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Abstract

A line type pulser has been developed to test the effects of steep-front, short duration (SFSD) pulses on distribution components. Risetime is 50-100 ns, and pulse duration is on the order of 300 ns. Terminators often shattered or punctured rather than flashing over. Insulator flashover voltage is approximately 1.5 times CFO for standard lightning impulses. Arresters exhibit an inductive character, with SFSD peak voltage at 10 kA approximately 4-5 times the 8x20 microsecond 10 kA discharge voltage. Polyethylene insulated cable has a characteristic degradation in which failure voltage decreases with number of SFSD pulses.

Introduction

Recent measurements of lightning transients on power distribution systems have revealed transients with rates of rise as high as 260 kA/microsecond (1). Switching operations in gas-insulated substations are also known to cause very fast, high voltage transients (2). The potentially most severe source of extremely fast, extremely high magnitude pulses is the electromagnetic pulse (EMP) radiating from a high altitude nuclear explosion. Such an EMP is estimated to generate a distribution system transient with risetime as short as a few nanoseconds and magnitude near 1 MV (3).

Although there is growing realization that fast transients may be present, there are few measurements on the withstand ability of distribution components to such impulses. Reference 1 reports that arrester protection levels for 100 ns risetime waves exceed the standard test wave voltages by 30% for ZnO arresters and 62% for SiC arresters. Burrage, et al, has found that 25 x 250 ns pulses result in about 285 kV critical flashover voltage for class 52-3 (5-3/4 x 10-3/4 inch) porcelain suspension insulators (4), compared with a CFO of about 100 kV for a standard 1.2x50 mcsec impulse (7). Thus, it appears that ordinary distribution insulation will have considerably higher short duration withstand capability, compared with standard lightning performance, but that considerably less protection is offered by the arresters.

In order to obtain a wider range of data on the effects of steep-front, short duration (SFSD) pulses on common distribution components, the Department of Energy, through Oak Ridge National Laboratory, is supporting the Mississippi State University High Voltage Laboratory to measure the SFSD response of terminations, arresters, insulators and cables. Some preliminary results on the cable tests are reported elsewhere (5). Recent measurements on all four classes of distribution components are included in this paper.

Test Facilities and Procedures

The line pulser system shown in Figures 1 and 2 was used for these measurements. The Marx-type impulse generator is used to charge the "peaking network", which consists of one to four parallel, high voltage coaxial cables, each 10.7 m long. Typically, 35 kV distribution cable has been used for these peaking cables. When the peaking cable charges up to the flashover voltage of the "peaking gap", that gap fires, sending a very steep-front pulse into the test piece. When a matching terminating resistor is used, a nearly square wave pulse is generated. The voltage wave is recorded by the resistive divider and digital oscilloscope. The step response of the divider is measured to be about 30 ns. Current is recorded using the high frequency current transformer.

A typical voltage wave with a terminator and matching resistor load, and no breakdown, is shown in Figure 3. Note that the risetime is approximately 60 ns, and the duration is about 300 ns. The low voltage "tail" on the waves is due to residual charge remaining on the impulse generator after the peaking cables have

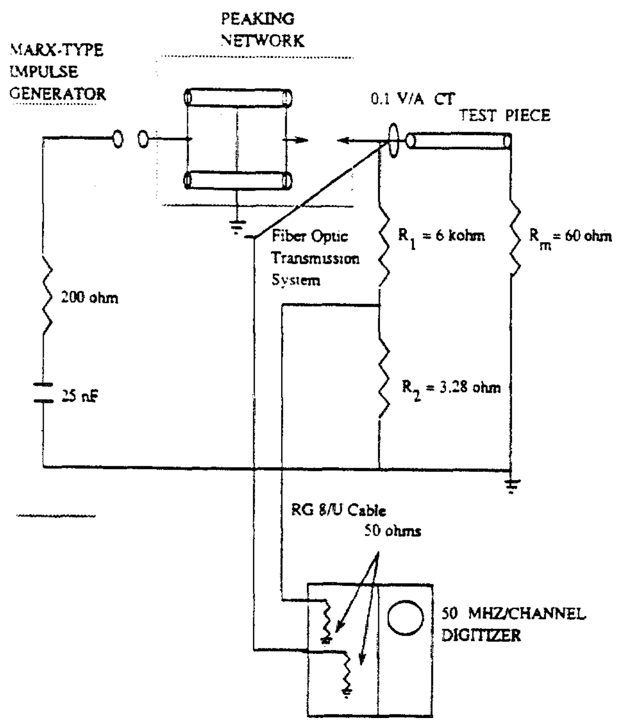

Figure 1 Line pulser and measurement circuits.

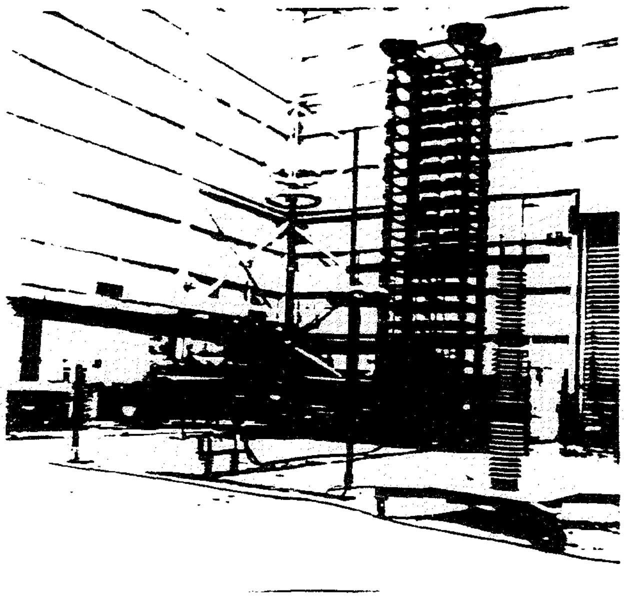

Figure 2 Photograph of the test system, showing the Marx impulse generator in the right background, the peaking gap with resistive load in the lower center, and twin peaking cable between the impulse generator and the peaking gap. The wire-wound voltage divider is visible in the right foreground.

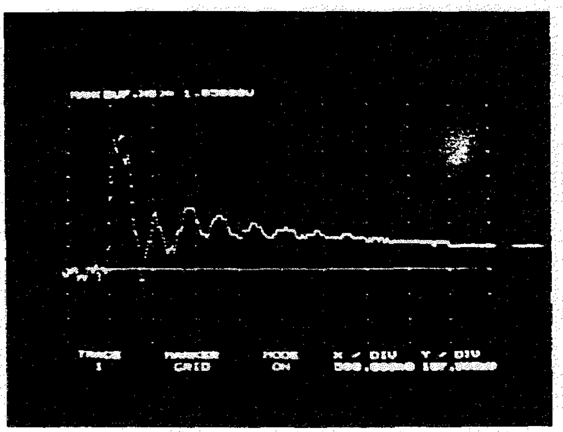

Figure 3 Voltage waveshape during terminator testing; 500 ns per horizontal division, 35.5 kV per vertical division, 198.5 kV peak.

discharged. Pulse charging of the peaking cable has the advantage over dc charging, since the high charging voltage appears only momentarily on the cable, and the peaking cable therefore does not need to have as high voltage rating. More details on this pulser are presented in Reference 6.

Terminators

A variety of terminator ("pothead") designs and ratings were tested, with the results shown in Table I. The lengths and diameters (l x d) of the 15 kV and 25 kV units were approximately 25 x 7 cm and 25 x 12 cm, respectively. In each test, the terminator was installed, following manufacturer's directions, on one end of a 4 meter long piece of distribution cable of the same rating as the terminator; the other cable end

Table I
Critical Flashover Voltage (CFO - ten shots)
- Terminator (potheads)
- Steep-front pulses (60 ns x 240 ns)
& (125 ns x 240 ns)*

Terminator	Rated BIL	CFO	Failure mode - voltage
E-1 15 kV porcelain	110 kV	289 kV	
E-2 15 kV porcelain			shattered - 330 kV
*E-3 15 kV porcelain			shattered - 330 kV
F-1 15 kV elastimer	95 kV		punctured - 297 kV
F-2 15 kV elastimer		289 kV	
F-3 15 kV elastimer		297 kV	
F-4 15 kV elastimer			punctured - 300 kV
*I-1 15 kV heat shrink	110 kV	251 kV	
*I-2 15 kV heat shrink		202 kV	
*I-3 15 kV heat shrink			punctured - 230 kV
H-1 25 kV porcelain	150 kV	397 kV	
H-2 25 kV porcelain			shattered - 397 kV
*L-1 15 kV elastimer			punctured - 222 kV
*L-2 15 kV elastimer			punctured - 295 kV
*L-3 15 kV elastimer			punctured - 244 kV
*M-1 15 kV elastimer	95 kV		punctured - 380 kV
*M-1 15 kV elastimer			punctured - 408 kV
*M-1 15 kV elastimer			punctured - 402 kV

was terminated in a matching low inductance resistor. The SFSD pulse was imposed directly into the air terminal of the terminator. The objective was to obtain the critical flashover voltage (CFO)(peak voltage during a flashover shot), where five out of ten shots resulted in flashovers of the terminator. The table shows in many cases that the test object punctured or shattered before the CFO voltage could be obtained. The high CFO or failure voltages of terminators shown in Table I corroborates the high withstand strength for insulators reported in Reference 4. This table also indicates, however, that the typical failure mode for SFSD pulses may be a destructive puncture rather than a recoverable flashover.

Arresters

The same pulser shown in Figures 1 and 2 was used for arrester testing, with peak current being the measure of comparison. Before the SFSD tests were made, the 10 kA discharge voltage of each arrester was measured, using a standard 8x20 microsecond pulse. Both gapped SiC and ungapped MOV arresters were tested. A typical test setup is shown in Figure 4: the lead lengths from the peaking gap to the arrester and from the arrester to ground are kept as short as possible (24" total) to minimize discharge circuit inductance. In all reported arrester tests, the arrester was connected across the input to a terminated cable, as shown in Figure 4. The total length of arrester lead (from cable terminator to arrester plus arrester to ground) was variable. The SFSD pulse was injected into the air terminal of the cable terminator, and the voltage divider measured the voltage at this point. SFSD current and voltage waveshapes are shown in Figure 5. In Figure 5, the voltage (top) and current (bottom) are synchronized. The voltage and current start at approximately the same time, but the voltage peaks at the time for maximum di/dt, suggesting that the arrester circuit has a strong inductive component which is being revealed by these fast-changing current pulses. Whether this "inductive" effect is due to true circuit length inductance or lag in the response of the MOV material has yet to be determined.

Figure 6 shows plots of SFSD voltage vs current for 10 kV SiC and MOV arresters. The MOV arrester is seen to give somewhat better protection for SFSD pulses. The

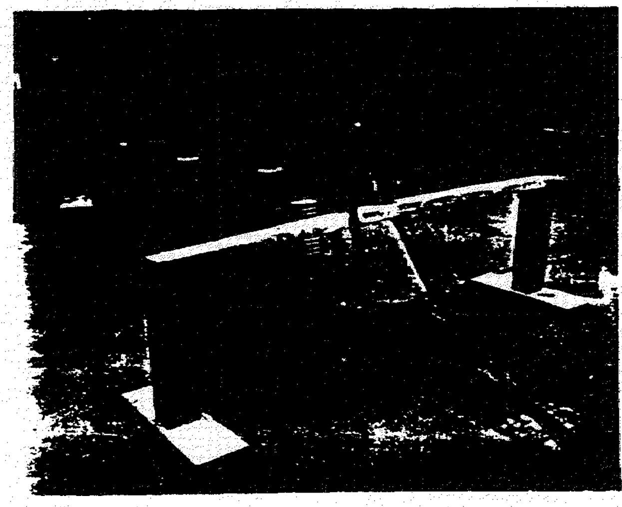

Figure 4 Arrester test setup, showing peaking gap on the upper left, test arrester at the center, terminated cable on the right, and arrester ground lead passing through the current transformer below the arrester.

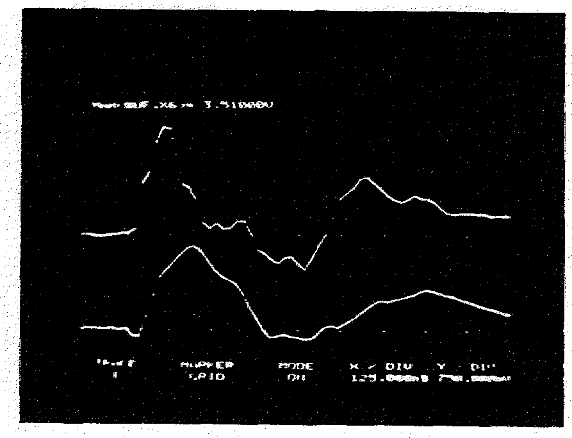

Figure 5 Typical MOV arrester voltage (top) and current waveshapes, 24 inches total arrester lead length, 125 ns/div, 14.2 kV/div, 1.20 kA/div, 66.4 kV peak, 4.2 kA peak.

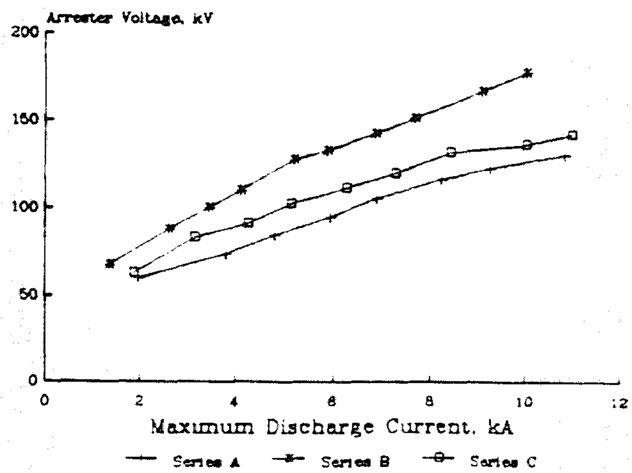

Figure 6 Arrester peak voltage vs. peak SFSD current. Series A: 10 kV MOV, 24" lead; Series B: 10 kV gapped SiC, 45" lead; Series C: 10 kV gapped SiC, 24" lead.

very important influence of lead length is also evident from these plots.

Table II shows the results of these tests. In all cases, the SFSD 10 kA voltage is considerably above the standard 10 kA discharge voltage of the arrester, and the "protective" level offered by the MOV is not appreciably lower than provided by the gapped arrester. The slightly non-linear character of the Figure 6 curves, even considering a ±10% error bar which could be attached to each data point, does indicate that the MOV material is adding some protection, inspite of the apparent inductance nature of the circuit.

TABLE II - ARRESTER TEST DATA

ARRESTER			SFSD IMPULSE		8/20 uS	
Sample	Type	Rating	Current (kA)	Voltage (kV)	Current (kA)	Voltage (kV)
G-3	SiC	10 kV	5.74	102.34		
			8.42	131.34		
			10.98	141.79	10.03	26.87
K-6	MOV	10 kV	5.94	94.95	5.50	30.63
			8.22	116.35	8.16	31.76
			10.83	129.97	10.56	32.62

Insulators

4-1/2" x 6-1/4" kV porcelain suspension insulators (88 kV CFO) of the type shown in Figure 7 were used for these tests. For these tests, the terminating resistor was not used, resulting in the long tail evident in the typical voltage waveform shown in Figure 8. Note that the voltage peaked at about 460 kV at 100 nanoseconds for this particular shot, and that the insulator flashed over at 1.15 microseconds.

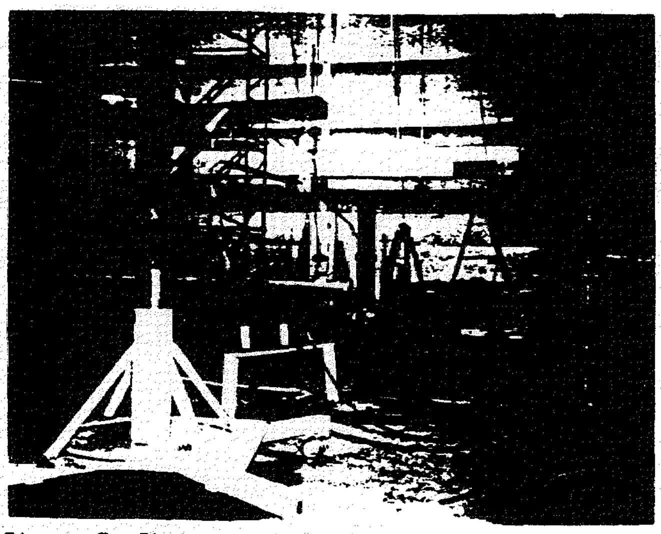

Figure 7 Photograph of insulator test setup, showing a four parallel section peaking cable, the peaking gap at lower center, and a two section suspension insulator string at upper center.

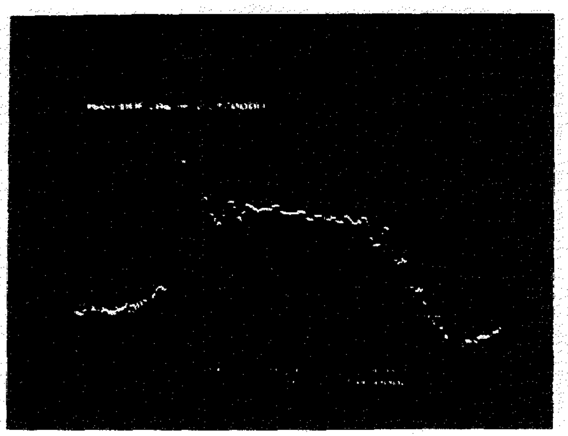

Figure 8 A typical voltage waveshape during insulator testing, 250 ns/div, 73.2 kV/div. Note the long "tail" time after the SFSD front portion of the pulse.

Figure 9 plots the time to flashover vs flashover voltage for one, two and three suspension insulators. Very high voltages are required to flash over these insulators with very short duration pulses. The minimum flashover voltages for SFSD impulses with these insulators are approximately 1.4-1.6 times the standard 1.2x50 CFO. All failures were flashovers around the insulators; no punctures or porcelain shattering were observed.

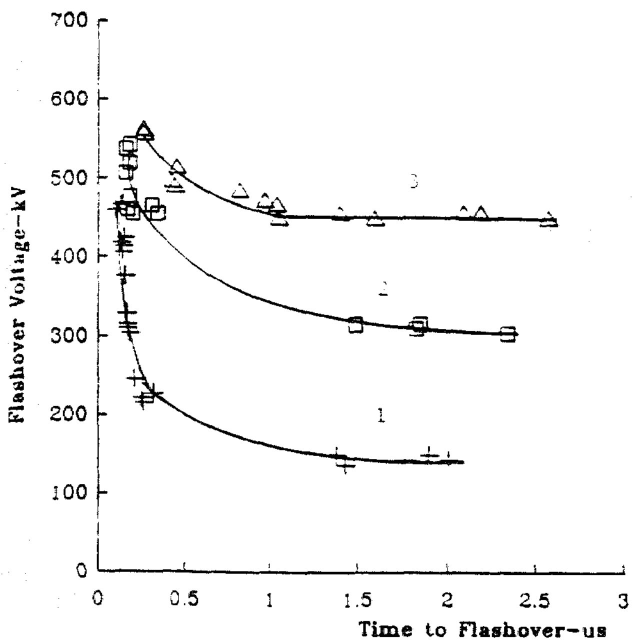

Figure 9 Plot of time to flashover vs. peak pulse voltage for one, two and three 4-1/4" x 6-1/4" suspension insulators.

Cable

The cable used for these tests had the following specifications: 15 kV, 175 mil XLPE insulation, semicon layers on the i.d. and o.d. of the insulation layer, and no tree retardant. Conductor size varied. The concentric neutral was stripped back approximately 1 m. None of the outer semicon layer was removed, and in fact, the outer semicon layer was connected to the center conductor at the input end of the cable in order to achieve uniform grading at each end of the test piece. Test pieces were 4.6 m long. Each test cable was terminated in a 60 ohm resistor.

The test procedure consisted of the following steps:

1. Measure capacitance (C) and loss tangent for each piece.

2. Subject the test piece to approximately 20 shots at a given peak voltage.

3. Remeasure C and tan delta.

4. Continue as above until the test cable fails.

5. Repeat as above with new test pieces at different peak voltages.

Representative voltage and current waveshapes during cable testing are shown in Figure 10. The results of two series of tests are shown in Figures 11 and 12. In the first case, new cable with 1/0 MCM conductor was used. In the second case, the 750 MCM test cable

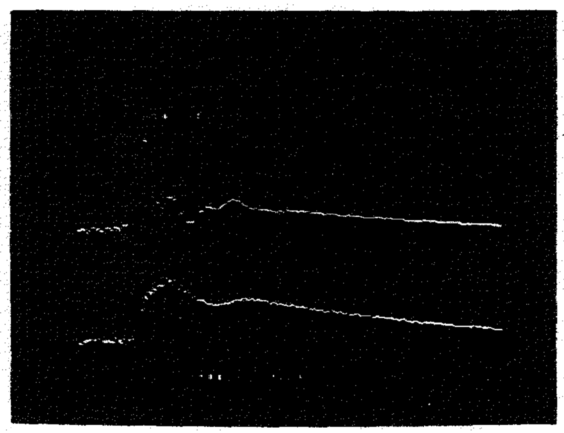

Figure 10 Voltage and current waveforms during a cable test; 15 kV cable, 4.6 m long, terminated in 60 ohms; 500 ns/div, 91.6 kV/div, 158 kA/div, 341 kV peak, .773 kA peak.

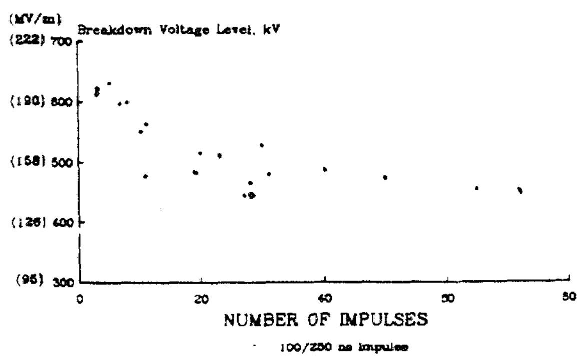

Figure 11 Number of pulses to breakdown vs. peak pulse voltage, new 15 kV XLPE cable, 1/0 conductor, 175 mil insulation.

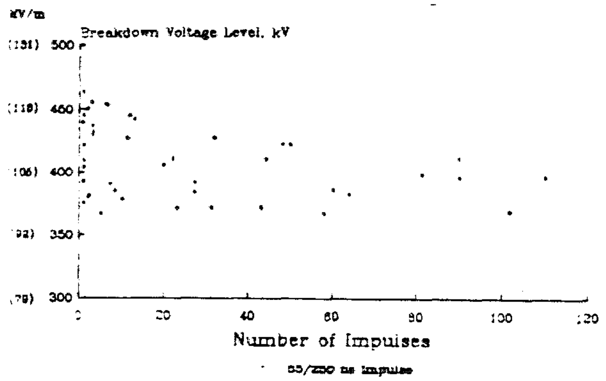

Figure 12 Number of pulses to breakdown vs. peak pulse voltage, field aged 15 kV XLPE cable, 750 MCM conductor, 175 mil insulation.

had been in service for about 15 years, in conduit, submerged in water. Both voltage and maximum electric field (at the center conductor) are plotted vs shots to breakdown. It appears that the field aged cable shows some loss in electric-field withstand capability, and that the used cable also has considerably more scatter in the data.

No significant change has been observed in capacitance or tan delta during the progress of recent tests. Since these and earlier tests indicate that degradation is progressive, some parameter of the insulation is probably changing but not observable by capacitance or tan delta measurements. The suggestions have been made that partial discharge measurement might give a more sensitive non-destructive indication of degradation, and that 60 Hz should be used as an indicator of decreasing strength.

Conclusions

1) Coaxial cable can be used with an ordinary Marx-type impulse generator to generate steep-front short duration pulses.

2) Porcelain, elastimer and heat-shrink terminators all show much higher voltage withstand capability to SFSD pulses (2-3 times higher), compared with response under standard lightning pulses. The failure with SFSD pulses is found often to be destructive.

3) Both gapped SiC and ungapped MOV arresters have largely inductive characteristics, contrasted with their capacitive character for lower frequencies. The 10 kA voltage is consequently much higher (4-5X) for SFSD pulses than for standard 8x20 lightning pulses. Some protection is, however, provided by the apparent non-linear i-v characteristic. Further study in real system configurations is required to differentiate the truely inductive effects from MOV material response processes.

4) The breakdown voltage of porcelain suspension insulators has been measured to be about 1.5 times higher for SFSD pulses than for 1.2x50 impulses.

5) 15 kV distribution cable has been found to have high withstand strength to SFSD pulses. Multiple pulses appear to cause progressive degradation of the dielectric and consequent decreasing of the breakdown voltage.

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