

AN EVALUATION OF NONLINEAR RESISTORS
FOR PULSE POWER SWITCHING
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Introduction

Inductive storage power supplies are capable of providing high pulse power with relatively low weight, except that the energy transfer to a load circuit in such a system requires the opening of the initial current storage circuit. The switch required for this has to be able to interrupt a substantial current, as well as permit a rapid build-up of a high voltage across its opened terminals.

Conventional switches that rely on the separation of two connecting members develop extremely high localized fields during opening.¹ These can ionize gas molecules or create a plasma from dislodged and ionized electrode material. In a plasma, the current carriers have to be removed or neutralized before its resistance goes up, and the time required to do this limits the rate of voltage build up or recovery. The resistivity of a solid on the other hand can be modulated by changes in effective carrier mobility as well as by the carrier concentration.

A nonlinear resistor can change its resistivity in response to an external stimulus.² Resistors that are sensitive to temperature are used here; specifically positive temperature coefficient resistors can exhibit increases in resistance over 3 orders of magnitude when their temperature exceeds a critical value.

These are particularly attractive since the application of a current can be used to raise their temperature relatively uniformly throughout their bulk. This internal (joule) heating does not require the relatively slow flow of heat; the rate of temperature increase is determined only by the power supplied per unit mass. Relatively fast switching speeds can therefore be attained. This is not the case for negative temperature coefficient

resistors that, for switching into the off state, require cooling by slower heat conduction.

The implementation of successful PTC resistors has so far been most successful in dual phase materials. Figure 1 shows the small signal resistivities of conductive polycrystalline Barium Titanate and of a carbon filled polymer switch material as they depend upon temperature.

Judicious processing of "N" doped Barium Titanate ceramic results in acceptor states in the grain boundaries, that then provide a network of high resistance barriers to current flow.³ Below 125° C, barium titanate is in a ferroelectric state that causes charges to appear on many of the grain surfaces. These charges "short circuit" the grain boundary barrier. The 125°C phase transition of Barium Titanate causes the ferroelectricity as well as these charges to disappear and, as a result, the resistivity increase shown in Fig. 1 is attained.

The carbon particles embedded in the polymer based switch make good electrical contact at room temperature.⁴ At about 100° C, the polymer has a phase transition that causes it to expand by about 4%. The resulting separation between the carbon particles causes the effective resistance of the composite to increase significantly.

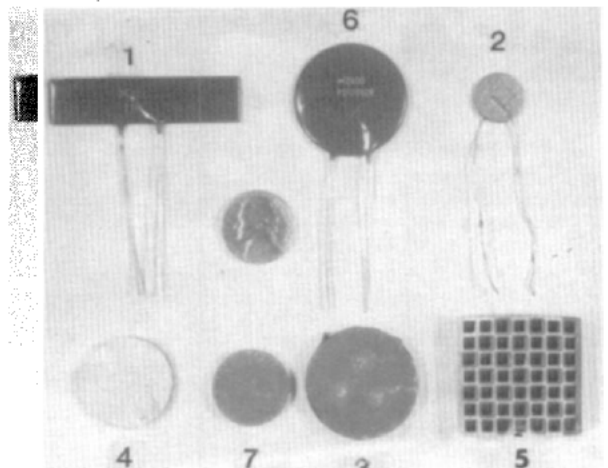
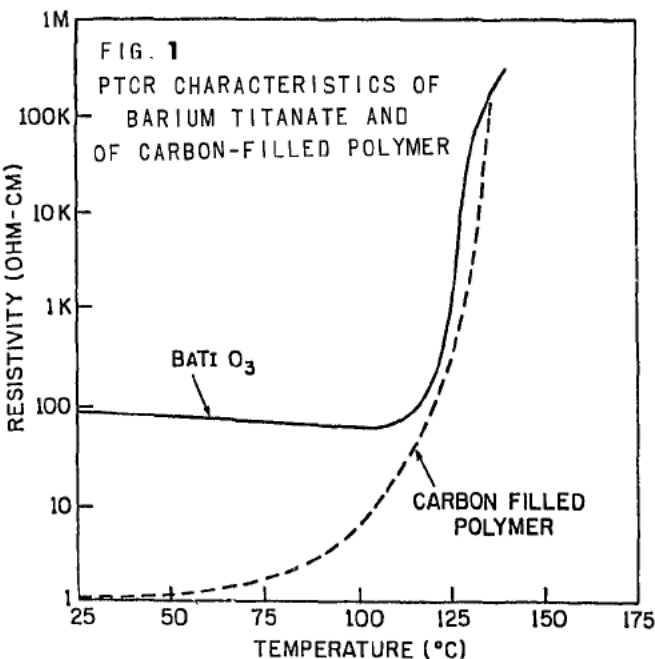


Figure 2 PTC Resistors

1. Carbon Filled Polymer, Epoxy Coated
2. Barium Titanate Ceramic Disc, Soldered Leads
3. Barium Titanate Electroded Ceramic Disc
4. Barium Titanate Electroded Ceramic Disc
5. Barium Titanate Electroded Ceramic Honeycomb
6. Carbon Filled Polymer, Epoxy Coated
7. Barium Titanate Electroded Ceramic Disc

Figure 2 shows the appearance of some PTC resistors as tested here. The conductive grains in these 2 phase systems serve to provide current carriers and to support the thin intergranular layers where the actual switching is taking place. This results in a lower materials mass utilization, since in the off condition, the voltage is applied across these barriers only. The advantage of this system is in the series parallel nature of the high resistance network. This divides the applied voltage to a lower value at each of many barriers,

Report Documentation Page

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1. REPORT DATE JUN 1985	2. REPORT TYPE N/A	3. DATES COVERED -	
4. TITLE AND SUBTITLE An Evaluation Of Nonlinear Resistors For Pulse Power Switching		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) Naval Research Laboratory Washington, DC 20375-5000		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 Approved for public release, distribution unlimited			
13. SUPPLEMENTARY NOTES 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.			
14. ABSTRACT			
15. SUBJECT TERMS			
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT
a REPORT unclassified	b ABSTRACT unclassified	c THIS PAGE unclassified	SAR
			18. NUMBER OF PAGES 4
			19a. NAME OF RESPONSIBLE PERSON

and the failure of a single barrier has only a negligible effect on the total circuit.

Experimental

1. Steady State Voltage Test

The purpose of this test is to determine the maximum steady state voltage that can be applied. It often causes thermal runaway and is determined by applying successively higher steps of DC voltage to the device under test, while monitoring the current at each step. The first voltage level at which the current did not stabilize was designated the "Steady State Runaway Voltage." This was particularly acute in Barium Titanate devices. The "Off the Shelf" PTCR components evaluated have cold resistance values from 9 milliohms to 30 ohms, and steady state voltage ratings between 15 volts and 1000 volts. A high current (20A) power supply is used to bring the cold PTCR to switching temperature. It is then necessary to add power supplies covering decreasing ranges of current at increasing voltage levels to arrive at the point where the resistance starts to decrease. The latter happens at device temperatures above the normal operating range that is shown in Fig. 1.

2. Maximum Current Endurance Test

The maximum current that a device is capable of interrupting was determined by applying a step function of voltage. The voltage across the device and its peak current were then used to calculate the large-signal resistance. After the PTCR switching interval, the voltage was disconnected. This was to prevent overheating where the steady state runaway voltage had been exceeded. This test requires a variable voltage, very low impedance source. Circuit inductance was minimized, since it tends to produce an over-voltage during switching. This could result in a voltage induced failure, rather than in an over-current failure.

A large battery bank comprised of 120 two volt cells, capable of delivering short circuit currents to 2000 amps, was used. Electrolytic capacitors with a capacitance of 0.092 farads were connected in series with the battery bank where higher voltage capability is required. A switching SCR capable of switching peak pulse currents to 10 kA is triggered to produce a fast current rise time in the tested component. This circuit performs well for most PTC resistors tested. However, the internal impedance of the battery (approximately 50-60 milliohm) produces some voltage drop so that when driving the 10-20 milliohm (cold resistance) polymer components, a significant voltage increase is observed at the test device after switching.

3. Constant Current Test Circuit

This test is designed to measure the maximum (short term) switched voltage tolerated by a PTCR when driven from a high impedance source. Since conventional constant current sources at the required energy levels are not readily available, a large air core coil was connected to a D.C. supply. Current flows through the coil and through a fuse until the desired peak current (set by supply voltage, coil resistance and fuse wire diameter) is reached. At this time, the fuse vaporizes to produce a high resistance that transfers the current into the PTCR under test. If the inductively stored energy is sufficient, the test device will be heated

by essentially a constant current, until it reaches switching temperature. The rapidly increasing resistance of the PTCR will then produce a corresponding voltage increase. A voltage sensing circuit across the PTCR is set to trigger a shunt SCR into conduction. The remaining energy in the coil is then dissipated in the inductor resistance via a diode connected from inductor input to ground, while a timing circuit and the circuit breaker remove battery power. After every pulse, the PTCR resistance is measured, and the voltage sensing circuit is set to a higher voltage until irreversible changes are detected in the PTC resistor.

Results and Discussion

TABLE 1 - PTCR SWITCHING PARAMETERS

DEVICE TYPE NUMBER	PTCR DIMENSIONS	INITIAL COLD RESISTANCE (SIGNAL SIZE)		MAX PULSED CURRENT (AMPS)	SWITCHED VOLTAGE (LOW IMPEDANCE SOURCE) (VOLTS)	MAX STEADY STATE VOLTAGE (VOLTS)
		SMALL	LARGE			
1	2.13" X .5" .09"	16.8-18.1 mΩ	24-26 mΩ	700-960	100-190	218-253
6	1.25" DIA. .065"	7.2-7.6 mΩ	8.0-8.7 mΩ	780-800	66-74	54.8-57.2
2	.56" DIA. .063"	2.1-2.2 mΩ	1.6-1.7 mΩ	70-80	102-106	55.1-63.1
4	1" DIA. .0125"	2.0-2.3 mΩ	1.5-2.0 mΩ			400
7	.875" DIA. .125"	6.8-7.0 mΩ	5.1-5.2 mΩ			595-772
3	1.22" DIA. .19"	412 mΩ				961
5	1.22" X 1.22" .25"	35.0 mΩ				56.6

Table #1 shows the dimensions of the PTCR devices evaluated, their cold resistances, the highest pulse currents tolerated without resistance changes and the highest voltages the devices were switched to with our "low" impedance source.

FIGURE 3
COLD LARGE-SIGNAL RESISTANCE VS PEAK PULSE CURRENT FOR SIX TYPE#6 PTCR'S

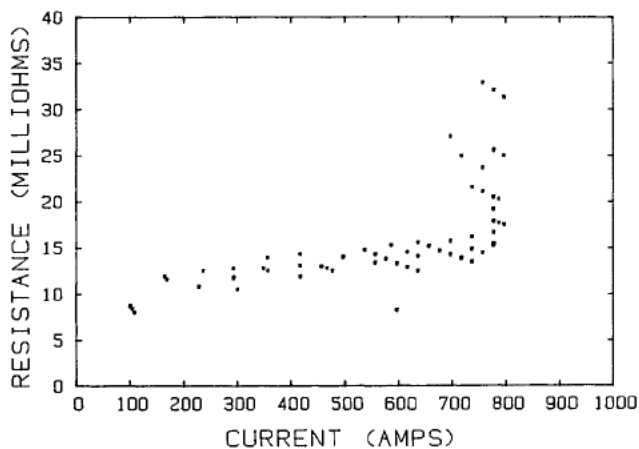


Figure 3 shows the large signal resistances of six polymer-carbon composite PTCRs (Type 6) determined during each current pulse having the magnitude shown on the abscissa. These pulses were applied in sequence by raising the supply voltage. These PTCR devices show a significant and irreversible increase in resistance after switching pulses in excess of 750A. At that point the current pulse is only about 3 milli sec long with a fall time of 0.2 milli sec (see Fig. 4). As one would expect from a variable resistor, the voltage rise

time has about the same duration. Similar data are shown in Figs. 5 and 6 for a small PTCR made out of

FIGURE 4
DURATION OF CURRENT PULSE AND CURRENT FALL-TIME VS PEAK PULSE CURRENT OF SIX CFP TYPE #6 PTCR'S

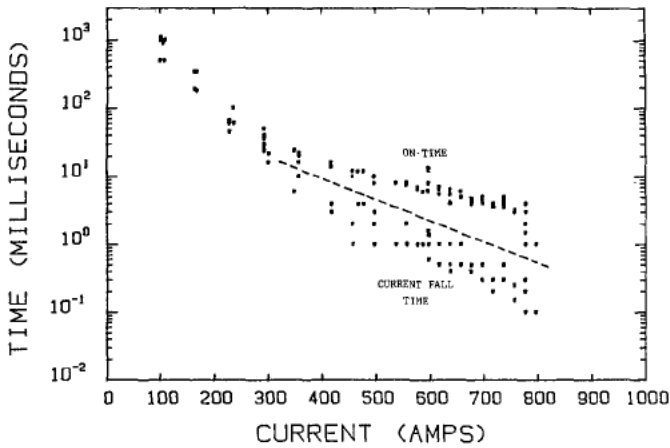


FIGURE 5
COLD RESISTANCE VS. PEAK PULSE CURRENT FOR BaTiO₃ TYPE#2 PTCR#4

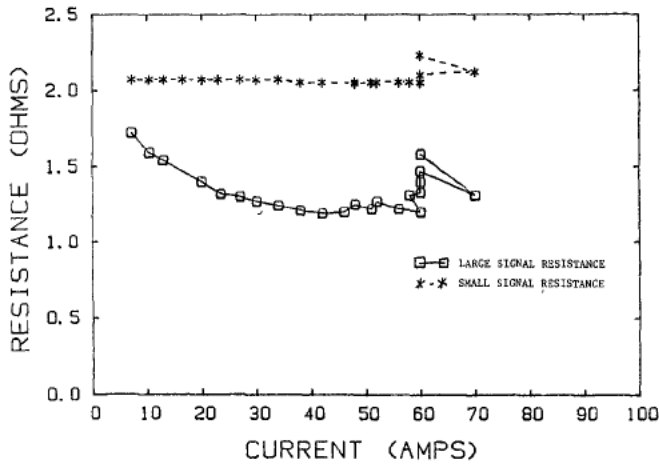
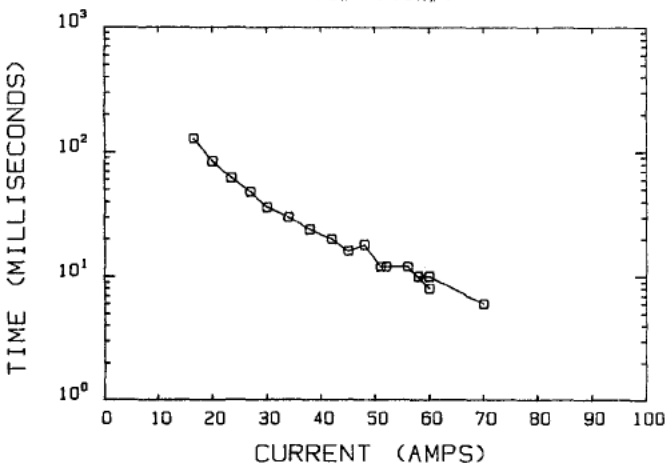


FIGURE 6
DURATION OF PULSE CURRENT FOR BaTiO₃ TYPE#2 PTCR#4



barium titanate. This device had a stable resistance slightly above 1 ohm even after having been tested with currents up to 50 amps. It gave pulse durations down to 10 milli sec with slightly

longer current fall times. It appears that for two out of the three types of PTCR devices tested so far, a higher voltage was sustained under pulse than under steady state conditions.

Failure Mechanisms:

"Voltage" failures were induced at relatively low current levels by applying D.C. power at a slower rate than the thermal time constant of the device. When this voltage heated Barium Titanate PTC thermistors above the temperature of maximum resistance, the current tended to increase spontaneously. Continuous application of such a voltage to Barium Titanate PTC resistors caused thermal runaway and melting of the solder where the device had leads attached.

In the carbon filled polymer devices on the other hand, there was at the maximum voltage only a relatively small increase in current, followed by voltage breakdown at the edge of the electrodes. This is shown for a Type 6 (round) carbon filled polymer device in Fig. 7 and for a Type 1 rectangular, carbon filled polymer device in Fig. 8. The latter broke down at 265 V D.C.



Figure 7 Appearance of Voltage Breakdown in CFP Type #6 PTCR

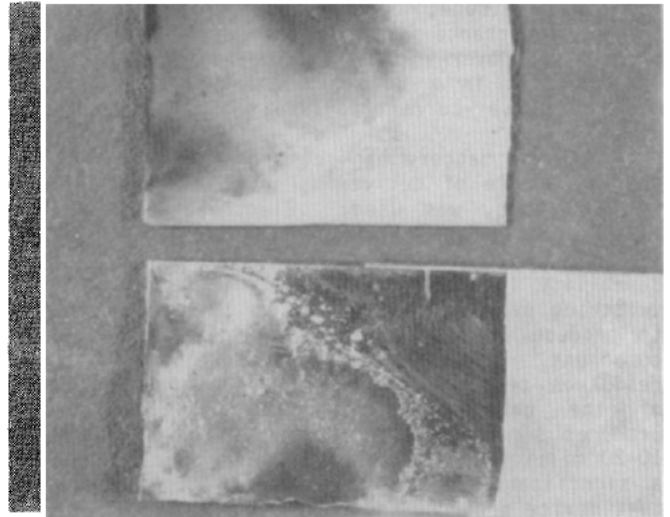


Figure 8 Voltage Breakdown in two spots in CFP Type #1 PTCR.

The Type 1 device had about 2 times the cold resistance and 4-5 times the maximum steady state voltage found in Type 6. It appeared that the higher breakdown voltage was induced at least in part by improved uniformity of the polymer-carbon system. Figure 8 shows two separate locations of breakdown that must have occurred simultaneously. Only one breakdown origin was observed in Type 6 (round) samples.

In all these devices, the electrodes extended to the edge of the polymer layer. This results in

an electrical field enhancement and voltage breakdown always took place there. It appears that an electrode free margin at the edge of the polymer film should increase its breakdown voltage.

The currents induced by a voltage step function at which the device resistances became unstable were shown in Figs. 3 and 5. The over-current induced resistivity increase was accompanied by physical damage and Fig. 9 shows a failure generated by 780A in a round, carbon filled polymer PTCR. It appears that excess current and excess heating caused here a sizeable hole with rounded, apparently molten, edges. It was located near the center of the sample. The sample cracked in the plane shown and was easy to separate into two thinner discs. Substantial large scale porosity in the polymer film is also evident.

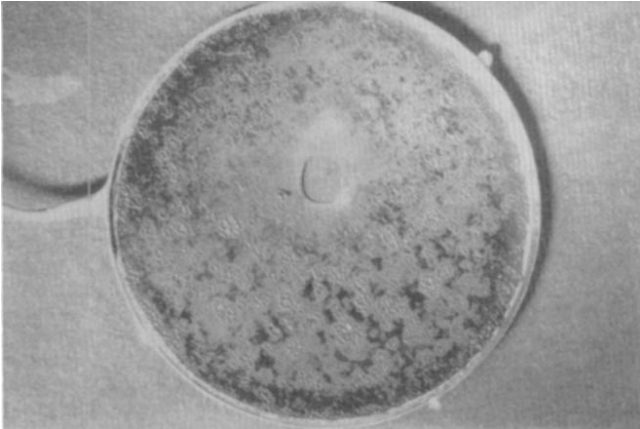


Figure 9 Current Failure in CFP Type #6 PTCR

A large proportion of the pulse current test failures of both round and rectangular carbon filled polymer PTCR'S were in appearance very similar to that of the low current, steady state voltage test failures shown in Figs. 7 and 8.

One may conclude that increased temperature is the main factor that determines when carbon filled dielectric breaks down. With a low impedance voltage source, one would expect most heating and therefore breakdown in the center of the part as appears in Fig. 9. A rapid voltage increase during switching on the other hand would cause dynamic temperature gradients, i.e., more induced heating in the edge regions that heated up slower and that switched slightly later at somewhat higher voltage. Together with the noted geometric field enhancement, this could then be the cause of the voltage breakdown observed during current testing. It consequently appears that the electrode free edge margins proposed above would also contribute to an increased pulse current capability of these devices.

The current switching capability of Barium Titanate based PTCR devices is similarly limited by edge breakdown, but this occurs from slightly different causes: these devices have at least 10 times the thickness of the polymer based devices and are therefore apt to develop during rapid switching axial temperature, resistance, voltage and dissipation gradients. This is caused by the thermal masses of the electrodes that delay the heat-up of the adjacent ceramic regions. As a result the central plane of the disc switches first, giving a spatial peak in resistivity that leads to a

peak in localized field strength that then can give breakdown in the center of the circumferential surface. Such a high current induced fault is shown for a Barium Titanate based PTCR that had been subjected to 60A in Fig. 10.

It should also be noted that ceramic Barium Titanate can fail due to thermal shock in a variety of other fracture modes: large flaws or density inhomogeneities can distort the current sheet. There is only a negligible amount of heat flow during the rapid switching interval and substantial internal temperature gradients can then occur. Flaw

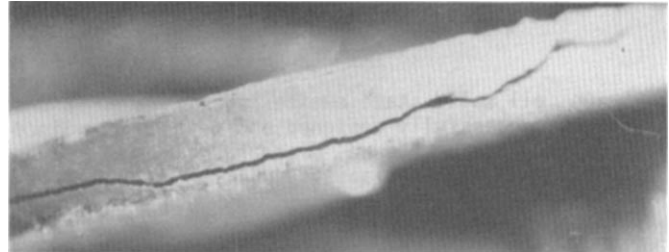


Figure 10 Current Failure in BaTiO₃ Type #2 PTCR

induced uniformities in mechanical strength contribute to the curvature of the fracture line in Fig. 10.

Summary and Conclusions

The present data show pulse current capabilities above 600 A for carbon filled polymer PTCR'S and about 1/10 of this for small Barium Titanate devices.

The failures of the polymer based devices are primarily due to edge breakdown. This limits the present design to 250V with low current and to 150V during switching. Improved electrode design could raise this. BaTiO₃ ceramic devices can suffer from dynamic axial instabilities that give thermal shock. They have a higher cold resistance, but also a significantly higher voltage capability. More testing with high impedance sources will give more details on these limits under pulsed conditions. Arrays could then be designed with BaTiO₃ PTC resistors having a smaller number of series elements. The increased number of parallel PTC resistors per plane should not be a hindrance, since only the series connections need load sharing devices.

Switching speeds of milliseconds are easily attainable, even without triggering. The large scale availability of commercially made PTC resistors should make their early application in pulse switching circuits feasible.

References

1. R. Ford, I.M. Vitkovitsky, IEEE Trans. on Electron Devices, Vol. ED-26, p. 1527-1531 (1979).
2. R.D. Ford, I.M. Vitkovitsky, M. Kahn, IEEE Trans. on Electrical Insulation, Vol. EI-20 No. 1, p. 29-37 (1985).
3. M. Kahn, Bulletin of the American Ceramic Society, Vol. 50, p. 676-680 (1971).
4. A.F. Doljak, IEEE Trans. on Components, Hybrids, and Manufacturing Technology, Vo. CHMT-4, p.372 (1981).