

# SINGLE SHOT AND BURST REPETITIVE OPERATION OF INVOLUTE GATE 125MM SYMMETRIC THYRISTORS UP TO 221 KA WITH A DI/DT OF 2.0 KA/US\*

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## Abstract

Previously [1], we reported on the operation and limitations of a six-point star gate design 125mm thyristor. An involute gate design has been developed that provides a significant increase in ability to handle higher peak currents and  $di/dt$ 's. For this study we selected a 2.5 kV symmetric version of the device. The test facility uses a 10 m $\Omega$  PFN with a rectangular pulse width (FWHM) of 465  $\mu$ s. All tests were performed with an essentially shorted load in order to achieve 200 kA operation and to instantaneously apply a full voltage reversal in less than 3  $\mu$ s at the end of the current pulse. Reliable operation was demonstrated at 2.6 kV forward voltage with a reverse voltage of 2.3 kV. The peak current was 203 kA with a  $di/dt$  of 1.8 kA/ $\mu$ s. The charge was 82 C and the action was 13.8 MA<sup>2</sup>s. The reverse charge was 0.19 C. The PFN was modified to reduce the impedance and simulate a sinusoidal pulse in excess of 1 kHz. Reliable operation was obtained at 221 kA with a  $di/dt$  at 2.0 kA/ $\mu$ s. The pulse width (FWHM) was 301  $\mu$ s with a base width of 455  $\mu$ s. Forward voltage was 2.4 kV with a reverse voltage of 2.3 kV. The forward charge, reverse charge and action were 63 C, 0.51 C and 10.9 MA<sup>2</sup>s respectively. Reliable repetitive operation was performed at 151 kA with a burst of 10 pulses and a 20 second interval between pulses. No temperature effects were observed.

## I. INTRODUCTION

SPCO has developed a new gate design for their 125mm thyristor. The new device uses an involute gate

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\*Supported in part by the Institute for Advanced Technology

with three internal leads to permit an increase in gate drive current. The design change provides the potential of significantly enhanced  $di/dt$  and peak current capabilities. For high-current applications, thinner, lower voltage devices are desirable to obtain shorter plasma spreading times and lower voltage drops, and hence lower power dissipation during the pulse. In addition, thinner devices have a lower thermal impedance. We selected a 2.5 kV symmetric device was selected for this study. The study was performed using a 10 m $\Omega$  pulse-forming network (PFN) with the load shorted. This demonstrated operation at a peak current in excess of 200 kA, followed by full voltage reversal in less than 3  $\mu$ s.

## II. SHORTED LOAD EXPERIMENT

The experiment was performed with the same PFN used to evaluate a previous 5.0 kV design[1]. The PFN impedance ( $Z_N$ ) was 10 m $\Omega$  and the pulse width was 0.5 ms (FWHM). The capacitance was 21 mF. Because the devices are symmetrical, it was decided to operate with a shorted load and the end-of-line clippers were disconnected. The reflected wave from the short instantaneously applied a fast-rising reverse voltage at the end of the pulse. In addition to shorting the load, the inductance of the first section was bypassed in order to improve the current rate of rise, which is a function of  $L/R$  of the circuit. The resistance and the inductance of the leads, connections and components effectively provided a load resistance ( $R_L$ ) of 1.45 m $\Omega$  and a loop inductance of 1  $\mu$ H. The steady-state reverse voltage ( $V_{RRM}$ ) is calculated as follows:

$$V_{RRM} = V_{DRM}(R_L - Z_N)/(R_L + Z_N) \quad (1)$$

where  $V_{DRM}$  is the forward potential.

## Report Documentation Page

*Form Approved*  
OMB No. 0704-0188

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1. REPORT DATE <b>JUN 1999</b>	2. REPORT TYPE <b>N/A</b>	3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>Single Shot And Burst Repetitive Operation Of Involute Gate 125mm Symmetric Thyristors Up To 221 Ka With A Di/Dt Of 2.0 Ka/Us</b>		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>U.S. Army Research Laboratory ATTN: AMSRL-SE-DP 2800 Powder Mill Road Adelphi, MD 20783-I 197</b>		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>			
13. SUPPLEMENTARY NOTES <b>See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.</b>			
14. ABSTRACT <b>Previously [1], we reported on the operation and limitations of a six-point star gate design 125mm thyristor. An involute gate design has been developed that provides a significant increase in ability to handle higher peak currents and di/dts. For this study we selected a 2.5 kV symmetric version of the device. The test facility uses a 10 n&amp;J PFN with a rectangular pulse width (FWHM) of 465 nJ. All tests were performed with an essentially shorted load in order to achieve 200 kA operation and to instantaneously apply a 111 voltage reversal in less than 3 ns at the end of the current pulse. Reliable operation was demonstrated at 2.6 kV forward voltage with a reverse voltage of 2.3 kV. The peak current was 203 kA with a di/dt of 1.8 kA/ns. The charge was 82 nC and the action was 13.8 nA*s. The reverse charge was 0.19 nC. The PFN was modified to reduce the impedance and simulate a sinusoidal pulse in excess of 1 MHz. Reliable operation was obtained at 221 kA with a di/dt at 2.0 kA/ns. The pulse width (FWHM) was 301 ns with a base width of 455 ns. Forward voltage was 2.4 kV with a reverse voltage of 2.3 kV. The forward charge, reverse charge and action were 63 nC, 0.51 nC and 10.9 nA*s respectively. Reliable repetitive operation was performed at 15 kA with a burst of 10 pulses and a 20 second interval between pulses. No temperature effects were observed.</b>			
15. SUBJECT TERMS			
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>	<b>SAR</b>
			18. NUMBER OF PAGES <b>4</b>
			19a. NAME OF RESPONSIBLE PERSON



Therefore,  $V_{RRM}$  is equal to  $-0.75 V_{DRM}$ .

Current flowing in the reverse direction immediately following the end of the current pulse significantly modifies the reverse voltage. The reverse voltage immediately after the end of the pulse will exhibit a sharp spike. This spike is a function of the circuit inductance and the rate of turn-off of the reverse current generated by the stored charge. The reverse voltage spike component generated by opening the switch is added to the normal reverse voltage. Based on measurements made at a forward voltage of 780 V, we estimated that at 2.5 kV, the peak reverse voltage would be twice the reverse voltage rating of 2.5 kV. As a result, a snubber was used for all tests performed over 1.0 kV. The snubber consisted of a  $0.2 \Omega$  resistor in series with either a  $42 \mu F$  or a  $84 \mu F$  capacitance. For higher current operation (221 kA), the PFN was modified to have two sections with a total capacitance of 17 mF.

The gate driver designed for this application is an E\* configuration PFN of five sections with a  $1 \mu F$  mica capacitor in each section. A  $0.5 \Omega$  load resistor was placed in series with the PFN to ensure a positive match. The peak current was 600 A with a risetime of  $0.73 \mu s$  and a pulsewidth (FWHM) of  $5.8 \mu s$ .

### III. EXPERIMENTAL RESULTS

We conducted single-shot testing with both configurations; this testing was limited by the  $V_{DRM}$  rating of the 2.5 kV thyristor. In addition, burst repetition rate testing was conducted at a peak current of 151 kA. Table 1 lists the pulse conditions of the three sets of tests.

#### Case A. 21 mF, Bell-Shaped

Operational tests were conducted in steps of 100 volts up to a forward voltage of 2.4 kV and a peak current of 193 kA. At this level, the peak reverse voltage rose to 2.56 kV. Since we did not want to exceed  $-2.6$  kV, another  $42 \mu F$  capacitor was added to the snubber to give a total capacitance of  $84 \mu F$ . We then raised the voltage to 2.56 kV and a peak current of 203 kA. The peak reverse voltage was  $-2.28$  kV and the steady-state voltage was 1.93 kV. The reverse steady-state voltage is consistent with calculations based on network and load impedance. This pulse was repeated twice and the results were the same. The current pulse under these conditions is bell-shaped. Figures 1 and 2 show the pulse characteristics.

#### Case B. 17 mF, Half-Sinusoid

Operating at 2.56 kV to demonstrate 200 kA peak current is too close to the peak forward voltage capabilities of the thyristor, which has a nominal forward voltage rating of 2.5 kV. Therefore, we modified the PFN configurations to provide a lower PFN impedance and a narrower pulse. The easiest modification was to reconfigure the PFNs from five to two sections with a total capacitance of 17 mF. The first inductor of each PFN was shorted. This type of network provides a half-sinusoidal pulse, which is typical of operation at 1100 Hz.

We operated the thyristor with the new PFN configuration at seven different voltages ranging from 200 V to 2.44 kV, using a snubber circuit with  $84 \mu F$  of capacitance and  $200 m\Omega$  of resistance. At 2.22 kV a

Table 1. Pulse Conditions	Case A	Case B	Case C
Number of PFN Sections	5	2	2
Capacitance	21 mF	17 mF	17 mF
Pulse Shape	Bell	Sinusoidal	Sinusoidal
Forward Voltage	2.56 kV	2.44 kV	1.7 kV
Voltage Falltime (10%-90%)	2.48 $\mu s$	1.49 $\mu s$	1.45 $\mu s$
Reverse Steady State Voltage	-1.93 kV	-1.93 kV	-1.41 kV
Reverse Spike Voltage	-0.35 kV	-0.39 kV	-0.46 kV
Peak Reverse Voltage	-2.28 kV	-2.32 kV	-1.86 kV
Peak Current	203 kA	221 kA	151 kA
Current Risetime (10%-90%)	151 $\mu s$	143 $\mu s$	143 $\mu s$
Maximum di/dt (differential)	1.8 kA/ $\mu s$	2.0 kA/ $\mu s$	1.4 kA/ $\mu s$
Current Faltime (10%-90%)	161 $\mu s$	151 $\mu s$	151 $\mu s$
Pulsewidth (FWHM)	465 $\mu s$	301 $\mu s$	301 $\mu s$
Basewidth	578 $\mu s$	455 $\mu s$	455 $\mu s$
Charge	81.9 C	63 C	42.9 C
Action	13.8 MA <sup>2</sup> s	10.85 MA <sup>2</sup> s	5.1 MA <sup>2</sup> s
Reverse Current (including snubber)	-9.0 kA	-9.0 kA	-7.0 kA
Reverse Charge (including snubber)	194 mC	570 mC	450 mC
Pulse Separation	Single	Single	20 s
Burst Length and Duration			10 pulses, 190 s

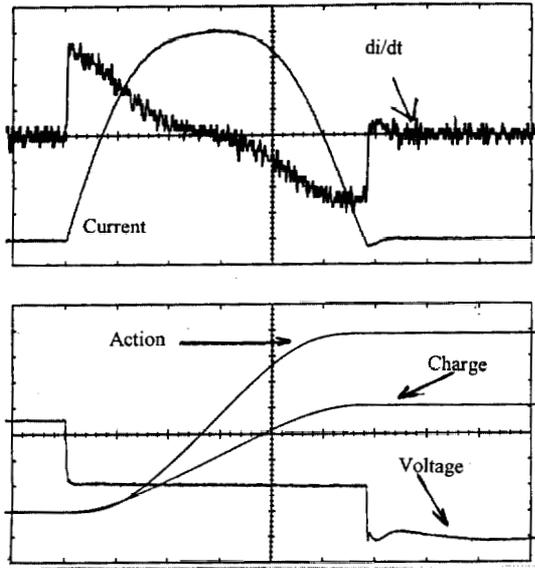


Figure 1. Operation of 2.5 kV 125mm thyristor at 203 kA with a shorted load and a snubber to limit reverse voltage spike. The upper graph shows the peak current and the differentiated current waveform. Scales are 25 kA and 0.5 kA/ $\mu$ s per division, respectively. The lower graph shows the voltage waveform, calculated action and charge. Scales are 0.5 kV, 2 MA<sup>2</sup>s and 20 C per division, respectively. Peak values are +2.56 and -2.28 kV, 13.8 MA<sup>2</sup>s and 81.9 C, respectively. Horizontal scale is 100  $\mu$ s/division.

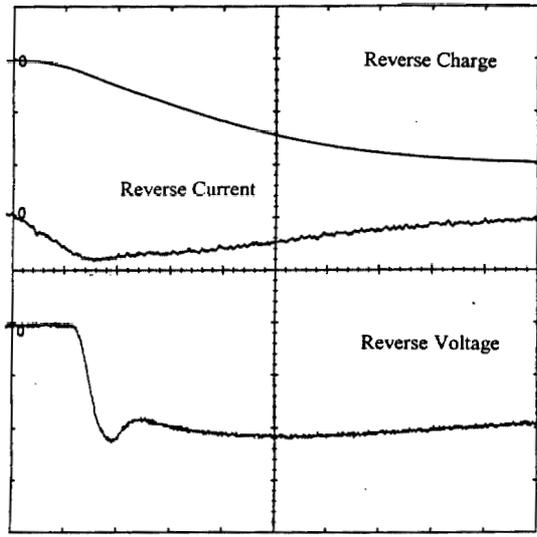


Figure 2. Reverse current, charge and voltage on an expanded scale of 5  $\mu$ s/division, for conditions in Figure 1. Vertical scales are 10 kA, 0.1 C and 1 kV per division, respectively. Peak values are -9.0 kA, -0.194 C and -2.28 kV (levels at -1.93 kV), respectively.

peak current of 203 kA was demonstrated. Since the total transferred charge and action at this current level were now reduced, the device could be operated at a higher current. The voltage was increased to 2.44 kV and the peak current to 221 kA. The thyristor successfully passed this current. The pulse characteristics are shown in Figures 3 and 4.

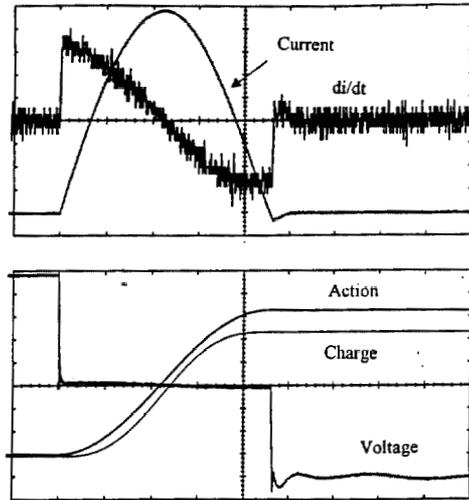


Figure 3. Operation of 2.5 kV 125mm thyristor at 221 kA, 2 kA/ $\mu$ s  $di/dt$ , with a modified PFN into a shorted load and a snubber to limit the reverse voltage spike. The upper graph shows the peak current and the differentiated current waveform. The scales are 25 kA and 0.5 kA/ $\mu$ s per division, respectively. The lower graph shows the voltage waveform, calculated action and charge. The scales are 0.5 kV, 2 MA<sup>2</sup>s and 10 C per division, respectively. Peak values are +2.44 and -2.32 kV, 10.85 MA<sup>2</sup>s and 63 C, respectively. Horizontal scale is 100  $\mu$ s/division.

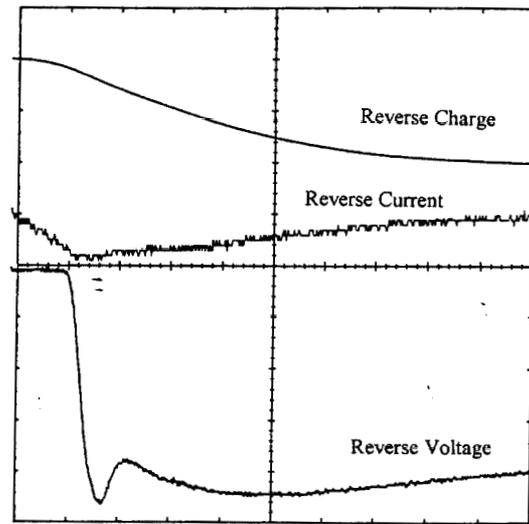


Figure 4. Reverse current, charge and voltage on expanded scale of 5  $\mu$ s/division for conditions shown in Figure 3. The voltage, current and charge scales are 1 kV per division, 10 kA per division and 100 mC per division, respectively.

### Case C. 17 mF, Half-Sinusoidal, Burst

In this series we demonstrated burst operation of 10 pulses with an interval of 20 seconds between pulses. A nominal peak current of 151 kA was chosen for this first test to determine the ability of the thyristor to operate adiabatically. No cooling was applied; the heat sink was the mounting clamp.

Figure 5 shows representative peak voltage and current waveforms. The top graph shows the complete waveform for an individual pulse at 100  $\mu$ s per division sweep speed and the lower graph windows the reverse waveforms at 10  $\mu$ s per division.

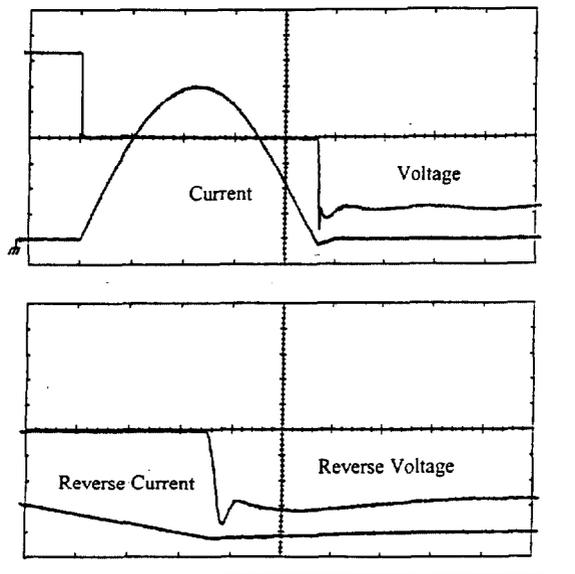


Figure 5. Pulse voltage and current waveforms at 1.68 kV forward voltage, 151 kA peak current under repetition rate operation. The upper graph shows the waveforms at 100  $\mu$ s per division. The lower graph windows the reverse waveforms at 10  $\mu$ s per division. The reverse current is -7.0 kA and the reverse voltage is -1.86 kV. The vertical scales for current and voltage are 25 kA per division and 0.5 kV per division, respectively. Horizontal scale is 10  $\mu$ s per division.

Figure 6 shows the firing of 10 pulses at 20 second intervals. The charging waveform, the voltage reversal and the charging current are recorded. The voltage reversals and the charging current peaks appear unequal from pulse to pulse due to resolving difficulties at a 20 second per division sweep speed of the digital oscilloscope used for these measurements. Data for each individual waveform were recorded. We superimposed the 1<sup>st</sup>, 4<sup>th</sup>, 7<sup>th</sup> and 10<sup>th</sup> pulses and they were essentially identical to those in Figure 5. No deleterious or temperature effects were observed. Further testing under more severe conditions is necessary to establish operating limits.

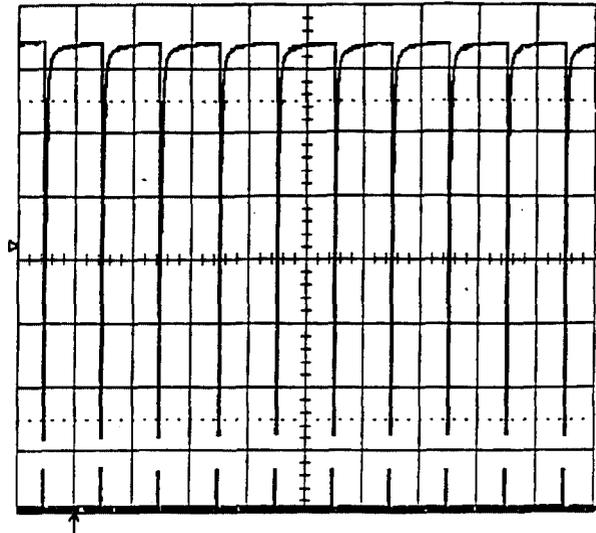


Figure 6. Repetition rate operation of a burst of 10 pulses at 20 s intervals (20 s per division). Charging voltage is the top trace. The vertical voltage scale is 0.5 kV per division. The bottom trace is the positive charging current. The vertical current scale is 100 A per division.

## IV. CONCLUSION

The 2.5 kV involute gate 125mm symmetric thyristor developed by SPCO has been evaluated for pulse power applications. The devices use an increased gate drive of 600 A and 5  $\mu$ s duration. The devices have been used to discharge 21 mF and 17 mF PFNs into a shorted load. Single shot operation up to 221 kA with a current rate of rise of 2.0 kA/ $\mu$ s with an instantaneous voltage reversal of 2.5 kV has been successfully demonstrated. Burst operation of ten pulses at a low repetition rate has also been demonstrated at a peak current of 151 kA. No devices failed under these conditions. Additional testing under more severe conditions is required to determine their reliability and lifetime. A more highly interdigitated thyristor is being developed and is expected to have enhanced capabilities.

## V. ACKNOWLEDGMENT

The authors express their appreciation to Ian McNab, IAT, for his support of this study.

## VI. REFERENCE

- [1] T.F. Podlesak, F. Simon, S. Schneider, "Pulse Operation of Involute Gate 125mm Thyristor," *Proceedings of the 1998 Twenty-third International Power Modulator Symposium*, Rancho Mirage, CA, June 1998, pp. 127-130.