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SOLID-STATE HIGH-VOLTAGE CROWBAR UTILIZING SERIES-CONNECTED THYRISTORS

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ABSTRACT

High-voltage (HV) crowbars in HV power supplies can often be found in assemblies that are constructed by using series ignitrons or HV switch tubes. They are normally connected across the output of the HV power supplies to protect the load, such as a gyrotron, tetrode, etc., in the case of a HV load fault. The use of ignitrons is being limited and may not be usable in the near future due to environmental concerns. Solid-state HV crowbars are now in development. Presented in this paper is one being developed by General Atomics that has thirty SCRs connected in series to withstand a normal operation voltage of 100 kVDC. The SCRs are triggered at the same time to their full conduction in less than 5 μs starting from the time when the crowbar receives the signal to fire. The selected SCRs are capable of turning-on in approximately 2 μs with a current rise of 1000 A/μs. The crowbar assembly can be set up to operate in either positive or negative polarity. In a typical application, simulations show that the crowbar can limit the energy into a load fault to less than four joules. The electrical design will be discussed including selection of the SCRs. For the mechanical design, both positive and negative assemblies will have the same dimensions and the same components, but the SCRs are installed in opposite directions. The estimate dimensions of the crowbar assembly are 46 in. H × 14 in. W × 14 in. D. The crowbar assembly is to be constructed and electrical tests will be performed, the results of which will also be presented. These tests are to demonstrate a solid-state crowbar to replace ignitron-based designs. The design has focused on triggering speed, limiting the on-state voltage drop, fast rate-of-rise of current, ease of adaption to different voltage levels and polarities, and the high voltage electrical and mechanical aspects of the design.

I. INTRODUCTION

High voltage power supplies with outputs voltages approaching 100 kV and 100 A are used in a variety of applications, such as for gyrotrons, tetrodes, and ion sources. Although these power supplies can output several megawatts, the energy deposited into a high voltage load fault must be limited to a low value, such as 10 Joules, to prevent damage from occurring to the load. Often these high voltage power supplies have a modulator employing tetrodes to regulate the output voltage, which must also be protected should it arc internally. This requires a fast acting device that must divert the energy from the high voltage fault within a few microseconds, normally less than 10 μs. Crowbars using series-connected ignitrons have been used for many years in high voltage power supplies for this purpose. There are eleven high voltage power supplies energizing either ion sources or gyrotrons at the DIII-D National Fusion Center at General Atomics that have ignitron crowbars, each with four ignitrons in series, to protect the tetrodes of the modulators and the load from high voltage faults. Some have been in operation for almost thirty years. Ignitrons contain mercury, which is becoming a bigger concern environmentally. Ignitrons must have the anode heated and the cathode cooled for reliable operation at high voltage. Crowbars have also been built using thyratrons [1] and triggered spark gaps [2]. More recently solid-state crowbars are being developed using series connected thyristors [3,4]. This is taking advantage of the higher voltage ratings of modern devices, reducing the number of thyristors that need to be connected in series to reliably hold off the high voltage.

II. CROWBAR CONSIDERATIONS

Several factors need to be considered in both designing a crowbar and in selecting components for it. Figure 1 shows a typical application of a crowbar, as well as other circuit elements to help limit the fault energy into the load until the crowbar can fire and divert the energy away form the fault.

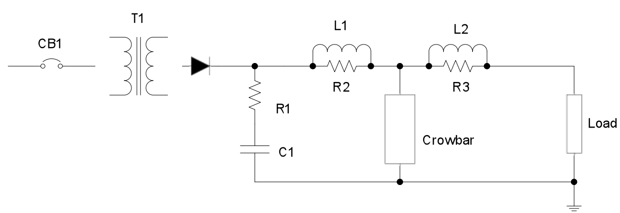

Fig. 1. Diagram showing a typical application of a crowbar.

The primary consideration is the speed at which the crowbar fires. The delay time between the issuance of the command to fire the crowbar and the crowbar beginning to conduct current must be minimized. A general requirement is to remove the energy into a high voltage fault within 10 μs. However, times less than this may be required and can be realized. Not all of the 10 μs can be in the turn-on delay time of the crowbar since it takes a microsecond or two to detect the fault and issue the command to fire the crowbar. The ignitron crowbars in the power supplies at DIII-D fire in two to three microseconds. The high voltage power supplies for the gyrotrons at DIII-D must pass a test to verify the 10 J fault energy limit. In this test, one side of a high voltage relay is connected to the cable from the power supply at the location of the gyrotron. The other side is connected through a six-inch length of 36 gauge wire to ground. The power supply is charged up to 80 kV and the relay is closed, shorting the power supply through the 36 gauge wire to ground. If the wire survives, the power supply successfully limited the energy into the wire to ≤ 10 J. Experience at DIII-D has shown that the crowbar must fire within three microseconds or the wire may not survive.

The crowbar must reliably hold off the high voltage without breakdown. A lot of stress is placed on the upstream equipment when the crowbar fires, especially the transformer(s) and the circuit break that is opening under high load current. Besides being a nuisance that temporarily takes the power supply out of operation and requires the power supply to be reset, these undesired breakdowns can lead to a failure in the upstream equipment or within the crowbar itself.

The crowbar needs to be able to handle high peak currents and high dI/dt. Peak currents as high as 1000 A can flow through the crowbar. The capacitor filtering the HVDC in the power supply must have a series resistor (R1 in Fig. 1) to limit the current to <1000 A and to help absorb the energy stored in it. This resistor also helps to limit the energy into a high voltage fault until the crowbar fires and diverts the current. Similarly, inductors (L1 & L2 in Fig. 1) should be used to limit the rate-of-rise of the current into a fault. This not only helps to reduce the fault energy, but also can control the rate-of-rise of the current into the crowbar. Limiting the dI/dt to below 1000 A/μs is good practice.

The crowbar must handle not only the current as the filter capacitor of the power supply is discharged, but also the current building up from the transformers until the circuit breaker opens, which can take one or more AC cycles.

To reliably hold off the voltage, the crowbar is very likely made of multiple devices in series. The voltage needs to be shared equally by the devices and all the devices need to be triggered at essentially the same time (within a narrow window of time) so as not to overvoltage one or more of the devices. Consequently one would like to minimize the number of devices in series, which means the voltage rating of each device needs to be as high as reasonably possible. This is a trade off with the voltage sharing networks, which get physically larger and have more demanding requirements as the voltage rating of the components increases. Additionally, the on-state voltage of the crowbar needs to be as low as possible. A high voltage load fault, which is likely to be a vacuum cathodic arc, will not stop until the current approaches zero, or the voltage falls to a low enough value so that the arc is not sustained. With many devices in series, the crowbar could have a higher than expected on-state voltage, especially at the initial high current levels, and lead to the fault lasting longer than desired.

III. CROWBAR DESIGN

A search of candidate SCRs resulted in the selection of device that is specified to have a maximum delay time of 2 μs. The peak surge current rating is >10 kA and it has a critical rate of rise of on-state current of 1000 A/μs. At 1000 A, the on-state voltage is less than 1.6 V. For a crowbar to operate at 100 kV, thirty devices will be used.

Figure 2 is a photograph of a single SCR assembly, showing the SCR on its support plate. The number of these assemblies required to hold-off the operating voltage of the crowbar would be assembled into the crowbar assembly and clamped. By changing the orientation of the SCR and its position relative to its gate drive, a crowbar for positive or negative voltage can be assembled. The configuration shown in Fig. 2 is positive polarity.

Fig. 2. Photo of single SCR assembly on support plate with triggering and monitoring PCB and toroidal transformer.

The printed circuit board (PCB) has the SCR gate drive which is triggered by a signal sent via fiber-optic cable from the crowbar processor at ground potential. This board has the static and dynamic voltage sharing network for the SCR on it. It also generates two signals that are sent via fiber-optic cables to the crowbar processor. One signal sends the status of the trigger circuit, which informs the crowbar processor that the voltage is present and ready to trigger the SCR. The summation of all of the SCR ready signals establishes the crowbar ready interlock. The second signal indicates that the SCR is properly supporting the voltage. If not, a fault signal is generated.

The toroidal transformer provides the AC power for the PCB. The primary of the toroidal transformer is a 150 kVDC insulated cable. This cable passes through all the toroidal transformers and couples them to an isolation transformer that is fed by the 120 VAC line.

The crowbar processor, shown in Fig. 3, receives the crowbar fire signal and transmits this signal fiber-optically to all the SCR gate drivers in the crowbar. There are 16 transmitters on one 6U VME PCB. It receives the trigger ready signals for each SCR and generates the crowbar ready signal to be used for interlocking purposes. A 6U VME PCB receives ten signals. It also receives the signals indicating that each SCR is supporting the voltage and generates a fault signal if any SCR is not. There are also ten signals per 6U VME board. LEDs are used to indicate which SCR trigger is not ready and which SCR has a fault. A crowbar control interface PCB provides the interface to power supply. It receives the crowbar fire command and sends it to the crowbar trigger cards. It receives and combines the crowbar ready and fault signals and sends them to the power supply controls. It monitors the crowbar current and determines if the crowbar fired within a specified time interval or whether the crowbar pre-triggered (current without a command to fire).

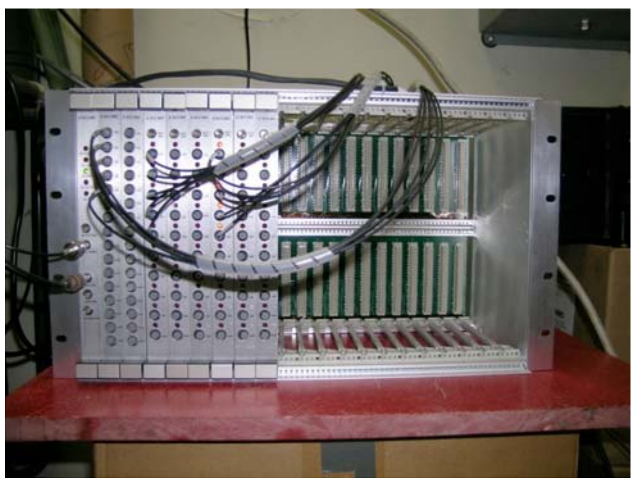

Fig. 3. Crowbar processor in use during crowbar testing.

IV. CROWBAR TESTING

Thirty SCRs were individually tested, each with its gate drive board, at voltages up to 3 kV. The 30 SCRs had a mean delay of 1.3 μs and a standard deviation of 0.1 μs. Six assemblies, each with five SCRs, shown in Fig. 4, were tested at voltages up to −15 KVDC, thereby testing the 30 SCRs going into the 100 kV crowbar under typical operating conditions.

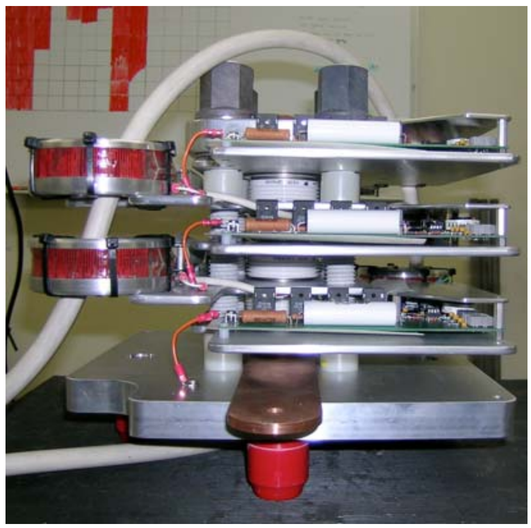

Fig. 4. Five-SCR crowbar assembly.

The test set-up is shown in Fig. 5. A 20 μF capacitor is charged by a hipoter. A 16 ohm resistor limited the peak current to about 1000 A and the 50 μH inductor limited the rate-of-rise of the current to 300 A/μs. A current transformer monitored the crowbar current and a high voltage probe monitored the voltage. These signals were displayed on an oscilloscope, along with the crowbar trigger command.

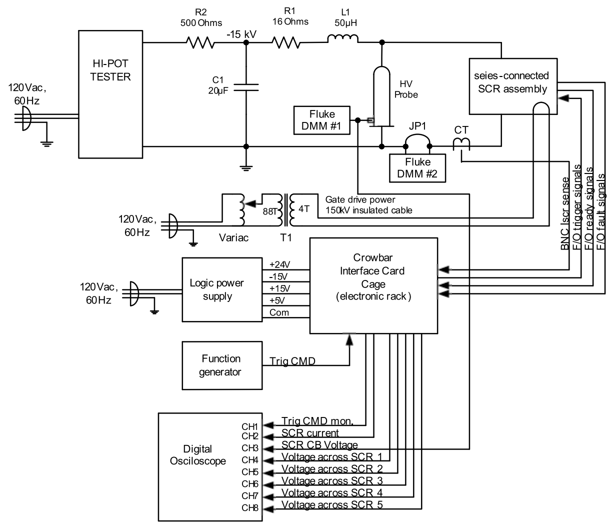

Fig. 5. Test set-up for five-SCR crowbar.

Figure 6 shows the traces when the crowbar was fired at −15 kVDC. The fire command is the red trace. The yellow trace is the voltage, which undershoots due to the AC compensation of the probe being slightly misadjusted. The blue trace is the current through the crowbar. Figure 7 is a zoomed view, showing that the crowbar fired within 1.8 μs of the command.

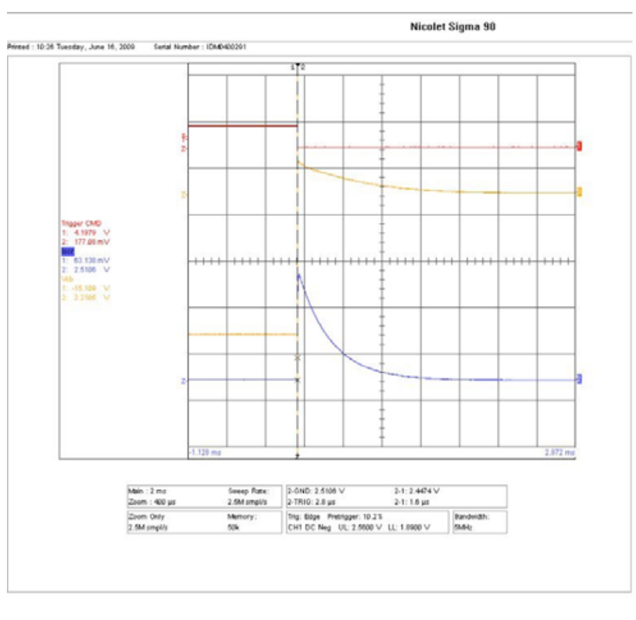

Fig. 6. Crowbar test at -15 kVDC showing the voltage across the crowbar (yellow) and current through it (blue).

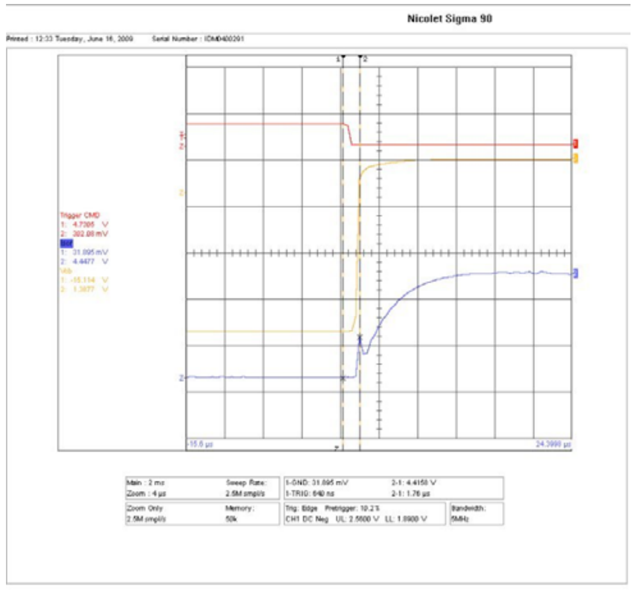

Fig. 7. Crowbar test at -15 kVDC shows crowbar delay time is less than 1.8 μs.

The thirty-SCR crowbar was assembled and is shown in Fig. 8. The unit is about 46 inches high and is about 14 inches on a side. This unit has been scheduled for testing at -100 kVDC. This test is confirmational – the individual components will see the same conditions as in the 15 kVDC tests.

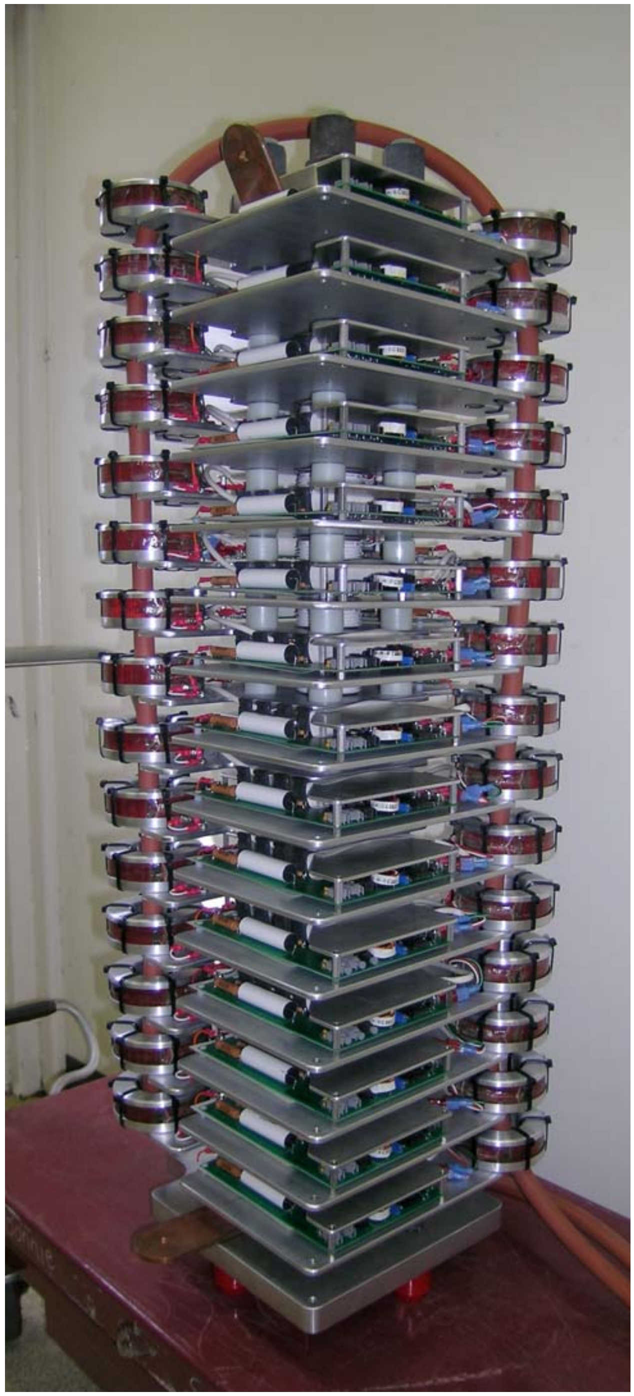

Fig. 8. Thirty SCRs assembled into a crowbar for operation at 100 kV.

V. CONCLUSION

A crowbar has been designed and built which uses thirty SCRs for operation at 100 kV. By using fewer or more SCRs, crowbars for operation at lower or higher voltages can be assembled. Also, the crowbar is easily configurable for either positive or negative polarity. The thirty SCRs were tested in five-SCR crowbar assemblies at -15 kVDC. The delay times were less than 1.8 μs. Confirmational tests at 100 kV are scheduled. This device uniquely provides protection for loads on high voltage, high current power supplies, which can be used for new requirements or replacements for existing ignitrons.

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