DESIGN AND DEVELOPMENT OF A 1 MV, COMPACT, SELF BREAK SWITCH FOR HIGH REPETETION RATE OPERATION

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Abstract

The design of compact, high voltage switches is generally plagued by the tradeoff between reduced size and the probabilities of bulk and surface breakdown. Moreover, typical breakdown field values for wide classes of materials with desirable electrical and mechanical properties are unavailable. In the development of a compact gas switch, capable of holding off voltages of up to 1 MV at repetition rates of 200 Hz, a criterion to insure the inhibition of surface flashover in a high pressure atmosphere has been developed.

The switch is composed of copper tungsten electrodes with a coaxial Torlon pressure containment housing of length 12.7 cm and a diameter of 15.3 cm. Pulse repetition rates in the 100's of Hz are achieved by using moderately hydrogen pressures as the insulating medium. The electrodes are shaped to produce a uniform field distribution in the gap with an adjustable spacing of 0.5, 0.75 and 1.0 cm. Additional stress is put on the switch by charging with a dual-resonant pulse transformer.

I. INTRODUCTION

For commercial applications, the size and weight of components alone may determine the feasibility of systems, and thus, compact pulsed power is becoming a technology thrust area [1]. High power switches are an integral part of most pulsed power systems and are on the critical path to compact system design. Little information has been published on the design of compact, high power switches, but notable exceptions are the works of DiCapua [2] and Goerz [3]. The self breaking, 2 MV switch described by DiCapua is approximately 16 cm long and insulated with sulfur hexaflouride (SF$_6$) but alludes to deviations in the scaling relations that can occur higher E/p ratios. On the other hand, the switch described in [3] is very compact, and capable of holding 100 kV with 100 psi of SF$_6$ but the PRR is limited to 15 Hz.

High pulse repetition rate (PRR) systems are increasin important to the commercial sector [1]. In general, desire for high PRRs mandate the switching media be eit high pressure gases or flowing oil [4]. Moreover, it has b shown that high-pressure hydrogen provides the best recovery characteristics [5]. Gaseous insulators are easie use and are generally preferred when the switches sealed. Flowing oil switches, while harder to implem offer an increased bulk breakdown strength and a stron dependence on the charging pulse duration than switches [6].

The compact, high PRR, high voltage parameter sp introduces new problems into the switch design. Comp high PRR, high voltage switch design is made m difficult because the widely accepted relations for both b breakdown and surface flashover are suspect, at least PRRs exceeding 100 Hz [7,8]. For gas switches, the h PRR mandates a high-pressure gas atmosphere, to prov the superior insulating recovery between pulses. This hi pressure gas, however, is detrimental to the mechan integrity of the switch. The energy of the compressed ga proportional to the volume, and thus, for maximum sa and ease of design, a minimum gas volume is desirable. the size of the switch is decreased, the probability of fail by surface flashover increases.

Surface flashover, under high PRRs and in a h pressure hydrogen atmosphere, has been prevented choosing 135 kV/cm as the maximum allowable tangen electric field along the interface. The compact gas swi demonstrated by Goetz also successfully inhibited surf flashover by limiting the electric field, the total elec field, along the gas/plastic interfacial surface to 130 kV [3]. The self breaking high pressure gas switch descri here is a compact design to reliably switch voltages on order of 1 MV and has been demonstrated at p repetition rates of 200 Hz.

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14. ABSTRACT

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II. SWITCH DESIGN

The final switch design took three iterations, all of which were instructive. The evolution of the switch design is presented. The initial design validated the proposed criteria for surface breakdown. While failure by surface flashover was anticipated, the first version failed by bulk breakdown. The second version determined that the discharge initiation site was the weak point and the third design managed the electric field distribution by reconfiguring the switch geometry to provide the reliable switching of 1 MV at a 200 Hz pulse repetition rate.

The design of the compact self breaking switch is a part of a highly integrated secondary side of an air core dual resonant transformer. The geometry of the secondary capacitor/switch configuration is shown in **Figure 1** and the location of the capacitor is indicated. The switch is located at the center terminal of the capacitor formed by the oil filled region between the inner and outer conductors. The center terminal of the capacitor is made of high quality 7075-T6 aluminum and the switch cathode is a copper tungsten extension inserted into to the aluminum. A uniform electric field is established between the electrodes set 7.5 mm apart. To provide reliable switching at 1 MV and 200 Hz with a 200 ns charge cycle under a bipolar charging waveform requires 1600 psi of hydrogen.

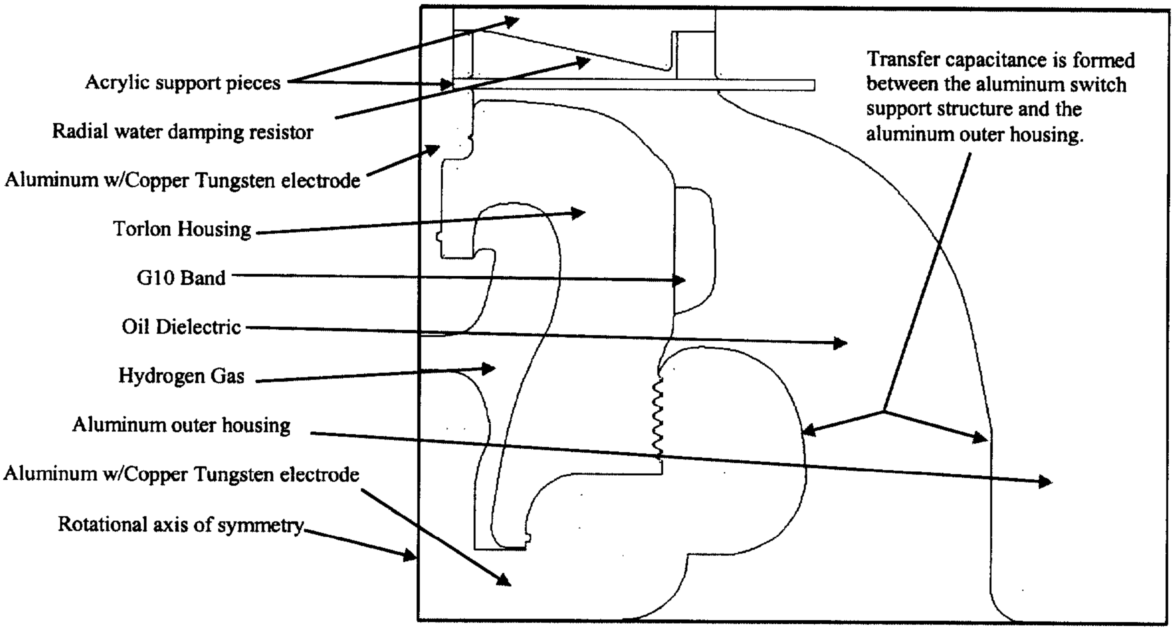

Figure 1. The half crossection of the initial switch design. The axis of rotation is the left border of the switch.

A. *Mechanical Design*

The main housing is made of Torlon [9], a high performance, molding polymer known for its strength. In addition to its outstanding mechanical strength, Torlon is easy to fabricate and has excellent creep resistance and thermal stability. Electrically, the relative dielectric constant is approximately 4 and it is known to be dispersive. The dielectric strength is listed in its data sheet as 225 kV/cm. Torlon is commercially available only in certain diameters, so to meet a factor of safety of four for manned operation, the Torlon housing was reinforced with a band of G-10 to hold the required pressure of 1600 psi. The air gap between the Torlon and the G10 is filled with Sylgard 527.

The precise tolerances achieved on the high-pressure hydrogen switch clearly demonstrate the power of computer aided mechanical design in combination with material selection and accurate finite element analysis. All parts of the switch were fabricated directly from 3D CAD electronic data to hold the close tolerances required for a complete seal. Machining from electronic data allowed surfaces defined by mathematical equations to be created exactly to specification. All components were fully rendered and fit checked as a 3D solid model that eliminated assembly mismatches. In addition to a tight seal to the high pressure insulating media, manufacture from electronic data files allowed the electric field profiles to be calculated precisely as fabricated and a weakness in the prototyping process was eliminated.

B. *Electric Field Considerations*

The initial design focused on the development of a criterion to prevent surface flashover along the hydrogen/Torlon interface. In particular, the tangential component of the electric field was kept at a maximum of 135 kV/cm. It should be noted that this is in addition to also considering the magnitude of the electric field. In addition to the surface breakdown specification, special attention to minimize the tangential electric field at the triple point where the hydrogen/Torlon interface meets the electrode. The electric field modeling package, Electro™, allows the electric field, and its components, to be computed along a specific surface [10]. This computation of the tangential electric fields along the hydrogen/Torlon interface is shown in Figure 2 and indicates values of less than 135 kV/cm at all points. The design criteria for the inhibition of surface flashover was deemed successful and the gas/plastic interface profile has been used in over 10,000 shots, under repetitively pulsed conditions.

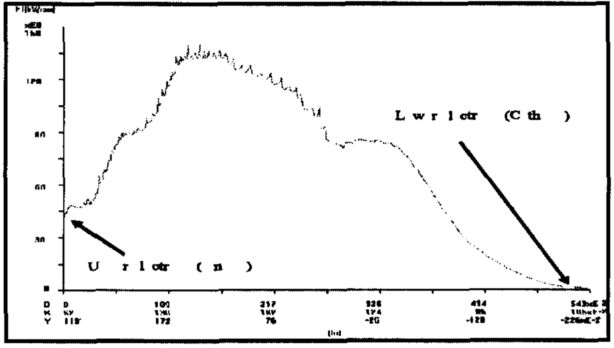

Figure 2. A plot of the tangential electric field along the hydrogen/Torlon interface indicate the highest tangential electric field along the interface is 130 kV/cm. The as-machined surface was closely simulated by using many straight line segments instead of a spline curve, which accounts for the jagged appearance of the field plot.

C. Switch Version 1

The switch did not fail via surface flashover, but did fail through the bulk after approximately 1500 shots at 1 MV. The failure path is bulk breakdown through the Torlon, along the Torlon/Sylgard/G10 interface and to the aluminum support structure. The equipotential plots and the approximate failure path through the switch assembly are shown in Figure 3.

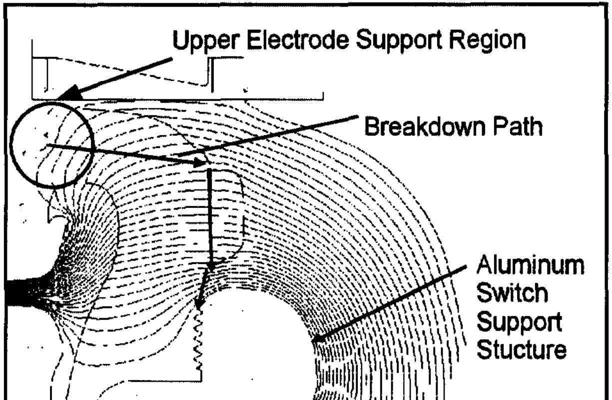

Figure 3. The switch failure path for switch version #1.

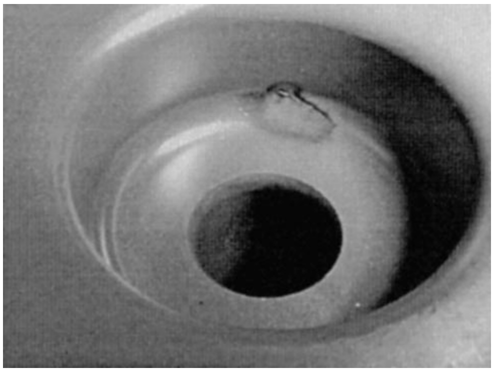

Figure 4. The initiation site of the initial switch design.

As indicated, the discharge initiated at the upper electrode region, traveled to the Torlon/Sylgard/G10 junction to the aluminum lower switch support. A photo of the failure initiation site is shown in Figure 4. The upper electrode support structure was analyzed by plotting its normal electric field component, shown in Figure 5, along its length. The maximum normal electric field along the length of the electrode is approximately 190 kV/cm and occurs in the location where the bulk breakdown occurred. The dip in the plot of Figure 5 which shows nearly zero normal electric field is the location of an o-ring.

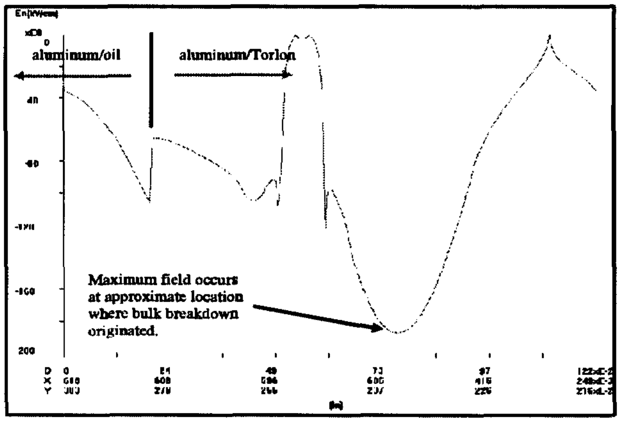

Figure 5. Normal electric field component for the upper electrode support structure circled in Figure 3. The location of the highest electric field (~190 kV/cm) corresponds to the failure initiation site.

D. Switch Version 2

Although the normal electric field along the upper electrode indicates with some certainty the likely discharge initiation site, the Torlon/Sylgard/G10 interface was also suspect. To test the influence of the three dielectric interface, the G10 band (along with the Sylgard) was eliminated. All the other switch components were kept the same, and tested. This version of the switch failed under nearly identical conditions as the first version: approximately 1500 shots and along the same path. This confirmed initiation at the aluminum/Torlon high field region. The fields of 190 kV/cm seems low for a homogeneous plastic, even under repetitive stress, and more data on the breakdown of Torlon would be useful. It is possible that breakdown in the hydrogen layer between the aluminum and the Torlon could be a factor, though the increase in field in the hydrogen by the ratio of the dielectric constants, to ~ 800 kV/cm, should not have exceeded the gas breakdown strength.

E. Switch Version 3

Even though experiments had shown the G10 band did not contribute to the electrical failure of the switch, the G10 band was eliminated from the switch design. Initially the G10 was placed there for mechanical integrity and to insure a factor of safety of 4 for gas pressures up to 2000 psi. Early experiments indicated an operating pressure of 1600 psi was sufficient. Elimination of the G10 band at 1600 psi gas pressure provided a factor of safety of over 3.5, which was deemed sufficient since it was also contained by a metal enclosure.

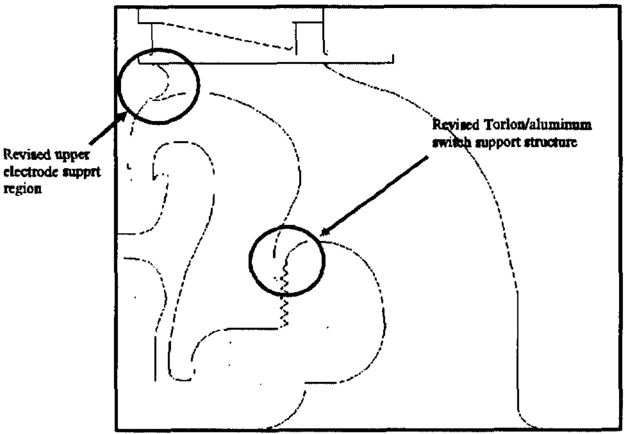

Figure 6. Final switch geometry.

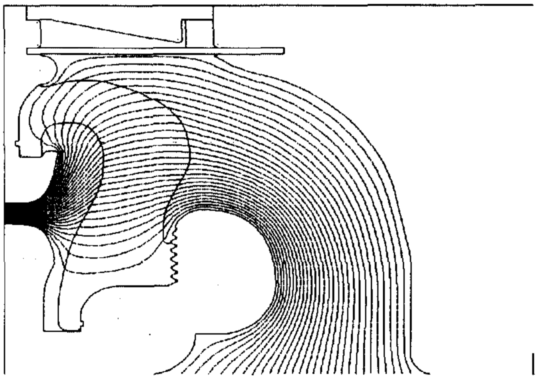

Figure 7. Equipotential plots of the switch of Figure 6.

The geometry of the switch housing was modified as shown in Figure 6, with the main changes shown in circles. The electric fields at the upper electrode region were reduced by adjusting both the Torlon and aluminum contours, thus increasing the fields in the transformer oil above the Torlon housing. The lower housing was modified to move the triple point at the Torlon/aluminum/oil interface further into the aluminum. Figure 7 shows the equipotential plot of the final switch configuration. The shift in the electric field is evident in the plot of the normal component of the electric field shown in Figure 8. The electric field along the aluminum / Torlon interface is just 50 % of that in the previous version of the switch.

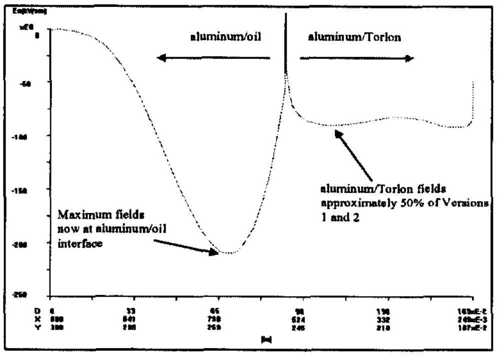

Figure 8. The peak normal electric field of ~200 kV/cm is forced into the oil. The final switch design was successfully tested to 1 MV and 200 Hz.

III. CONCLUSIONS

The design of a 1 MV compact, high-pressure gas switch for high repetition rate operation has been detailed and demonstrated. A practical criteria for the inhibition of surface flashover along the high pressure gas/insulating solid interface has been proposed and successfully demonstrated under pulse repetition rates of 600 Hz. Excellent commercially available electrostatic field solvers enabled the use of complex interface shapes.

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