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Ultrafast Gas Switching Experiments

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ULTRAFast GAS SWITCHING EXPERIMENTS

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ABSTRACT

We describe recent experiments which studied the physics of ultrafast gas breakdown under the extreme overvoltages which occur when a high pressure gas switch is pulse charged to hundreds of kV in 1 ns or less. The highly overvolted peaking gaps produce powerful electromagnetic pulses with risetimes < 100 ps which can be used for ultrawideband radar systems, particle accelerators, laser drivers, bioelectromagnetic studies, electromagnetic effects testing, and for basic studies of gas breakdown physics. We have produced and accurately measured pulses with 50 to 100 ps risetimes to peak levels of 75 to 160 kV at pulse repetition frequencies (PRF) to 1 kHz. A unique gas switch was developed to hold off hundreds of kV with parasitic inductance less than 1 nH. An advanced diagnostic system using Fourier compensation was developed to measure single-shot risetimes below 35 ps. The complete apparatus is described and wave forms are presented. The measured data are compared with a theoretical model which predicts key features including dependence on gas species and pressure. We have applied this technology to practical systems driving ultrawideband radiating antennas and bounded wave simulators. For example, we have developed a thyristor/pulse transformer based system using a highly overvolted cable switch. This pulser driving a Sandia-designed TEM cell, provides an ultra wideband impulse with < 200 ps risetime to the test object at a PRF > 1 kHz at > 100 kV/m E field.

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INTRODUCTION

This paper describes experiments which studied production of high voltage pulses with risetimes below 100 ps by extreme overvoltage of high pressure gaps. The basic method, as described by Fletcher in his classic 1949 paper¹, is to insert a small high pressure gas switch in a length of coaxial cable. The input pulse forming cable is rapidly pulse charged to achieve high overvoltage. The fast pulse is observed at the output cable. More recently, many groups, including researchers at Sandia National Labs^{2,3,4}, Naval Surface Warfare Center⁵, Phillips Lab⁶, and Lawrence Livermore National Labs⁷, have studied the phenomena of small sparkgap switching.

The new features of our study are the generation and measurement of faster switching times (as fast as 50 ps), faster diagnostics, and a spark gap theory. We obtain the faster switching times by high overvoltage, with gap fields to several MV/cm in high gas pressure with very fast pulse charging.

APPARATUS

The experimental apparatus is shown schematically in Figure 1. The small sparkgap to be studied is inserted between an input and an output cable. The input pulse forming cable is rapidly pulse charged by the SNIPER² pulse generator, and the resulting sharpened voltage pulse is measured in the output line. SIPER has been previously described in detail² and will only be outlined here. The SNIPER pulser can operate at repetition rates exceeding 1 kHz but was power supply limited to 400 Hz for these experiments. SNIPER consists of a gas switched, oil insulated Blumlein which is pulse charged in 250 ns by a thyatron-driven nickel-iron core ($k=97$) pulse transformer. An oil peaking switch can be employed to sharpen the output pulse to < 200 ps risetime, or the direct Blumlein output risetime of 2 ns can be used. This arrangement injects pulses up to 200 kV into the input forming cable in 200 ps to 2 ns. The charging waveform is somewhat oscillatory, that is, non-rectangular. Since the test gap is an open circuit, the voltage almost doubles.

Fig. 1 The experimental apparatus is based on an in-line cable switch in a 50 ohm system.

Type RG-220 50 ohm high voltage coaxial cable is used for the pulse forming and output lines. The cable's polyethylene dielectric is used for the gas switch pressure barrier. The 0.875 inch cable outer conductor diameter is held constant while an abrupt transition in inner conductor diameter maintains 50 ohm impedance. The differential path length suffered by a plane wave traversing the switch is only a few ps. A strong clamping and sealing arrangement holds the polyethylene cable dielectric against the high pressure gas. There is no separate pressure barrier other than the cable dielectric. This arrangement achieves $< 1\text{ nH}$ of parasitic inductance. The switch was hydrostatically pressure tested to 10,000 psi with no measurable deflection of the metal housing. The switch is routinely operated above 2,000 psig since high gas pressure is essential to fast risetime at high voltage. Physical displacement of the cable ends in the housing allows gap adjustment between zero (0) and 100 mils. Pressure inlet and outlet lines allow operation in either static or flowing gas mode. The pulse in the output cable is terminated at the end of the line with a shielded Carborundum resistor. Time isolated D-dot monitors consisting of open ended 0.085" coax cable and having response to beyond 30GHz⁸ are used to observe the waves traveling in the input and output lines. Where possible, microwave techniques such as foamed Teflon cables with 3.5mm precision connectors were used. The D-dot signals are numerically integrated to recover the voltage waveforms of the incident, reflected, and sharpened waves.

FAST DIAGNOSTICS SYSTEM

The fast breakdown studies required a very fast data acquisition system (DAS) capable of triggering on a single external event and acquiring the waveforms for both input and output signals simultaneously. Existing systems were inadequate. Stroboscopic sampling systems cannot acquire single shot data. Triggering from external events, which requires signal delay lines that degrade system risetime to $> 35\text{ ps}$, is the fastest available single shot DAS in the Nation. Two Tektronix SCD-5000 digitizers are used with fast delay lines to give two independent channels with random event triggering. The 4.5 GHz 3-dB bandwidth SCD-5000 has a measured response which extends beyond 15 GHz with smooth roll-off. It also incorporates a high degree of over sampling and, at 5 ns full sweep, gives 1024 digitizing points for 5 ps per sample. The combination of attributes allows Fourier compensation to well beyond 10 GHz with FFT processing software⁹.

It is essential to use the full dynamic range of the instrument both in experimental data collection and calibration. A step pulse with a risetime of 15 ps to 10 volts is applied directly to the D-dot monitor input cables for calibration. The high voltage level is needed to give a full deflection during calibration. The step pulse generator is employed as a transfer standard for calibration against a Tektronix CSA-803 stroboscopic sampling scope. The FFT processing is performed on an 80386-based personal computer located in the same portable shield box with the two digitizers. We developed an algorithm which employs Nicolson de-ramping¹⁰ of step waveforms for FFT signal compensation. The waveform processing requires only a few seconds and can thus be viewed in near real time.

Figure 2 shows a fast calibration pulse measured with the SCD-5000 digitizer before and after compensation compared to a 20 GHz sampling scope. The processed data indicates the degree of bandwidth enhancement possible with the system. If desirable, we filter to 10 GHz to minimize the level of high-frequency deconvolution noise.

Fig. 2 Calibration data shows a fast pulse measured with the SCD-500 digitizer before and after compensation compared with a 20 GHz sampling system display.

EXPERIMENTAL RESULTS

After a pulse charging waveform, gas type, and gap spacing are chosen, the gas pressure is varied to optimize the switching action as diagnosed by the incident, reflected, and transmitted waveforms. Typically the highest pressure with the shortest gap spacing produces the fastest output risetime and minimum switch loss. Over 600 complete data sets were taken in the experiments. N_2 , H_2 , and SF_6 gas mixtures were compared for a number of gap spacings. In this brief report, we discuss a few examples in detail emphasizing the waveforms obtainable with the optimum parameters.

Figure 3 overlays the incident pulse charging voltage waveform and the output sharpened pulse as a function of time. For this example the H_2 gas pressure was optimized at 1790 psig for the 0.076 cm gap spacing to give stable breakdown at 85% of peak on the 2 ns charging waveform. The output waveform has a fast rise to 110 kV with overshoot to

128 kV. The overshoot is not an artifact of the diagnostics but rather a ringing of the gap inductance and capacitance which will be described in the following section. The pre-pulse which occurs before gap breakdown is due to the charging of the small (1 pF) gap capacity. The switching is highly efficient with little energy loss occurring after the initial turn-on phase. At the time of switching, approximately 220 kV appears across the 0.076 cm gap causing a peak E field level of 3 MV/cm.

Fig. 3 Pulse charge and output voltage waveforms for a 0.076 cm gap at 1790 psig hydrogen show pulse sharpening.

Figure 4 shows the output waveform of the same shot with finer time resolution. The output 10-90% risetime is 67 ps when corrected for the 35 ps system response. The maximum dV/dt is 1.3×10^{15} V/s. The switch was operated repetitively at these levels in bursts of several thousand shots at 400 Hz without gas flow. The maximum rate was limited by the power supply not the switch. A slight pressure increase was required in repetitive operation. Operation with a shorter gap and lower pulse charge level gives even faster risetimes at approximately the same dV/dt . For example a 0.03 cm gap at 1790 psig H_2 gave a 52 ps corrected risetime to 60 kV with overshoot to 75 kV peak voltage. This was achieved with a peak E field level of 4 MV/cm. This data is compared to theory in the following section and is shown in Figure 7.

Fig. 4 Fast switching is achieved by rapid pulse charging.

Operation with N₂ gas gives similar results except that lower pressures are required and risetimes are not quite as fast due to the higher gas density. For the 0.076 cm gap operating at 720 psig N₂, we measure a 93 ps corrected risetime to 160 kV with dV/dt of 1.4×10^{15} for a maximum E field of 4 MV/cm. We achieved the highest overvoltage and fastest risetime by pulse charging very rapidly using the sharpening switch in SNIPER. For a 0.05 cm gap with 2200 psig H₂ and pulse charging to 300 kV gap voltage in < 300 ps, we measured E fields of 6 MV/cm and produced an output pulse of 140 kV with risetime below 50 ps and dV/dt exceeding 2×10^{15} V/sec. This level of dV/dt exceeds the largest pulse power machines such as HERMES III and PBFA.

COMPARISON THEORY

We now compare our measurements to a simple model¹¹, which model assumes a constant limiting spark channel conductivity which causes the switch resistance to vary with the inverse square of the channel radius. This radius is calculated self-consistently from the energy deposited in the channel resistance. The simple hydrodynamics calculation is implemented through a subroutine called the SCREAMER circuit solver code. Figure 5 shows the simple circuit used to model the switch. The source and the load transmission lines are modeled as 50 ohm resistances. The gap inductance L is proportional to the gap length, and the gap capacitance C is matched to the measured pre-pulse levels. The time dependent channel resistance $R(t)$ is calculated using a limiting resistivity which is unique to each gas type. The key parameters of the switch model are not arbitrary but rather determined by the geometry and gas properties. The time of closure and number of switching channels are chosen to best match the data and are the only adjustable parameters.

Fig. 5 Schematic of the switch model shows fixed gap C and L and the variable channel resistance which is calculated self-consistently.

We compare predictions to experiment for the case of a 0.03 cm gap at 1790 psig H_2 . Figure 6 shows calculated gap voltage (dashed curve) and output voltage. The measured incident voltage was used as an input to the model. The calculation shows that the incident voltage almost doubles at the gap to give a 110 kV gap voltage. When the gap breaks down, the voltage across the switch gap rapidly drops to zero as a fast rising 60 kV voltage pulse ($V/2$) is launched. The model predicts (and we observe) a pre-pulse coupled across the gap capacity which resembles the time derivative of the charging waveform, and an overshoot due to oscillatory currents from the gap inductance and capacity.

Fig. 6 Calculated waveforms for gap voltage (dashed curve) and load voltage (solid curve) show sharpening.

Figure 7 compares predicted and measured outputs. The choice of 64 channels gave agreement with the experimentally measured risetime of 52 ps (with measurement system correction). The predicted ringing frequency is a good match to the measured frequency giving us confidence in the model where $L = .54\text{nH}$ and $C = 1.3\text{PF}$ were derived independently from the geometry.

Fig. 7 Comparison of measured (solid curve) with calculated (dashed curve) load voltage shows agreement of risetime and ringing frequency.

Figure 8 compares the calculated channel current (dashed curve) to the calculated load current. The channel current is oscillatory ringing at the LC frequency until the energy stored in the gap capacity is dissipated in heating the gas. It is clear that most of the channel current is supplied from the gap capacitance during the channel heating phase. This source of prompt energy is essential to the rapid turn-on of the switch. The calculated energy balance shows electrostatic energy being stored in the gap capacitance as it charges during the pre-pulse phase. A maximum of 8 mJ is stored. This is transferred to heating of the gas (dotted curve) during the turn-on phase. Then energy is delivered to the load efficiently. We note that the electrostatically stored energy is similar to the minimum laser energy required to laser trigger a small switch³.

Fig. 8 Channel current (dashed curve) is larger than load current (solid curve) due to prompt energy delivery from gap capacity.

PRACTICAL APPLICATION

We have used the ultrafast gas switch for practical applications. For example, an ultrawideband impulse simulator has been built which produces a high quality electromagnetic pulse environment in a TEM exposure cell. The peak field exceeds 100 kV/m with a risetime below 200 ps delivered to the test objects at PRF > 1 kHz. The TEM cell is an expanding, cross-section square transmission line with symmetrically placed center conductor septum, terminated by a combination of pyramidal absorber and discrete resistors. The TEM cell, which was inspired by Sandia's EMES design¹², matches the 50 ohm impedance of RG-220 cable and incorporates ultrawideband high voltage connectors.

The pulse generator supplies a 25 kV step with a risetime below 200 ps and width of 4 ns to the 50 ohm cable at the 1 kHz rate. The in-line gas switch is located between the 40 cm long forming cable and the feed cable to the TEM cell. The gap with spacing of 0.05 cm, was operated with either N_2 or H_2 . The input cable was pulse charged to 50 kV in 2 μ s by a capacitor discharge unit switched by a single thyristor driving a (100:1) ferrite core pulse transformer. The unit was simple and reliable with millions of shots delivered to the load at kHz rates. The ultrafast gas switches have also been used for calibration pulsers, antenna measurements, and with radiated field simulators producing GW pulses from TEM horns and other antennas. The reliability and utility of the ultrafast gas switches is well demonstrated by these diverse applications.

DISCUSSION

The experimental results and comparison to theory suggest a number of conclusions about the operation of the small, highly overvolted sparkgaps. Fast transition times of 50 to 100 ps are achieved with rapid pulse charging. High pressures were shown to be necessary for the production of the fastest risetimes. The higher pressures allow the switch to hold off long enough to achieve very high overvoltage with E fields to several MV/cm being necessary for the fastest switching. At these high field levels the linear dependence of breakdown voltage on pressure has ceased and further pressure increase has minimal effect on the strength. This condition can occur when the E field is so high that the electrodes have large current emission. The large number of channels needed for the model to agree with experiment suggests a diffuse discharge caused by the copious source of initiating electrons leading to the very fast breakdown times observed. The comparison of H₂, N₂, and SF₆ mixtures is in agreement with the E field divided by density dependence suggested by Tom Martin¹³. That is, for a given E field, the switching time decreases with gas density. The gap capacitance has been shown to be the primary source of the prompt energy which heats the channel rapidly to give fast turn-on of the switch. In summary, we have demonstrated gas switching with risetimes as fast as 50 ps and dV/dt to 2×10^{15} V/sec. Output voltages to 160 kV can be delivered to a 50 ohm load at high repetition rates. These parameters are achieved by very rapid pulse charging of small low inductance in-line cable switches to high overvoltage. Hydrogen gas gives the fastest breakdown since it is the lowest density. Hydrogen is also favored for high repetition rate applications. Comparison of theory to experimental data in the extreme overvoltage regime has led to new insights into the fundamental physics of gas switching, particularly the importance of the gap capacitance in supplying prompt energy for channel heating and the volume discharge associated with copious emission of initiating electrons from the electrode under high E fields. This fact coupled with the very low jitter associated with subnanosecond pulse charging suggests that the construction of a new generation of very fast high power pulse generators using multiple, self-breaking, highly overvolted gas switches is possible. The fast, single-shot data acquisition system which was constructed for this experiment allows risetime measurements to 35 ps. Finally, we have already applied the technology of the small, highly overvolted switches to practical systems which deliver sub-nanosecond pulses to TEM cells and radiating antennas.

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