of the transmitter. Not shown are the low-voltage power supplies for the ion pump and magnets.

2 OPENING SWITCH ADVANTAGES

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 the upper diagram of Figure 3. An alternative way to protect a klystron is to use a switch that opens during an arc, as shown in the lower diagram of Figure 3. Opening switches have substantial advantages over crowbars:

1. No series resistor is required in the circuit, so an opening-switch system has higher efficiency.
2. Opening switches couple less energy into an arc; because of this, they give substantially longer RF tube lifetime.
3. Because the energy-storage capacitor does not

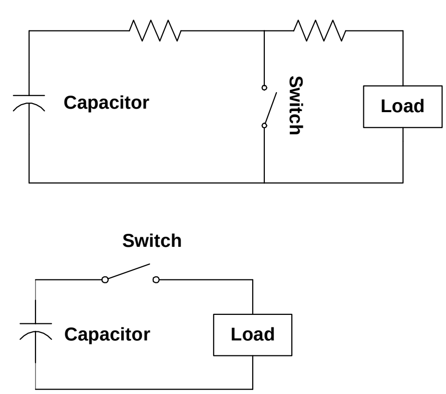

Figure 3. Circuit diagrams for crowbar (upper) and opening switch (lower).

discharge during an arc, high voltage (and RF) can be turned on again immediately after the arc clears.

4. Solid-state opening switches use no mercury, in contrast to the ignitrons typically used in crowbars. Mercury clean-up from an exploded ignitron is time-consuming and costly.

Diversified Technologies has developed opening switches made from series arrays of solid-state IGBTs and FETs. These have much longer lifetimes than vacuum tubes. 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 years.

An additional benefit of the series-array opening switch is its redundancy. The switch is made with excess voltage capability, similar to high voltage rectifier stacks. A switch can continue operating even if several devices should fail, since IGBTs always fail shorted.

3 OPENING SWITCHES

3.1 Current Ratings

DTI's opening switches use different components, depending on the current required. The switch built for the Argonne transmitter uses IGBT modules, and is rated for 100 A DC and up to 750 A pulsed. A single switch plate is shown in Figure 4. Some DTI switches use higher-current IGBT modules, at up to 400 A DC and 5 kA pulsed. For lower-current applications, discrete IGBTs are used; these carry currents of up to 25 A DC, and 200 A pulsed. All of these switches require an output current monitor and fast logic that opens the switch when a short-circuit is detected.

3.2 Opening Switch Operation

The typical time between fault sensing and switch opening is 700 ns, depending on the specific switch and controls configuration. This is roughly five times faster than a conventional crowbar system, and dissipates several orders of magnitude less fault energy into the load. Figure 5 shows the response to an arc in a system installed at CPI.

Figure 4. Solid-state switch plate for the Argonne Advanced Photon Source. Each plate is rated at 3.3 kV, 100 A continuous; 36 plates are connected in series to achieve over 100 kV switch capability.

After an arc, the switch can resume normal operation in less than 100 µs- the actual time depends on the load recovery. This fast response may make it possible to retain a circulating beam in an accelerator after a klystron fault. The fast response can also be of high value in a military radar system.

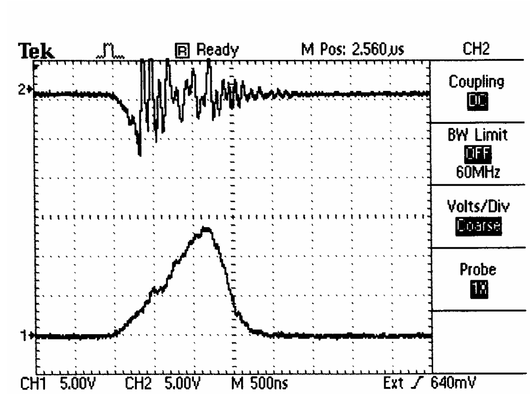

Figure 5. Waveforms of a deliberate opening switch deliberate arc. Upper trace, voltage, 50 kV/division; lower trace, current, 250 A/division.

The current in a pulsed system is typically measured with a current transformer. In a DC system (such as the Advanced Photon Source at Argonne National Laboratory) a current transformer does not work well, because the ferrite saturates. DC systems use a Hall-effect current monitor, which both operates with constant current, and has a pulse response 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 detection to gate drive output, as quickly as possible.

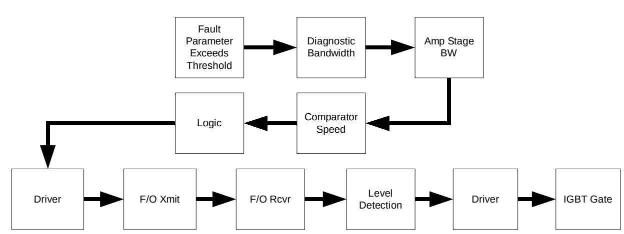

Figure 6. Opening switch fault action.

4 MODULATING ANODE SUPPLY

The modulating-anode (or mod-anode) supply provides feedback from the circulating accelerator beam to the klystron. Previously to this, mod-anode supplies were made using vacuum tubes, which have a limited lifetime. DTI has developed a long-life solid-state mod anode supply.

The mod-anode supply is implemented as a resistor-transistor divider, which has simple controls and no crossover distortion. A simplified circuit diagram[1] is shown in Figure 7. The entire string comprises sixteen circuits, each made of ten IGBTs. Each 10-IGBT array is driven by a single photo-transistor connected to the gate of the bottom IGBT; the phototransistor is driven by a fiber-optic cable. A sample voltage waveform is shown in Figure 8.

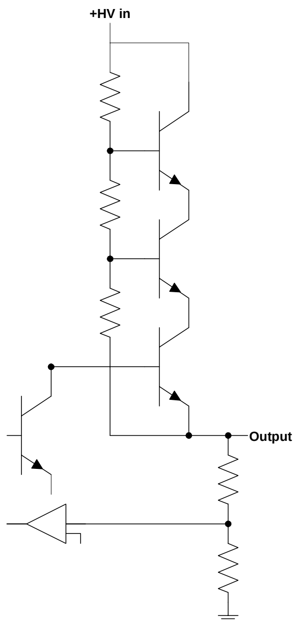

Figure 7. Series linear transistor circuit.

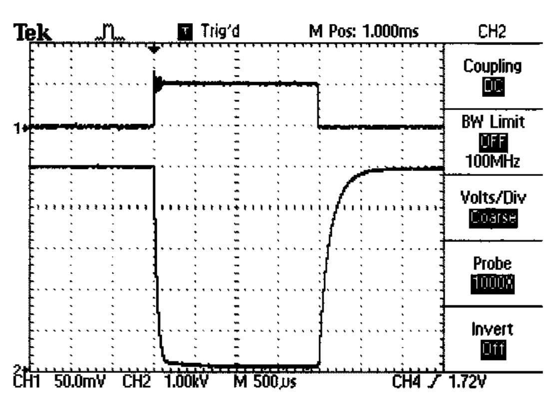

Figure 8. Pulsed waveforms for 10-IGBT linear circuit. Upper waveform: Trigger voltage, 50 mV/division. Lower waveform: Voltage across the array, 1 kV/division. Sweep speed: 500 µs/division. 5 kV was applied across the stack; load resistance was 100 kΩ. The circuit was driven from off to fully conducting.

The full mod-anode supply has a minimum off-voltage of 3.6 kV. The slew rate of supply is limited by the load capacitance, 630 pF, and maximum current that can charge this capacitance without causing an over-current trip, 10 mA. These two quantities give a slew rate of 16 kV/ms in the cathode direction, and 12 kV/ms in the anode direction at a voltage of 30 kV between the mod anode and ground. The slew rates exceed the operational requirements.

5 APPLICATIONS / SUMMARY

Any high voltage system which requires a crowbar for load protection can be upgraded to a fast opening series switch. The advantages of this approach include:

1. Faster arc response
2. Lower energy delivered into the arc
3. Much lower fault currents – by orders of magnitude in many cases
4. Nearly immediate (microseconds) resumption of operation
5. Significantly lower stresses on the upstream power components in the system, such as transformers, circuit breakers, and capacitors

In a pulsed power system, these advantages are essentially free. The same series switch can function as both the pulse modulator and the series opening switch.

Simply adding a series opening switch to a high voltage system can be a highly beneficial path to increased reliability and operability. If a simple 50/60 Hz transformer-rectifier power supply is used, however, the overall system design must also address the *unloaded* voltage of the supply – since opening the series switch essentially presents the supply with an open circuit at its output. If the series resistance of the power supply is high (which is typical in a crowbar system to limit currents into a crowbar), this unloaded voltage may be higher than the typical operating voltage. A switching power supply, capable of responding quickly to changes in load, eliminates this concern.

ACKNOWLEDGEMENTS

This work was supported by the DOE under SBIR grant #DE-FG02-99ER82778. We appreciate the collaboration of Geoff Pile and Doug Horan of Argonne National Laboratory.

---

[1] See, for instance, Horowitz and Hill, *The Art of Electronics, Second Edition*, pp. 371-2. Cambridge University Press, 1989