DESIGN AND TESTING OF A HIGH PRESSURE, REP-RATE, LIQUID DIELECTRIC SWITCH FOR DIRECTED ENERGY APPLICATIONS*

J. Leckbee, R. Curry[ξ], K. McDonald, P. Norgard, R. Cravey[1], G. Anderson[2], and S. Heidger[3]

University of Missouri-Columbia, Department of Electrical Engineering, Columbia, MO 65211

[1]Alpha-Omega Power Technologies, 3701 Hawkins Street NE, Albuquerque, NM 87109

[2]The Boeing Company, P.O. Box 516, St. Louis, MO 63166

[3]Air Force Research Laboratory, AFRL/PRPE, 1905 5th St, Wright Patterson AFB, OH 45433

Abstract

A high power, rep-rate, liquid dielectric switch has been designed to meet future requirements for a variety of directed energy applications. A flowing, high-pressure liquid dielectric was chosen for the design of a megavolt class switch intended to operate continuously at pulse repetition rates in excess of 100 pps. This paper reports on the design efforts and initial testing of a full size prototype, 250 kV switch. The design capitalizes on lessons learned from experiments with a single shot concept validation high pressure liquid dielectric switch. Design efforts include extensive electric field modeling, circuit model simulations, and fluid flow simulations. The design facilitates fast rise times, quick switch recovery, and long electrode life. Rep-rate testing of the high pressure dielectric switch includes testing at rep-rates up to 100 pps and voltages up to 250 kV. The design of the pulser used to test the rep-rate switch is described in a separate conference paper. Switch diagnostics include D-dot probes and a Rogowski current probe. Results from the experimental switch tests will be compared to circuit models and the data presented showing the operating characteristics of the switch for various pressure ranges.

I. INTRODUCTION

Directed energy research has fueled the need for more compact switches for use in high repetition rate systems. A flowing, high pressure liquid dielectric switch is being developed to meet these needs. A switch is required near term that will switch 250-1000 kV and currents on the order of 50-250 kA. Other requirements of this switch are listed in Table 1.

When a high voltage pulse is applied to a liquid dielectric switch and the switch breakdown voltage is reached, a streamer is launched and subsequent avalanche ionization and breakdown of the dielectric results [1]. The arc then ionizes the dielectric medium and a gas bubble is formed between the electrodes. At atmospheric pressure the diameter of the bubble expands well beyond the electrode separation distance, thereby precluding the possibility of operating a liquid dielectric switch at the goal of 100-150 pps, when transfer energies are in excess of 1 kJ. Subsequent growth of the gas bubble and the formation of microbubbles as the gas bubble collapses prohibit reapplication of the voltage until the entire volume of oil in the switch is exchanged. The UMC design circumvents this problem by leveraging upon the results of previous research that demonstrated that pressurization of the fluid reduced the diameter and volume of the gas bubble [2][3].

Testing of a single shot Concept Validation Test (CVT) switch yielded results that were used to design the rep-rate high pressure oil switch. Some of the important results include the effects of high pressures on the breakdown strength of oil, the formation and expansion of byproducts, and oil flow requirements [4]. Pressurizing the liquid resulted in greatly reduced bubble size and a modest increase in the carbon production. The carbon particles were observed to move away from the arc site at much slower velocities than the expansion velocity of the gas bubbles. The design of an oil flow scheme is described in this report.

Table 1. Rep-rate switch requirements

Voltage	100-1000 kV
Current	50-250 kA
Risetime	<50 ns
Charge transfer	~0.5 Coulombs/pulse
Jitter	<50 ns
Pulse repetition rate	50-150 pps
Pulse width	50-500 ns
Lifetime	10^7-10^8 pulses

The parameters of the switch requirements have been expanded to include switches in the 100 kV voltage range, commensurate with rep-rate Marx generator applications. Accordingly, a switch operating at 100 kV has been built and tested on a trigger test stand at the University of Missouri.

The breakdown strength of oil was found to increase with increasing pressure, up to about 1500 psi, with no further increase for pressures up to 2000 psi. The breakdown strength of sub-millimeter oil gaps that are

* Work supported by the USAF, AFRL at Wright Patterson AFB, under contract No. USAF F33615-01-C-2191.

ξ curryrd@missouri.edu

consistent with a 100 kV switch is somewhat unpredictable. Experiments on the trigger test at voltages of 100 kV showed that the breakdown strength at any given pressure for sub-millimeter gaps can vary by as much as ±20% of the average breakdown value. Shot to shot variations of this magnitude would result in extremely large jitter values. A single shot triggered switch has been developed to explore the feasibility of reducing jitter and is discussed in the paper.

II. REP-RATE SWITCH DESIGN

Design of the rep-rate test switch required significant electric field and mechanical stress simulations. Other computer design tools include a switch model program written in Matlab [4], PSpice circuit simulations, and fluid flow simulations. The switch was designed for use in a rep-rate system, described in a separate conference paper [5], in which a 4.8 Ω water transmission line is charged to 250 kV at 100 pps continuous rep-rate operation.

$$p = 0.5\left(\frac{E}{E_{br}}\right)^{\frac{1}{0.075}} \quad (1)$$

Calculations of the probability of breakdown of oil based on equation (1) predict that a field stress of about 26% of the breakdown strength will result in a probability of one breakdown out of 10^8 shots. Insulators in a switch designed with electric field stresses below 26% of breakdown are expected to have a lifetime of about 10^8 shots. Equation (1) expresses the probability of oil breakdown in terms of the actual electric field stress and the electric field breakdown strength of the oil. J. C. Martin's equation, equation (2) gives an explanation of how the breakdown field strength (MV/cm) is affected by the charge time (μs) and the stressed area (cm^2) [6][7]. Using equation (2), for the breakdown strength of oil predicts that for an effective charge time of 1.07 μs and a stressed area of 9.5 cm^2 the breakdown strength will be 560 kV/cm. To achieve the desired switch lifetime, the electric field simulations were run and the switch was modified so that the maximum field strength on the conductor surface was not greater than 140 kV/cm, and the field stresses at the triple points were no greater than half this value.

$$E_{br} = 1.41\left(\frac{.48}{t_{eff}^{1/3} A^{0.075}}\right)\left[1 + 0.12\left(\frac{E_{\max}}{E_{mean}} - 1\right)^{1/2}\right] \quad (2)$$

Circuit and electric field simulations were used to determine the placement of diagnostic probes. D-dot probes are optimal for use in transmission lines and geometries where the electric field is very uniform. Electric field simulations were done to aid in the placement of the D-dot probes in locations where the electric field is most uniform. Accordingly, D-dot voltage probes will be placed in the housing around the switch to measure the voltage at the top and bottom of the switch. These measurements coupled with the current, as measured with a Rogowski coil mounted around the switch, will provide an approximation of the energy dissipated in the switch.

Testing of the CVT switch confirmed that the volume of byproducts is reduced by increasing the hydrostatic oil pressure. A plan is presented below for clearing these byproducts from the switch to facilitate rep-rate operation and to meet the goal presented in Table 1. The CVT tests also revealed that the reproducibility of the breakdown voltage must be improved to meet the jitter specification. Experiments with a high pressure oil trigatron, described below, have shown that the jitter can be reduced through the use of an electrical trigger pulse.

Fabrication of the complex rep-rate switch hardware is nearly completed. The switch will be installed on the rep-rate test stand and experiments will determine the minimum flow rate needed to achieve 100 pps operation at 300 kV, the maximum rep-rate possible for the available maximum oil flow rate, optimum oil pressure, and repeatability of the breakdown voltage.

In the interim, a simplified high pressure oil switch with 3.81 cm diameter flat electrodes has been built and tested and is described in a separate conference paper [5].

III. CLEARING THE ELECTRODE GAP

Experiments with the single shot CVT switch at various pressures confirmed that the size of the bubbles formed by an arc through oil decreases with increasing pressure. The amount of carbon produced by each arc was found to increase somewhat with increasing pressure. As shown in Figure 1, the carbon clouds that are formed at high pressures, expand at a much lower rate than do the bubbles formed at atmospheric pressure. The initial bubble expansion velocity was about 25 m/s while the initial expansion rate of the carbon clouds was 3-5 m/s. The result is that increasing the pressure of the oil decreases the expansion rate of the byproducts formed, and thus decreases the oil flow rate required to clear the electrode gap between shots.

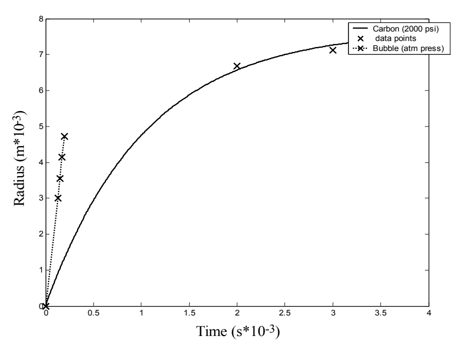

Figure 1. Comparison of the expansion of carbon clouds at 2000 psi to the expansion of bubbles at atmospheric pressure.

The CVT switch was utilized to determine the ability of a flowing oil switch to clear byproducts formed by arcing through the oil from the electrode gap. Several flow geometries were tested, including: directed cross flow, axial flow (through the ground electrode), and flow through a "pin-in-hole" electrode geometry. The motion of the byproducts was observed utilizing a Kodak HG Model 2000 Imager at the maximum frame rate of 2000 frames per second with an exposure time of 983 μs. The images acquired from this setup were used to determine the velocity of the particle motions as they were displaced by the flowing liquid. The time required to clear the gap of byproducts was observed for each of the flow geometries.

The pin-in-hole geometry, forces all of the oil to flow through the electrode gap and also decreases the byproduct expansion into the low flow velocity regions of the switch outside the electrodes. Oil flows into the switch at several entry points around the high voltage electrode and then must flow through the discharge site and exit the switch through the center of the ground electrode. Utilizing this electrode geometry, a flow rate of 0.5 l/s at 2000 psi should be sufficient to clear the byproducts from the electrode gap and enable rep-rates of at least 100 pps [4].

Furthermore, fluid flow simulations of the pin-in-hole electrode geometry revealed that flowing a small amount of oil through the center of the high voltage electrode will prevent byproducts from collecting at the tip of the electrode. The rep-rate switch is designed with separate sources for the flow around the high voltage electrode and through the center so that the flow rates can be varied independently.

IV. TRIGGERED EXPERIMENTS

One method of reducing the jitter of a switch is by active triggering. There are many different methods that can be used to trigger a switch including: laser, mid plane, trigatron, and surface discharge. An electrical trigger pulse was chosen for testing due to the availability of pulse generators in our lab. Due to the very small gap spacings (~0.1 cm) necessary for testing at voltages on the order of 100 kV, a mid plane trigger is not practical. Hence, trigatron and surface discharge geometries were selected for testing on a single shot test stand.

A trigger test stand was designed and built to determine the effectiveness of a high pressure liquid trigatron switch. The trigger test stand utilizes two pulsers to test a static high pressure oil switch in single shot operation. The main high voltage electrode pulse is provided by a TG-125 that charges a 10 nF capacitor through a 5 Ω resistor to 100 kV with a 10-90% charge time of about 350 ns, as shown in Figure 3. The trigger pin can be pulsed to 50-100 kV by a Mini Pulser with a 10-90% risetime of 5 ns. The Mini Pulser consists of a mini Marx bank charged to ±25 kV. After the Marx erects, it charges a peaking capacitor and a pulse is sent down a 50 Ω coaxial cable. The trigger pulse is delayed so as to arrive at the switch when the main gap reaches about 90% of full charge. A resistor is placed between the Mini Pulser and the trigger pin for protection when an arc forms from the high voltage electrode to the trigger pin.

Figure2. Photograph of trigger test stand.

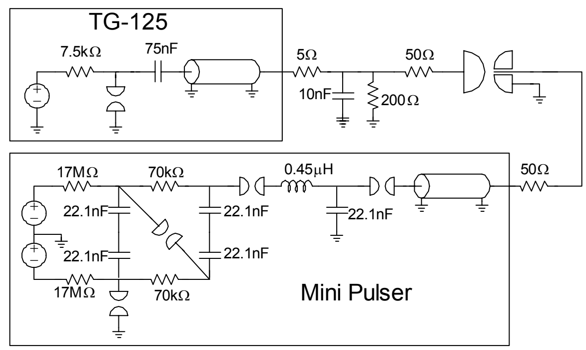

Figure 3. Circuit diagram of the trigger test stand. A TG-125 provides the main gap voltage and a Mini Pulser pulses the trigger pin.

Previous research with liquid trigatron switches has shown that the shortest delay to breakdown can be obtained for a switch that is anode triggered [8][9]. The switch tested on the trigger test stand is supplied with a negative polarity high voltage pulse to the main electrode. A trigger pin imbedded in the anode receives a positive polarity pulse. This combination of polarities has been found to result in the lowest required field stress on the main electrode gap [9].

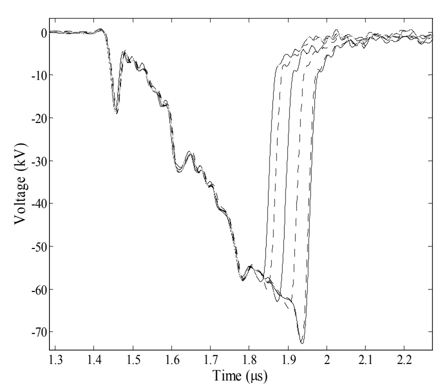

Figure 4. Plot of 10 self break shots from the trigger test stand.

Several trigger electrode geometries have been tested. The final trigger electrode design, shown in Figure 5, utilizes a 2.54 cm diameter hemispherical electrode with a 0.3175 cm diameter trigger pin. The trigger pin is held in place with a polycarbonate insulator and fits into a hole in the electrode tip of about 0.366 cm diameter. The trigger pin is flat on the end and is placed so the tip is nearly flush with the tip of the electrode.

Preliminary results from atmospheric pressure oil testing of the trigger electrode show a typical delay to breakdown of about 60 ns and a jitter of $1\sigma \approx 30$ ns. Self break tests with the same electrodes, shown in Figure 4, produced a jitter of $1\sigma \approx 50$ ns. Similar tests at 1000 psi and 2000 psi resulted in jitters of $1\sigma \approx 13$ ns and $1\sigma \approx 27$ ns, respectively. Further optimization of the trigger scheme should reduce the delay to breakdown and also the jitter.

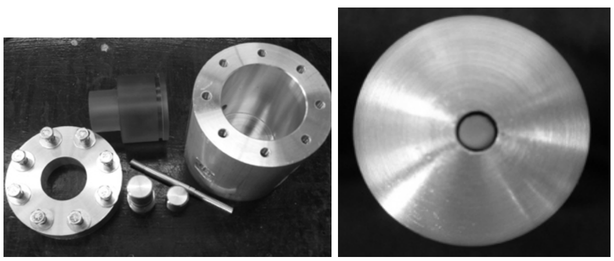

Figure 5. Photograph of the high pressure oil switch hardware on the left, and a closeup of the trigatron electrode on the right. Trigger pin is 0.3175 cm diameter stainless steel.

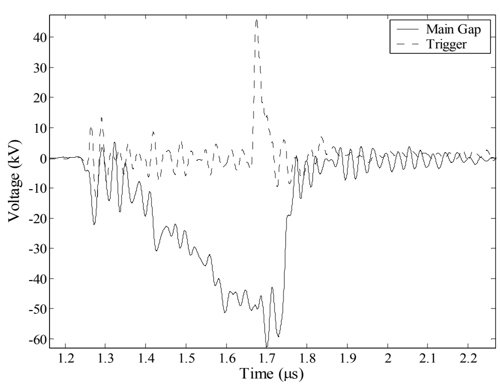

Figure 6. Typical waveform for a triggered shot. The delay to breakdown for this shot is about 75 ns.

Inspection of erosion patterns on the ground and trigger electrodes indicates that when triggered, some shots form an arc from the high voltage electrode to the ground electrode, while in other shots the arc forms from the high voltage electrode to the trigger pin and then transfers to the ground electrode, as documented by previous research [9]. It appears that jitter may be lower when an arc forms from the high voltage electrode to the trigger pin, however the erosion problems can be exacerbated. Further tuning of the trigger electrode geometry should result in a greater reduction of the switch jitter.

V. SUMMARY

A rep-rate high pressure oil switch has been designed to meet the needs of directed energy research and will be tested in the coming months. A plan has been presented for overcoming the remaining obstacles to meeting all of the switch requirements.

The rep-rate switch design is based on lessons learned from a single shot CVT switch. High flow rates combined with a novel electrode geometry will clear byproducts from the electrode gap and allow the switch to achieve 100 pps repetition rates.

A single shot test stand for trigger experiments has been designed and tested. The ability to trigger the switch at high pressures with a trigatron electrode geometry has been demonstrated. Tests at atmospheric pressure and 1000 psi have shown a reduction in jitter when the switch is triggered.

VI. REFERENCES

[1] E. Kuffel, W.S. Zaengl, High Voltage Engineering, Pergammon Press, 1984, Oxford.

[2] J. W. Strutt and Rayleigh, “On the pressure developed in a liquid during the collapse of a spherical cavity,” *Phil. Mag.*, vol. 34, pp. 94–98, 1917.

[3] R. H. Cole, *Underwater Explosions*. Princeton University Press, 1945.

[4] J. Leckbee, R. Curry, K. McDonald, R. Cravey, and A. Grimmis, “An advanced model of a high pressure liquid dielectric switch for directed energy applications,” in Proc. 14th IEEE Int. Pulsed Power Conf., 2003, pp 1389-1393.

[5] P. Norgard, R. Curry, and K. McDonald, “Design notes and initial results from a 100 pps, 250 kV switch testing platform,” in Proc. IEEE Int. Power Modulator Symposium, 2004.

[6] J. C. Martin, “Nanosecond pulse techniques,” *Proc. IEEE*, vol. 80, no. 6, pp. 934–945, 1992.

[7] R. J. Adler, “Pulse power formulary,” North Star Research Corp., June 2002.

[8] P. Watson, W. Chadband, and W. Mak, “Bubble growth following a localized electrical discharge and its relationship to the breakdown of triggered spark gaps in liquids,” IEEE Trans. Electrical Insulation, Vol EI-20, No. 2, pp 275-280, 1985.

[9] J. Maksiejewski, “The breakdown process of a liquid trigatron,” IEEE Trans. Electrical Insulation, Vol. 23, No. 2, pp 227-230, 1988.