HIGH-CURRENT, HIGH-COULOMB TESTING OF IGNITRONS

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Ignitrons used as isolation switches for staged homopolar-generator-charged inductor discharges must carry megamp currents with charge transfers of several thousand coulombs per discharge. The current and coulomb transfer duty approaches the limit of commercially available ignitrons. Tests were completed to verify the high-current, high-coulomb capability of size "E" ignitrons under actual discharge conditions and determine the failure modes. Based on the test results, a set of parallel-connected ignitrons were successfully used as isolation switches in actual high-current, staged, HPG/inductor discharge experiments. Circuit impedance of the ignitrons was determined and circuitry for reliably triggering the devices both actively and passively was developed. The present work presents the results of the test program and the details of the implementation of ignitrons on a 60 MJ HPG/inductor modular power supply.

Ignitrons were chosen for use as isolation switches to effect the parallel staging of six homopolar-generator-charged inductors. Each generator stores 10 MJ of energy and delivers 1.2 MA of current into a 6.5-µH inductor through a low impedance explosive opening switch with a characteristic opening time of about 140 µs, generating about 15 kV emf into a given load. Staging of the six inductors requires an isolation switch which can hold off a 15 kV reverse voltage during the early part of the discharge sequence and then rapidly switch to carry an on-state current exceeding 1 MA. The total coulomb transfer depends on the load impedance, but can exceed 3,000 C per inductor.

During the initial design of the isolation switches, size "E" ignitron tubes were rated by the manufacturer at peak currents of 600 kA and charge transfers of 1,500 C. Subsequent testing at LLNL showed that the tubes were actually limited to lower peak currents, and that coulomb transfer ratings might be in question[1]. Space constraints on the 60 MJ HPG/inductor supply allow for only two tubes to be used with each inductor so the practical limits of the ignitron tubes limit the energies that can be delivered in a staged discharge. There was also some concern that failure of the tube during a high-energy discharge could lead to catastrophic results.

Test Program

Ignitron Impedance

The primary test completed was one to determine the circuit response of the ignitrons. In initial circuit simulations the ignitrons were taken to present a constant 100 V potential which seemed to give reasonable results in the simulation of power supply operation. To verify the circuit response of ignitrons more accurately, a pulsed current from a 4 kV, 0.001-µF capacitor was discharged through "D" size ignitron tubes, and the voltage across the tubes was measured. Three different tubes were used to insure that the measurements were not due to individual tube defects. The peak currents of the discharges were about 43 kA. A typical voltage trace from a discharge is shown in figure 1a. The tube impedance was taken to include resistance, inductance, and a DC voltage drop. Then the voltage across the tube at any time during the discharge can be expressed:

$$V = IR + L\left(\frac{dI}{dt}\right) + V_o \qquad (1)$$

thus, using the current and voltage waveforms, the values of R, L, and V_o can be computed. Initial attempts to invert the waveforms gave erratic results however due to some time dependence in the impedance values. Also, the constant voltage term did not appear to be consistent with the voltage waveform. Ultimately, constant values for the resistance and inductance were found to give reasonable agreement to the experimental results. For the three different tubes, the resistance values were computed to be about 1.46, 1.55, and 1.87 mΩ, and the inductance values were computed to be about 195, 192, and 165 nH. The computed voltage waveform for the experiment shown in figure 1a using the appropriate constant impedance values is shown in figure 1b. The computed waveform is found to match the experiment to within 10% at early times and is within 25% of the experiment during the entire shot. Differences between the two waveforms tend to indicate lower resistance in the tubes at later times, suggesting a time or current dependence to the resistance. It should be noted that the mounting of the tubes in an appropriate buswork will probably affect the impedance somewhat. The mounting for all three tubes was the same in this experiment.

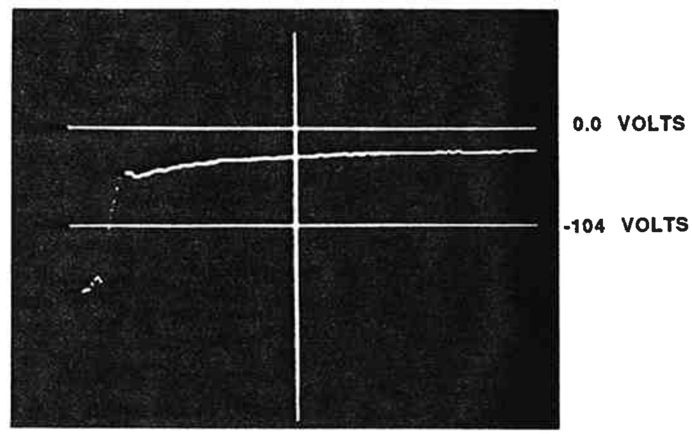

Figure 1a. Experimentally measured ignitron voltage

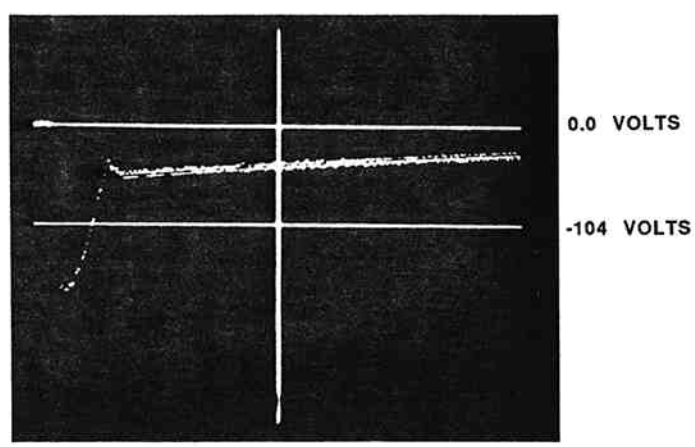

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Figure 1b. Ignitron voltage predicted from V = LdI/dt + IR

The size "E" ignitrons used in the other tests reported in this paper have been analyzed less carefully, but show a typical inductance of about 200 nH and a resistance of about one mΩ The resistance is also found to drop during high-current shots to about half its initial value. The magnitude of tube resistance agrees well with the measurements of Kihara[2].

Parallel Ignitron Operation

Due to high-currents from the 60 MJ power supply, parallel operation of ignitrons is required, with current sharing nearly equal between a pair of size "E" tubes. A series of tests were performed to verify the current-sharing characteristics of parallel mounted ignitrons. The discharge circuit is shown in figure 2. The ignitrons were mounted in a test fixture designed to be used in the 60 MJ power supply. The current traces from a typical test are shown in figure 3. Over a series of ten, 40 kA pulsed discharges the ignitrons were found to share equally during the first 200 μs, and thereafter one of the ignitrons was found to decay preferentially while the other continued to carry a steady current roughly equal to its initial peak current. Although an inequality in current sharing was indicated, the difference was deemed harmless to the operation of the 60 MJ power supply. The inequality in current sharing may have been due to a non-symmetric current feed to the test fixture (which was itself symmetric). In the 60 MJ supply the current feed is completely symmetric.

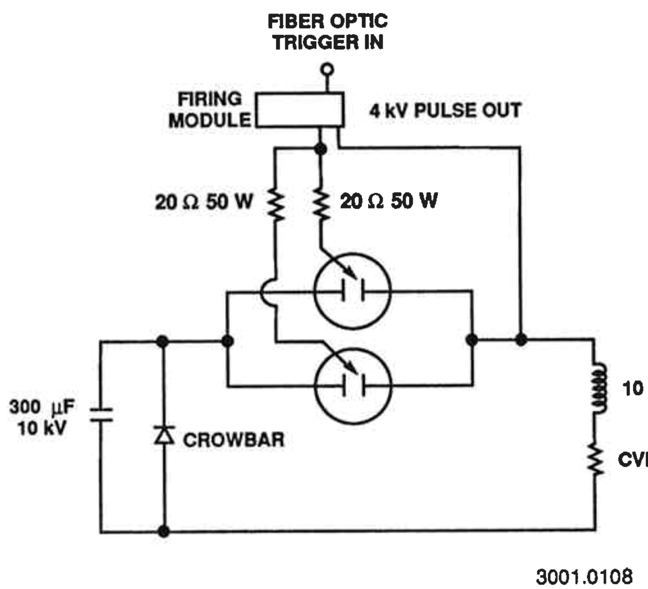

Figure 2. Test circuit for parallel-operating ignitrons

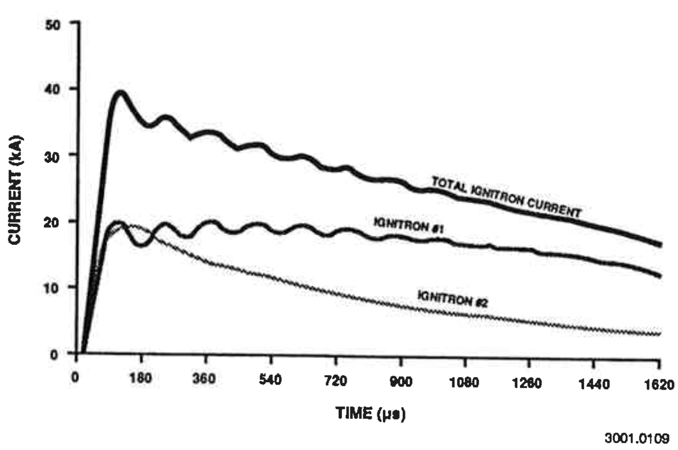

Figure 3. Current sharing between parallel "E"-size ignitrons

Failure Testing

A series of three shots testing the current capability of a size "E"ignitron was completed using a 6.2 MJ HPG/inductor to generate a high-current, high-coulomb discharge. The buswork to the ignitron was completely coaxial to minimize mechanical effects which could damage the glass insulator on the ignitron. The ignitron was triggered actively with a 200 amp pulse coincident with the detonation of the inductor opening switch explosives. A parallel, passive trigger circuit (self-triggering) turned on the ignitron as voltage developed across the switch.

The numerical results of the shots are shown in table 1. The first shot was a 150 kA check-out shot to verify correct operation of all systems. No further conditioning was required before proceeding to the next shot.

Table 1. High current NL-8205 ignitron tests

TEST #1	
Peak current	150 kA
Coulombs	700 C
Hi-pot	5 kV
Post-shot ignitor resistance	48 Ω
TEST #2	
Peak current	300 kA
Coulombs	2,000 C
Hi-pot	5 kV
Post-shot ignitor resistance	40 Ω
Test #3	
Peak current	280 kA
Coulombs	5,000 C
Hi-pot	600 V
Post-shot ignitor resistance	
Before reconditioning	2 Ω
After reconditioning	15 Ω

The second shot represents approximately one-half the current and charge transfer that will be seen through one ignitron when the 60 MJ system is taken to full power. The ignitron survived the shot, but only high-potted to 1.5 kV after cooling. Conditioning was accomplished by heating the anode to ~120 °F for four hours, after which a hi-pot to 5 kV was successful. On the second shot, the ignitron resistance was measured at about 0.9 mΩ initially, falling to about 0.5 mΩ later in the shot. Ignitron inductance was measured at about 170 nH. The current and voltage traces for this shot are shown in figures 4 to 7.

A third test was attempted successfully, but the ignitron was unable to hold off more than 600 V following the shot even with conditioning. The failure mechanism was identified by disassembling the ignitron. A bolt holding a baffle had melted halfway through, allowing the baffle to make galvanic contact with the anode of the tube. The deep melting had liberated enough gaseous contaminants that the tube vacuum was not low enough to hold off voltage. Had the baffle not been there it is likely that the ignitron would have been good for more shots.

Based on the findings of this test, modified ignitrons similar to the originals but with the internal baffle removed were obtained from the manufacturer for use on the 60 MJ power supply.

Operation of Ignitrons on the 60 MJ Power Supply

Parallel pairs of modified ignitrons have been installed and used on the 60 MJ power supply. The functional circuit of the ignitron trigger scheme is shown in figure 8. Resistor, R_1, and diode, D_1, comprise a passive trigger system which triggers ignitron conduction when the voltage developed by the opening switch exceeds the load voltage by about 1 to 2 kV. Resistor, R_1, is 10 Ω at 200 W. Diode, D_1, is a diode stack of 100, 1 kV peak inverse voltage (PIV) diodes with a pulsed current rate exceeding 250 A with parallel voltage dividing elements of 1 MΩ, 2 W resistors and 30 nF, 2 kV capacitors. The full stack makes a 100 kV (PIV) diode able to carry the 250 A ignitor current with a 70 V forward diode drop. The high PIV rating is required to stand off load fault voltages of up to 50 kV. The 70 V forward drop helps protect the passive trigger from triggering on-shot noise. The diode string is insulated against the high reverse voltage by potting the assembly inside a polyethylene casing.

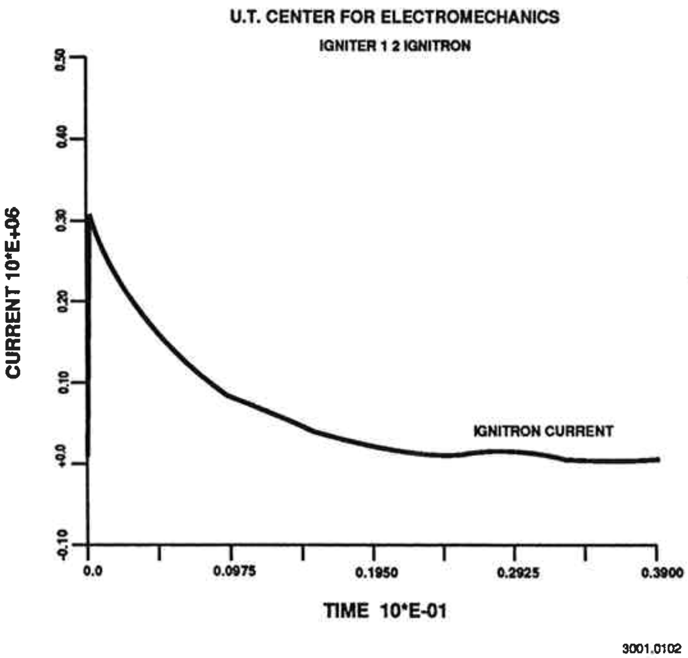

Figure 4. Ignitron test #2--discharge current

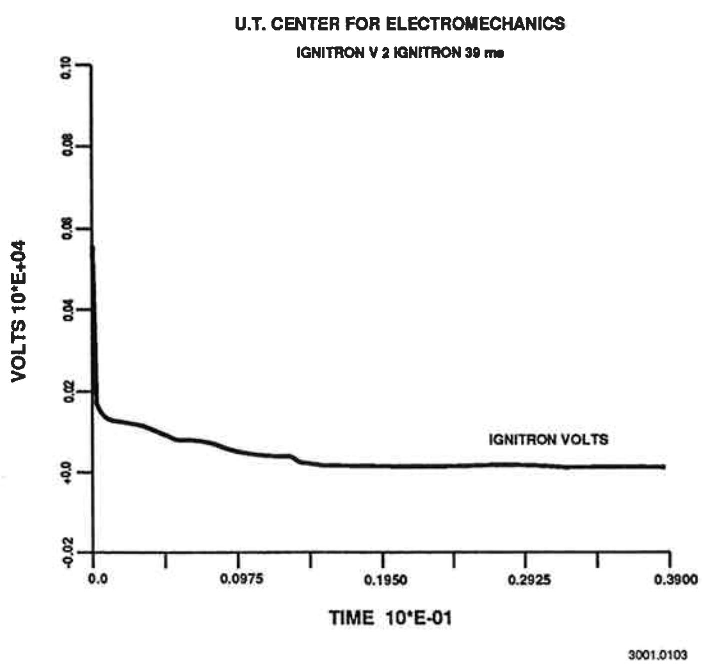

Figure 5. Ignitron test #2--discharge voltage

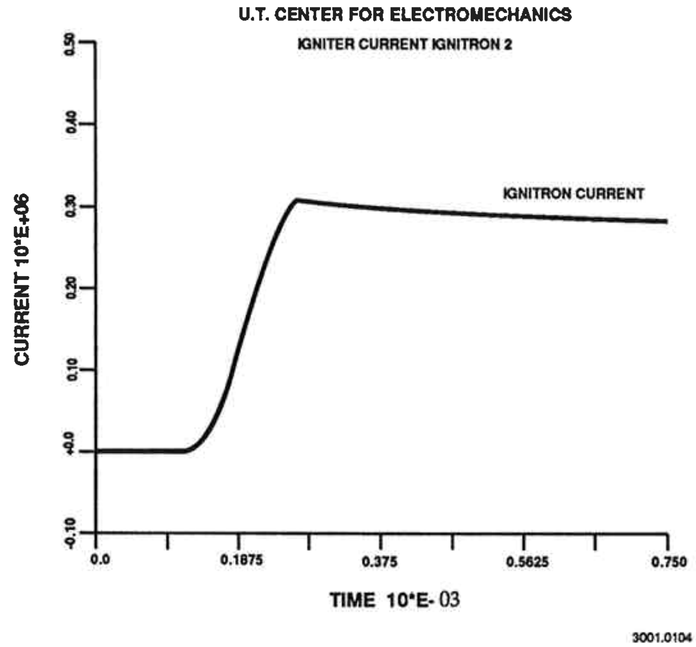

Figure 6. Ignitron test #2--early discharge current

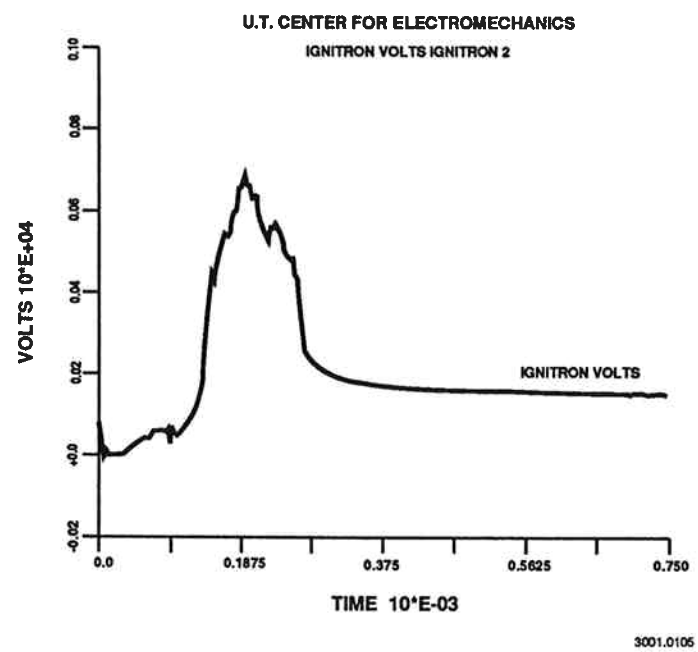

Figure 7. Ignitron test #2--early discharge voltage

The active ignitron trigger employs a factory standard FS-10 firing module which produces a 4 kV pulsed output with a risetime of about 1 μs or less. The output from a single module is used to trigger a pair of ignitrons. To insure that both ignitrons receive an adequate trigger pulse, a 20 Ω, 200 W resistor, R_2, is used to limit the current into each ignitor. Diode, D_2, is a 5 kV PIV, 500 A diode which protects the firing module from forward voltage developed across the igniter circuit during passive triggering.

Initial use of the isolation system took place in July of 1986 when a single pair of ignitrons was used to stage the second inductor of a two inductor discharge. The current transferred from the second inductor was only 170 kA (85 kA per tube). Correct current sharing between the tubes was verified.

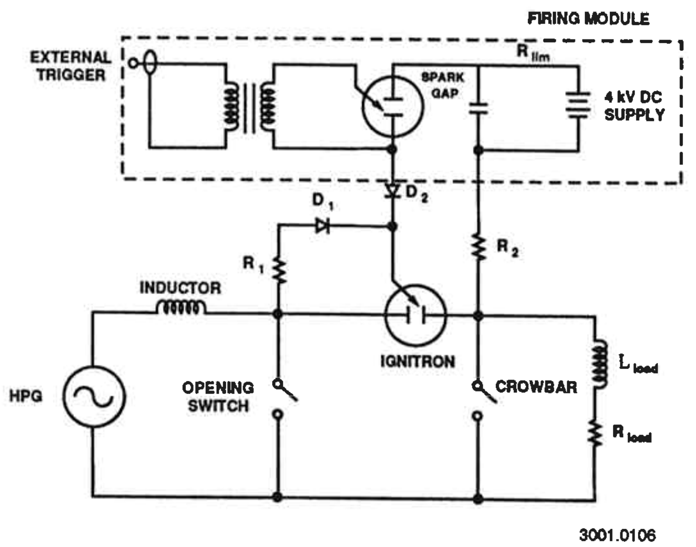

Figure 8. "Trigger" schematic for 60-MJ system

A four stage discharge was made in September 1986 using three pairs of ignitrons. Currents transferred through the three stages were 144, 197 and 232 kA. The current trace for that discharge is shown in figure 9.

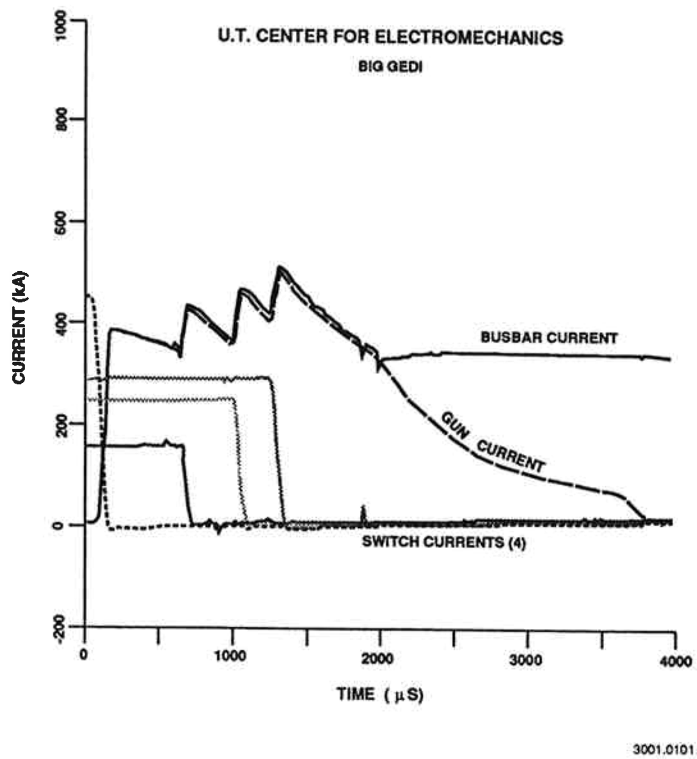

Figure 9. Current traces from four stage HPG/inductor discharge using ignitron isolation switches

In June 1988, a pair of ignitrons transferred 720 kA (360 kA per tube) to a railgun during a single inductor discharge. At the end of the railgun event, explosive crowbars were closed in order to shunt excess energy from the gun and to reduce circuit voltage. The ignitrons carried coulombs far in excess of their rating. Post-shot inspection revealed broken glass insulators, arc burns on the inner tube wall adjacent to the bottom edge of the anode, and extensive arc burns on the header cup above the anode. The flexible inner coax conductor of the buswork permitted downward movement of the anode assembly which galvanically contacted the header cup. One of the ignitrons was welded together at this area by the current occurring after glass failure. It is unknown what mechanism caused the glass failure, although it is suspected that at late times in the shot the ignitron arc may have anchored between conductors at the top of the tube thereby heating the glass to failure.

A judgement of the failure time was made using the data collected for the current. After crowbarring, the data followed a typical exponential decay up to a point in time when a deviation indicated a decrease in resistance. This was considered the failure point. Current duty per ignitron was determined:

$$\int i\,dt = 1240 \text{ Coulombs}$$

$$\int i^2\,dt = 4.5 \times 10^8 \text{ A}^2\text{s}$$

Despite the failure at this level, ignitrons are the preferred choice over explosive isolation switches in the 60 MJ system during certain low level tests. Advantages are the ability to passively trigger the devices on an opening switch voltage rise and the more rapid and accurate switching time compared to explosive switches.

Conclusions

The high-current, high-coulomb operation of ignitrons used as isolation switches for an HPG/inductor power supply has been examined. Characterization of the ignitron circuit impedance was determined. Successful parallel operation of the tubes was demonstrated. Failure testing of a size "E" ignitron was completed. Reliable trigger mechanisms for triggering the ignitrons both passively and actively have been demonstrated. Successful use of ignitron isolation switches in a 60 MJ power supply has been achieved.

Acknowledgments

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References

1. Anton Shulski, private communication.

2. R. Kihara, "Evaluation of Commercially Available Ignitrons a High-Current High-Coulomb Transfer Switches", 6th IEEE Pulsed Power Conference, Arlington, VA, June 29-July 1, 1987.