HIGH PEAK CURRENT BURST REPETITIVE OPERATION OF A 125MM THYRISTOR

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Abstract

Repetitive operation of symmetric 125-mm thyristors has been demonstrated under burst conditions consistent with some electric gun applications. The thyristor was produced by Silicon Power Corp. and utilizes a unique compact package that provides for double-sided cooling with a thermal resistance from junction to sink of 0.0033 K/W. Single shot testing[1] was performed using a 10-mΩ pulse-forming network with a total capacitance of 21 mF into a matched load to determine operational limits. Computer simulations of the temporal behavior of the device using actual current pulse shapes were consistent with the experimental results. The device operated in a satisfactory manner at 120 kA peak current. Repetition rate testing was performed under burst conditions with large voltage reversals at the end of the pulse. A 26-mΩ PFN with total capacitance of 14 mF charged to 3 kV with a stored energy of 63 kJ was initially operated into a mismatched load of 13 mΩ. This provided a peak forward current of 75 kA and transferred charge of 45.4 C and a peak reverse current of 2.5 kA and 0.029 C residual charge. At the end of the pulse a negative voltage spike of -1.8 kV of 12 μs duration was generated with -0.86 kV remaining on the network. Since no deleterious effects were observed, all additional tests were performed with a shorted load. The pulse amplitude was 111 kA (64.5 C) with a di/dt of 800 A/μs. At the end of the pulse, a negative pulse of -4.2 kV of 13 μs duration was generated with -2.3 kV remaining on the network. A peak reverse current of -5.5 kA (0.049 C) with a di/dt of -600 A/μs and 21 μs duration was observed. Pulse bursts were generated at 6 pulses per minute (PPM) for 10 pulses, and at 12 PPM for 5 pulses. Recovery characteristics were typical of normal recovery, with no evidence of heating effects. No deleterious effects were observed. Failure occurred at a forward current di/dt of 1062 A/μs and a reverse current di/dt of 812 A/μs. A device design with involute gate structure has been developed and reliable operation with di/dt's in excess of 1 kA/μs and higher current levels is anticipated.

Introduction

Electric guns require switch arrays capable of conducting millisecond current pulses in the 100's of kiloamperes to megamperes while firing bursts of several shots per minute. The situation is complicated by the need for a compact, lightweight package. This is because the electric gun systems will be mounted on combat vehicles where space is at a premium and weight must be minimized. Conventional thyristor designs are heavy and bulky. Silicon Power

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14. ABSTRACT
Repetitive operation of symmetric 125-mm thyristors has been demonstrated under burst conditions consistent with some electric gun applications. The thyristor was produced by Silicon Power Corp. and utilizes a unique compact package that provides for double-sided cooling with a thermal resistance from junction to sink of 0.0033 K/W. Single shot testingl was performed using a 10-mf2 pulse-forming network with a total capacitance of 21 mF into a matched load to determine operational limits. Computer simulations of the temporal behavior of the device using actual current pulse shapes were consistent with the experimental results. The device operated in a satisfactory manner at 120 kA peak current. Repetition rate testing was performed under burst conditions with large voltage reversals at the end of the pulse. A 26-mC! PFN with total capacitance of 14 mF charged to 3 kV with a stored energy of 63 kJ was initially operated into a mismatched load of 13 mfl This provided a peak fonvard current of 75 kA and transferred charge of 45.4 C and a peak reverse current of 2.5 kA and 0.029 C residual charge. At

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Corp., of Malvern, PA, is developing a 125-mm die diameter thyristor that has the potential of meeting the 200-kA pulse current requirement in a compact lightweight package.

Figure 1 shows the new 125-mm thyristor next to a conventional presspack 100-mm thyristor. The features of the SPCO design are seen in the cross-sectional drawing in Figure 2.

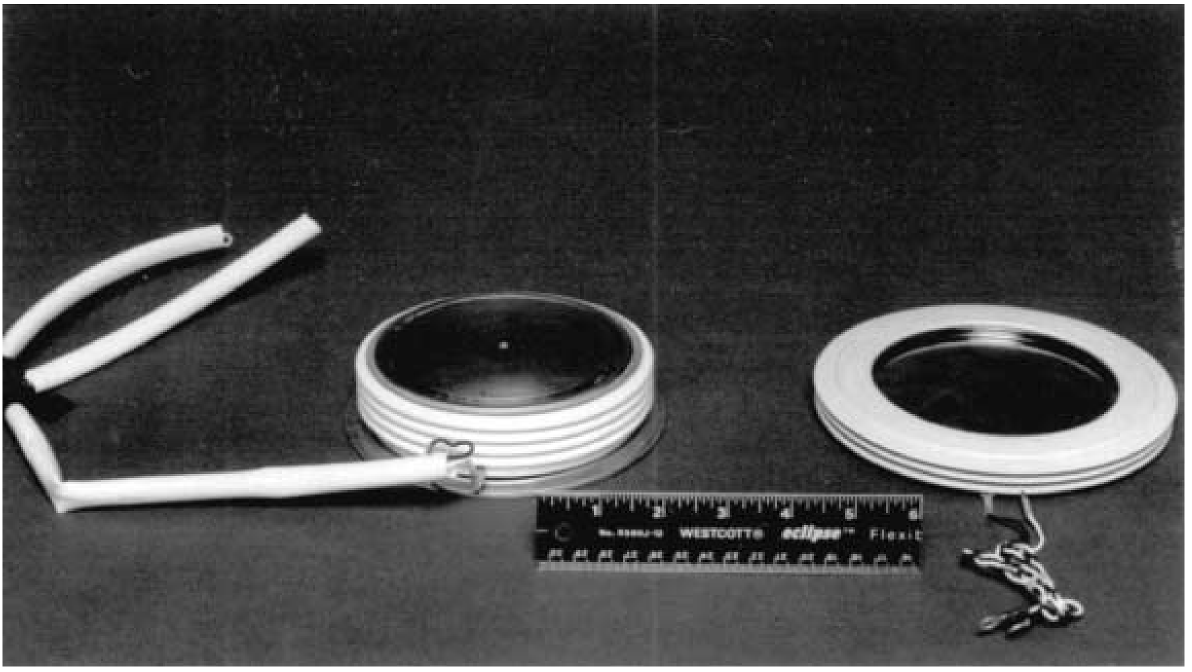

Figure 1 . Photograph of 125-mm device (right), compared with conventional 100-mm device (left).

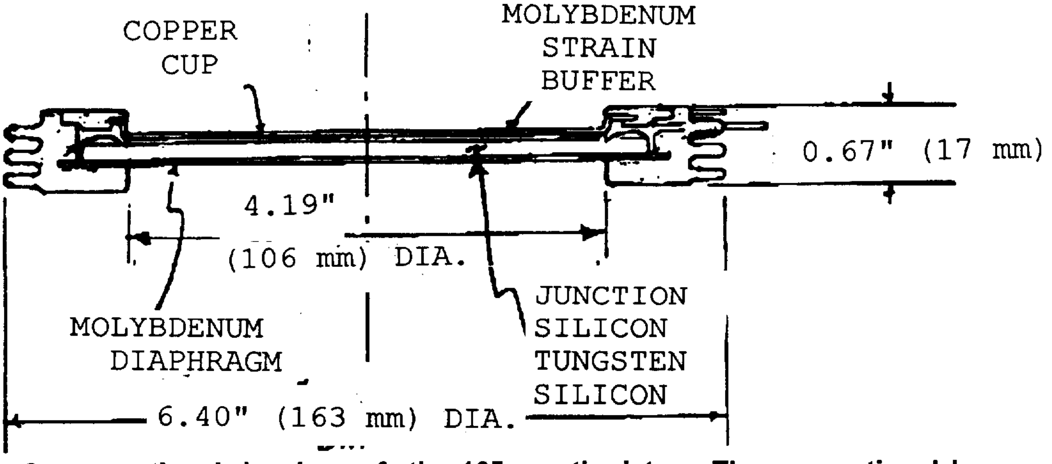

Figure 2. Cross-sectional drawing of the 125-mm thyristor. The conventional heavy, bulky refractory metal pole pieces have been eliminated and the insulator is plastic, instead of ceramic. The junction assembly consists of a bonded assembly of 1.0-mm silicon, 0.4-mm tungsten, and 1.0-mm silicon.

The difference in thickness is due to the absence of large, heavy, refractory metal pole pieces. Expensive refractory metals are used to match the coefficient of linear expansion with that of the silicon wafer. This adds considerable weight and size to conventional devices of this type. The insulator in the 125-mm device is not ceramic but plastic, resulting in further weight and cost savings. For a 6-kV blocking voltage rating, the separation between the external anode and cathode surfaces in a conventional presspack is 38 mm, versus 4.7 mm in the new design. The flange diameter of the 100-mm thyristor is 142 mm, versus 163 mm for the plastic insulator diameter of the 125-mm thyristor.

The enabling technology for this radical design is the junction assembly. The active silicon wafer is 1 mm thick and is bonded to a 0.4 mm thick tungsten wafer. A second layer of silicon of comparable thickness is bonded to the other side of the tungsten to cancel any bowing. The structure is bonded using an aluminum-silicon vacuum alloy process. The design enables highly efficient cooling, with a thermal resistance of 0.0033 K/W and the ability to cool from both sides. The net effect of the design is to reduce the volume to 3.54×10^{-4} m^3, one-fifth that of a conventional thyristor of equal die diameter.

The thyristor is designed with the standard six-star gate and amplifier for phase control applications. For the purpose of this study, the *amplifier was shorted* to permit the use of increased drive currents.

Experimental Testbed

The 125-mm thyristor was initially tested on the 21-mF pulser shown schematically in Figure 3 and photographically in Figure 4. The pulser consists of three 7-mF pulse-forming networks in parallel and a common load. Each PFN is a five-section E-type and can be configured for 30 to 52 mΩ per line by changing the taps on the inductor. For the single-shot tests, the three networks were each configured for 30 mΩ per line and operated in parallel. End-of-line clippers were included on each line, to prevent voltage reversals on the PFNs by matching their resistance to the line. The load is constructed of disk type resistors and was set to 10 mΩ. With this configuration, the pulsewidth is 0.5 ms FWHM, 0.85 ms at the base, and at 4 kV the peak current amplitude is 200 kA. The waveforms are monitored with a Tektronix high-voltage P6015A probe, a Pearson 2093 current transformer for the pulser current, a Pearson 410 current transformer for gate current and a 60 V biased diode arrangement for voltage drop measurements. The data is recorded on a Tektronix DSA 602A digitizing signal analyzer. For repetition rate tests, two PFNs were configured in parallel, providing an impedance of 26 mΩ into either a negatively mismatched load of 13 mΩ or a short.

Single Shot Operation

The results of our experimental measurements of the operation of the 125-mm device in single-shot mode have been previously reported.[1] The thyristor operated successfully at peak currents up to 119 kA. Several thyristors failed at peak currents of 142 to 146 kA. Computer simulation at this current level indicated a junction temperature excursion of 363 K had occurred. The device was opened and examined, and showed melting and a fracture as a result of the large thermal excursion. The large thermal excursion is the result of high commutation dissipation caused by an inadequate gate area for this type of application. The six-star gate has recently been replaced by an involute gate design to increase the rate of plasma formation and horizontal spreading and will be evaluated at peak currents up to 200 kA.

Repetitive Rate Operation

Repetitive operation has been demonstrated under burst conditions. Testing was performed using two PFNs in parallel, providing a network impedance of 26 mΩ. The PFNs

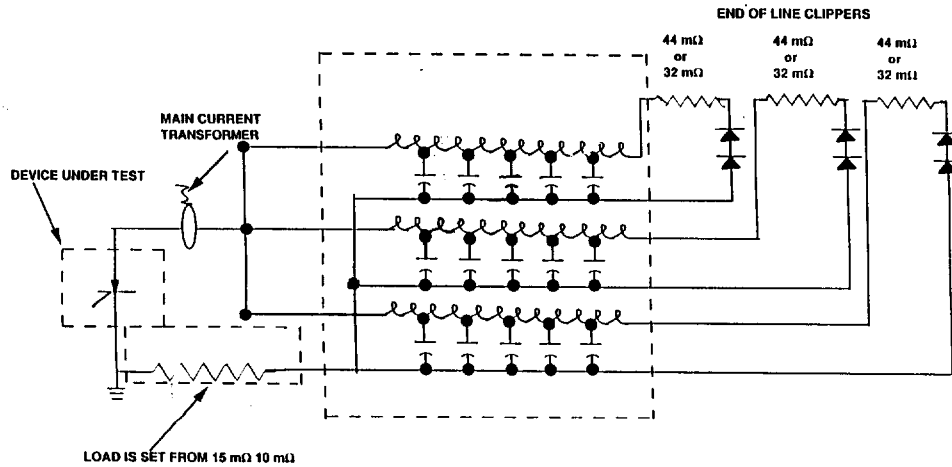

Figure 3. Schematic of 125-mm testbed pulser. The pulser consists of three E-type lines, each with an optional matched end of line clipper to prevent reversals. The impedances of each line and each clipper are adjustable.

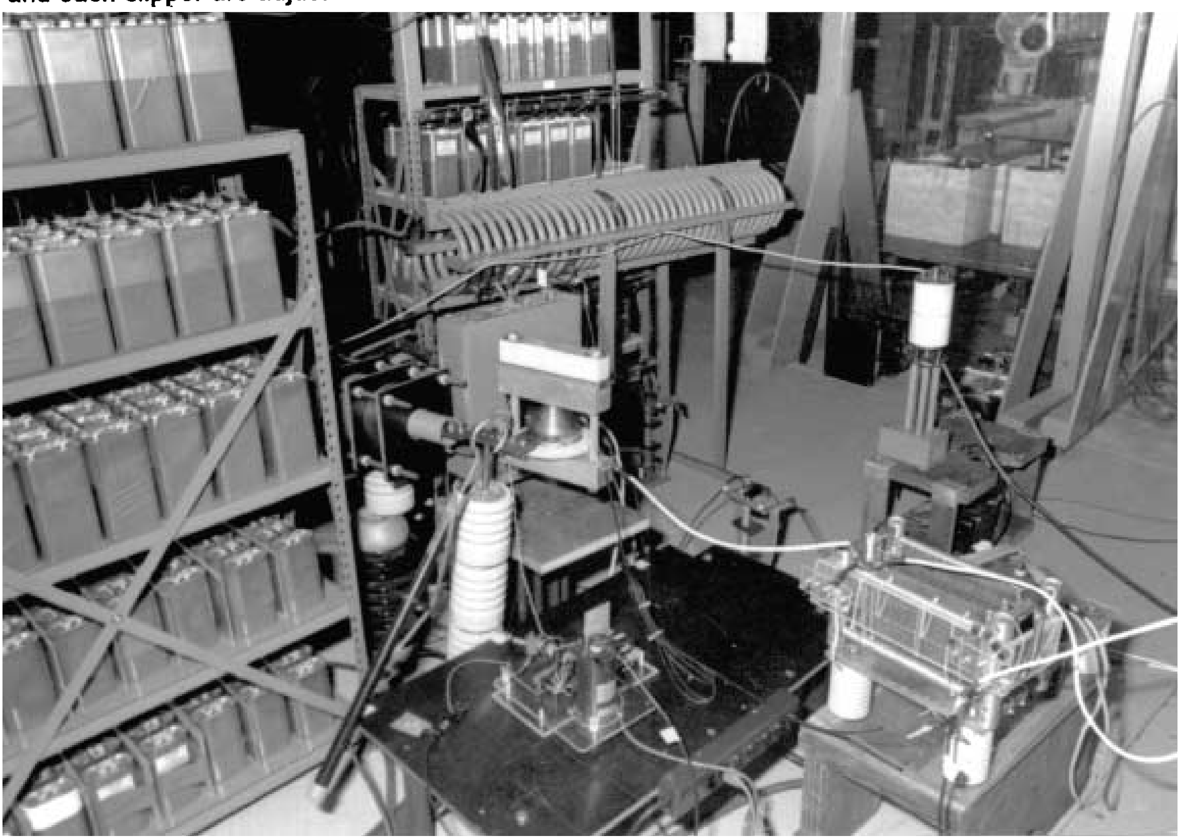

Figure 4. Photograph of testbed, with 125-mm device at center, two PFN lines, driver in foreground and voltage drop measurement arrangement at lower right.

were discharged into either a negative mismatched load of 13 mΩ or a short. No end-of-line clippers were used. The PFNs were resistively charged through a 20-Ω dilute copper sulfate solution resistor and a hold-off diode to protect the power supply from the voltage reversals. At 3 kV (Figure 5) into a 13-mΩ load, the rectangular current pulse had an amplitude of 75 kA with a half-width of 0.63 ms, a base-width of 0.78 ms, a 10-90% risetime of 0.13 ms (di/dt = 473

A/µs) and a 10-90% falltime of 0.18 ms. The energy stored on the PFN was 63 kJ, and the charge per pulse was 45.4 C. At the end of the pulse a negative voltage spike of -1.8 kV of 12 µs duration was generated, with -0.86 kV remaining on the network. An out-of-phase reverse current of 21 µs duration preceded the voltage spike, peaked at -2.5 kA, and terminated during the voltage spike. The total charge in the reverse current pulse was 0.029 C. A burst of 10 pulses was generated at a rep-rate of 6 pulses per minute, followed by an eleventh pulse 30 seconds later to discharge the PFN. A total of 0.5 kC was switched, and no deleterious effects were observed on the thyristor. Further testing was conducted, under more severe conditions with a shorted load, at a peak current of 111 kA and a forward voltage of 3.0 kV. The pulse characteristics are shown in Figure 6. Reverse voltages generated consisted of a -4.16 kV voltage spike of 13 µs duration, followed by -2.3 kV residual on the PFN. A -5.5 kA (-600 A/µs) triangular shape reverse current of 20 µs duration was observed. The total charge in the reverse current pulse was 0.049 C. The recovery di/dt is 750 A/µs . Figure 7 shows a plot of the di/dt

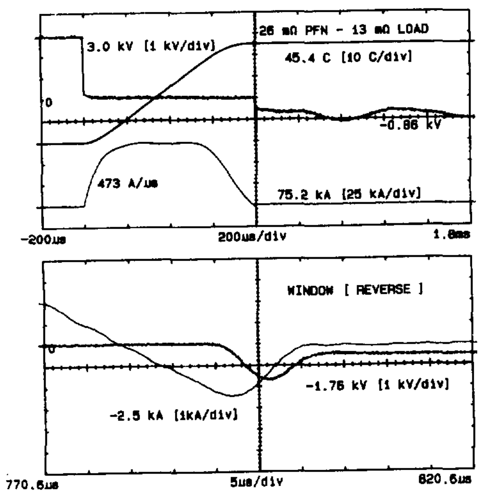

Figure 5. A single pulse during rep rate operation at 3 kV with a PFN impedance of 26 mΩ and a load impedance of 13 mΩ. The upper set of current, voltage, and charge waveforms show the pulse characteristics and charge transfer at a sweep speed of 200 µs/div. The lower set shows the reverse current and voltage waveforms at a sweep speed of 5 µs/div.

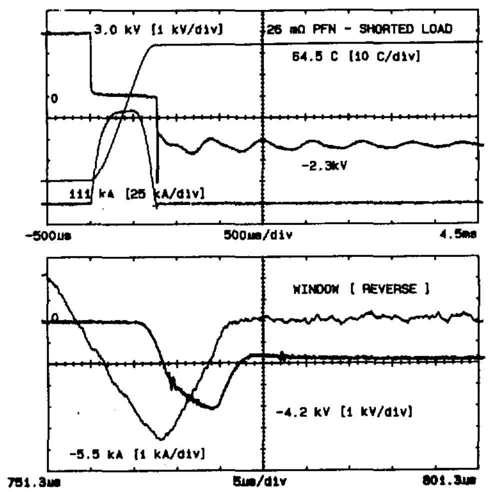

Figure 6. A single pulse during rep rate operation at 3 kV with a PFN impedance of 26 mΩ and a shorted load. The upper set of current, voltage, and charge waveforms show pulse characteristics and charge transfer at a sweep speed of 500 µs/div. The lower set shows reverse current and voltage at sweep speed of 5 µs/div. Reverse di/dt is -600 A/µs, recovery di/dt -750 A/µs.

during the pulse. Since the curve has been smoothed to remove some noise, the peak positive and negative di/dt values shown are 4% lower than the measured value. The actual rate of rise of current is 800 A/µs, and the rate of fall of current is 600 A/µs. A computer simulation of the behavior of the thyristor under these conditions was performed in order to determine the junction temperature change (Δt_j) during both the forward and reverse current flow through the thyristor. Figure 8 shows the results. With this particular gate structure, half of the Δt_j occurs in the first 100 µs of the pulse. At the end of the forward current, Δt_j is 92 K. Another 5 K temperature rise occurred during the recovery current, for a total Δt_j of 97 K. Since the current conductors connected to the thyristor are 1/4 in. (6 mm) thick by 2 in. (50 mm) wide

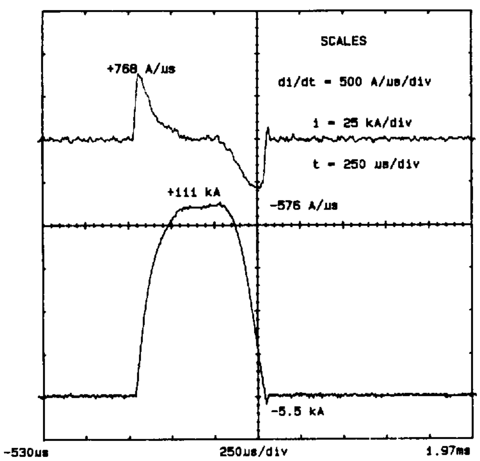

Figure 7. Smoothed plot of di/dt of the current pulse under shorted conditions. Measured peak values are 4% higher; 800 A/µs and -600 A/µs.

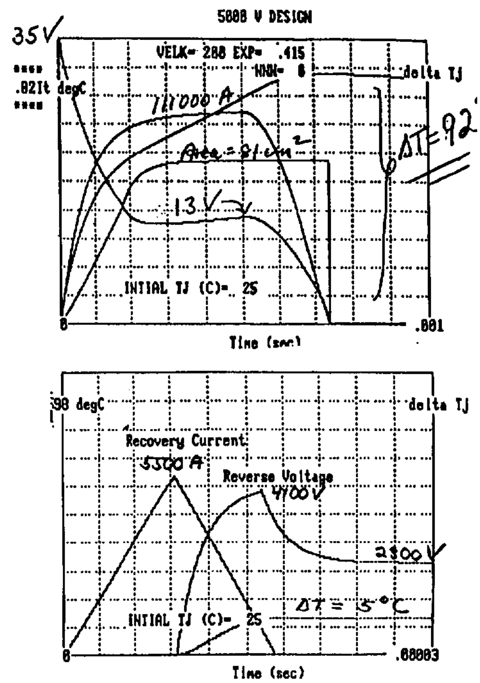

Figure 8. Computer simulation of operation at 3 kV with a peak current of 110 kA to determine junction temperature rise (Δt_j). The upper waveforms show forward current (15 kA/div), voltage drop (3.5 V/div), plasma spread (14 cm^2/div), and Δt_j (10.5 K/div). The time scale is 100 µs/div. The lower waveforms show the reverse current (875 A/div), reverse voltage (700 A/div), and Δt_j (3.75 K/div). The timescale is 3 µs/div.

copper busbars, the thyristor has more than adequate heat sinking for burst operation. Tests were conducted at a) ten shots at 6 pulses per minute (PPM) at a peak current of 111 kA and b) 5 shots at 12 PPM at a peak current of 109 kA. At 12 PPM the recharge time constant was not quite adequate to reach full voltage. The charging voltage is shown in Figure 9. The reverse voltage spikes do not appear because of the slow sweep speed and sampling rate of the oscilloscope. One test of a significant pulse to pulse temperature rise is to check for any significant changes in the reverse change in the reverse current and voltage behavior. Figure 10 shows this behavior for a 10 shot 6 PPM burst. The first, third, seventh, and tenth reverse current and voltage waveforms are superimposed. No significant changes were observed. After

150 shots, of which one-third were at 110 kA, leakage tests were performed on the thyristor. The results are shown in Table I. The device exhibited no significant increase in leakage with either forward or reverse voltage.

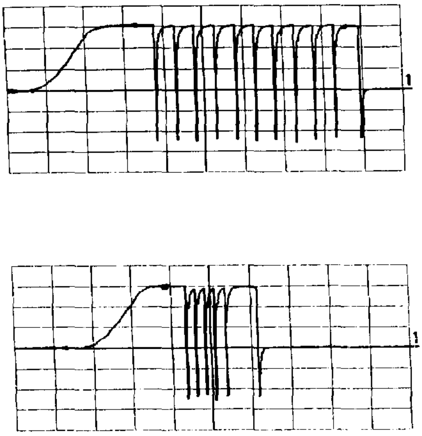

Figure 9. The charging waveforms under the repetitive pulse operation shown in Figure 6, at a pulse repetition rate of 6 PPM (upper) and 12 PPM (lower). The sweep speed is 20 s/div, and the voltage scale is 1 kV/div.

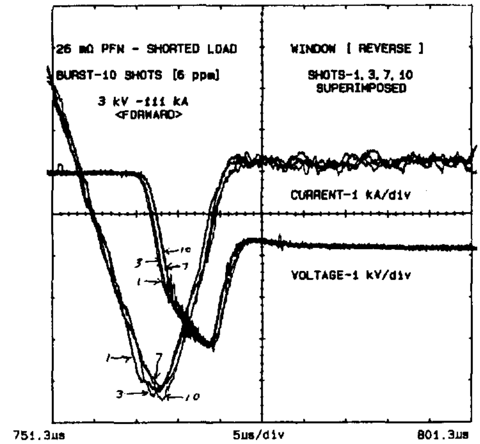

Figure 10. Reverse current and voltage waveforms during operation at 6 PPM. The first, third, seventh, and tenth waveforms are superimposed. No significant changes occurred.

Table I

LEAKAGE TESTS AFTER 150 SHOTS WITH ONE-THIRD AT 110 KA

Forward Voltage (kV)	1	2	3	4	5
Leakage Current (μA)	25	60	410	2300	4500
Reverse Voltage (kV)	1	2	3	4	5
Leakage Current (μA)	10	35	75	140	1900

After leakage tests, tests were resumed on the device. On the seventh run, at 12 PPM, the device failed on the third pulse. This is shown in Figure 11. An analysis of the first current pulse of the run indicated a change in pulse conditions. The pulse current, the di/dt rise of the forward current, and the di/dt of the reverse current had risen to 114 kA, 1062 A/μs, and 812 A/μs, respectively. The peak forward current had risen only 2.7%, but the di/dt of the forward current had risen 33%, while the di/dt of the reverse current had risen 35%. This caused an eventual di/dt failure. Temporal behavior of the current and the di/dt are shown in Figure 12. An examination of the pulser showed the reason for the large change in the di/dt's. The first section of the inductor on one of the networks, because of high action, had deformed and compressed, shorting out the inductance in the first section of the PFN, thus increasing the di/dt by 33%. Further testing was temporarily suspended pending completion of a move of the laboratory facility from Fort Monmouth, NJ, to Adelphi, MD.

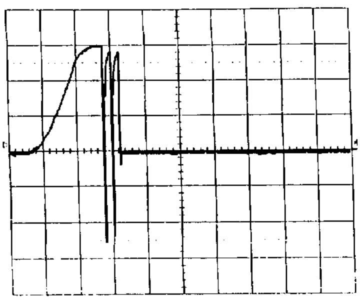

Figure 11. Failure of thyristor on third pulse at 12 PPM as a result of di/dt increase to 1062 A/µs on forward current and to -812 A/µs on reverse current. Voltage scale is 1 kV/div and sweep speed is 20 s/div.

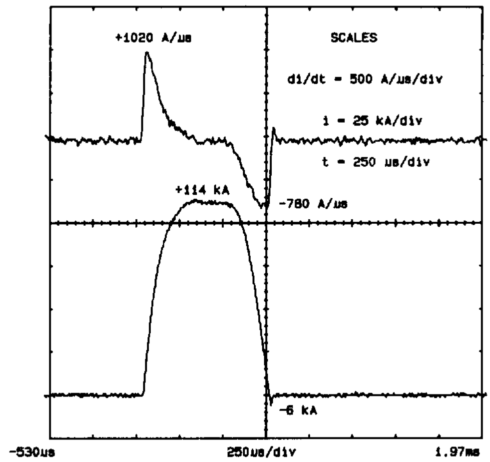

Figure 12. Temporal behavior of current and di/dt for first pulse shown in Figure 11. The di/dt values are 4% lower because of curve smoothing. The actual values are 1062 A/µs and 812 A/µs.

The thyristor was opened and examined, and showed melting and a large crater as a result of high commutation dissipation caused by high di/dt. The failure occurred at one of the gate tips. A photograph of the cathode of this thyristor is shown in Figure 13.

Conclusions

SPCO has successfully developed a new mechanical design for building a symmetrical 125-mm thyristor that reduces volume and weight to one-fifth of a conventional presspack design. The initial devices were constructed with the six-star gate design normally used for phase control applications. The high current pulse performance of these devices was evaluated with a rectangular pulse with a 0.6 ms pulse width (FWHM). Experimental peak current operation and limitations experimentally determined were in agreement with computer simulations. Burst rep rate operation at 3 kV, 111 kA, a forward current di/dt of 800 A/µs, and a reverse current di/dt of 600 A/µs with a shorted load and full voltage reversal was demonstrated at 6 pulses per minute for 10 pulses and at 12 pulses per minute for 5 pulses. The thyristor exhibited normal recovery characteristics with no observed deleterious effects. At a forward current di/dt of 1062 A/µs and a reverse current di/dt of 852 A/µs, the thyristor failed. The six-star gate design provided an inadequate rate of plasma expansion for high di/dt (1000 A/µs) applications. A computer simulation with an appropriately scaled involute gate design, shown in Figure 14, that had been used successfully in a prior investigation on 100-mm thyristors showed that reliable operation at high currents and di/dt's can be expected. The rate of conducting area

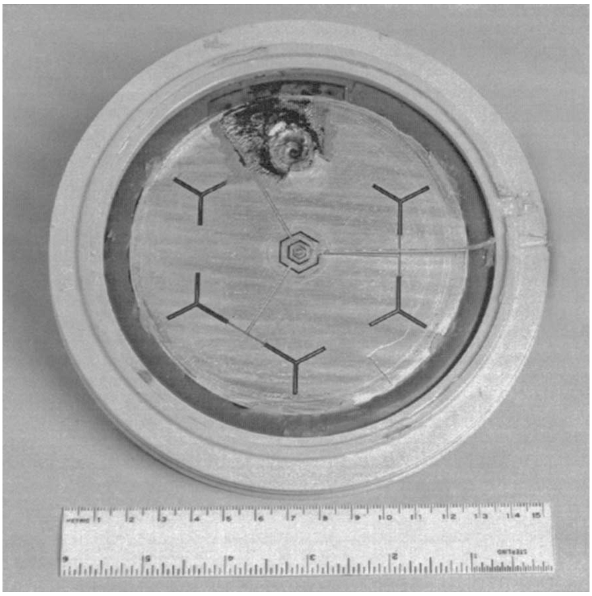

Figure 13. Photograph of cathode of thyristor, after di/dt failure.

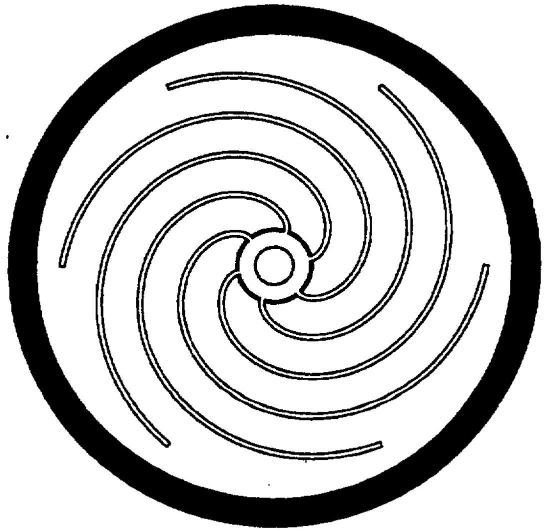

Figure 14. Involute gate pattern.

expansion is increased by a factor of three. Further studies will be performed with the new gate design.

Acknowledgment

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Reference

1. T. F. Podlesak, H. Singh, S. Behr, S. Schneider, "A Compact Lightweight 125mm Thyristor for Pulse Power Applications," *Proceedings of the Twenty-Second International Power Modulator Symposium,* Boca Raton, FL, June 1996, pp. 43-46.