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AN IMPROVED, EXPLOSIVELY ACTUATED CLOSING SWITCH FOR PULSED POWER APPLICATIONS

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AN IMPROVED, EXPLOSIVELY ACTUATED CLOSING SWITCH FOR PULSED POWER APPLICATIONS

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Abstract

An improved, explosively actuated closing switch has been developed for the Pegasus II capacitor bank. The new switch design uses an annular metal jet as the switch contact. It has lower resistance and inductance at early time than the original design. A parallel array of 24 switches on Pegasus II has a resistance of less than 10 μΩ after 300 ns. Measured time behaviors include an intrinsic jitter of 50 ns and a switching delay that depends inversely on the applied voltage.

Introduction

Pegasus II is a fast-discharge capacitor bank capable of producing a peak current of >12 MA in 6 μs. Because the bank operates at a relatively low charge voltage of ± 50 kV, it is important to keep the system inductance and resistance low. Among the alternatives available for switching Pegasus II, explosively actuated closing switches provide the lowest inductance, due to the close spacing of the switch electrodes. The most serious limitation of explosively actuated switch is the turn-around time required to replace the dielectric and the explosive element between discharges. For the current Pegasus II shot rate of < 1 /week, switch refurbishment is not an important consideration, and explosively actuated switches have been in use for several years.

The switch design shown in Fig. 1 was used for several years on the original Pegasus I capacitor bank. The actuator is a commercial RP-1 detonator [1] that uses an electrically exploded bridgewire to initiate 0.6 grams of high explosive. Pressure from the explosive charge forces the copper foil through 1.27 mm of polyethylene dielectric to complete the electrical circuit.

Each of the four bank modules used 6 switches in parallel to minimize the circuit inductance and to limit the peak current in each switch to ~300 kA. This arrangement worked with great reliability at voltages as high as 130 kV. The explosive switches are essentially immune to many problems that plague gas switches, e.g., prefire and failure to multichannel.

When we began planning for the upgrade of Pegasus I (1.5 MJ, 8 MA) to Pegasus II (4.3 MJ, 12 MA) in 1992, it was decided that the early time behavior of the Pegasus I switch would not be acceptable for Pegasus II. Fig. 2 shows typical waveforms for Pegasus I. The output voltage rises over a period of almost 1 μs instead of exhibiting the instantaneous step expected from an ideal switch. This slow rise results from a combination of excessive jitter and high initial resistance.

This paper describes the design of an improved switch with lower initial resistance and reduced jitter. Section 2 describes hydrodynamic calculations for the new switch design. Measurements on a single switch element to verify the design are discussed in Section 3. The last section presents the results achieved with the new switch on the Pegasus II bank.

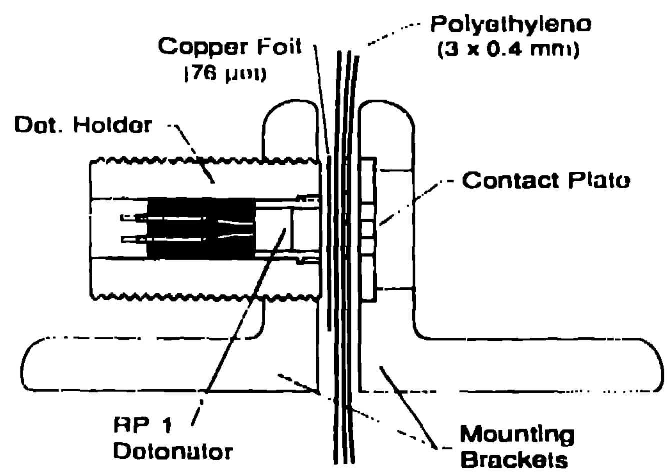

Figure 1. Expanded view of the explosively actuated closing switch used on Pegasus I. During operation, the dielectric is tightly sandwiched between the detonator and the contact plate.

Switch Design Calculations

The principal change in the switch design is the addition of a jet-forming element between the explosive charge and the dielectric. The jet-forming element is an aluminum disk with an annular groove on the side facing the dielectric as shown in Fig. 3. Interaction between the shock wave from the explosive and the annular groove produces an annular jet of metal that penetrates the dielectric.

There are three advantages to this design. First, by spacing the jet forming element away from the dielectric, switching occurs before the explosive pressure compresses the dielectric. In the original design, switching occurs in a material that has been compressed to a pressure of greater than 100 kbar. This raises the density in the switching arc and, thus, its resistance. Second, the jet provides a larger cross sectional area of metal to carry current. In the original design, current is carried by a thin copper foil that has been severely distorted by the action of the explosive. There is evidence that this foil never provides a metal to metal contact during switching. Third, the metal jet reaches a higher velocity than the copper foil in the original design, resulting in reduced jitter.

The annular jet design concept was used successfully on the Procyon pulsed power system [2], but with a much larger explosive charge (~5 grams). The 0.6 gram charge in the RP-1 detonator is more appropriate for a laboratory facility but we were not sure that it would provide enough energy to form an annular jet. Calculations were performed for several groove geometries using a 2-D hydrodynamics code. The main design parameters were groove width and groove depth. In all cases the jet material was aluminum and the insulator

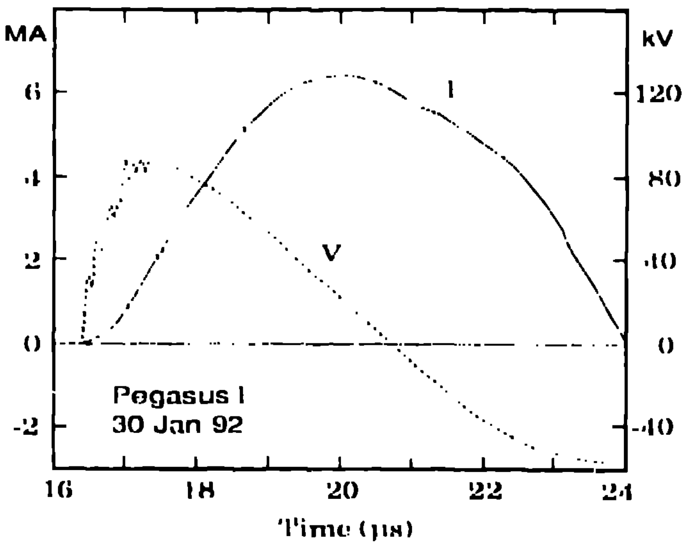

Figure 2. Current and voltage waveform from Pegasus I, showing the effect of non-ideal switch behavior at early time.

The 2-D code has a programmed-burn model for explosive detonation and the detonation was assumed to start as a full pressure, point source at the location of the bridgewire. Fig. 4 shows the calculated motion of the jet for the chosen configuration. The factors that were considered in selecting this configuration were jet velocity, cross-sectional area of the jet and stability of the jet as it penetrated the dielectric.

Fig. 4a shows the initial configuration for the calculation. Note that the annular groove is spaced away from the dielectric by a protrusion at the rim of the jet-forming element. Fig. 4b shows an early stage of jet formation, before the jet has reached the dielectric. In Fig. 4c, the jet has nearly penetrated the insulation. A typical "mushroom" shaped head has developed. The main body of the jet is not in contact with the dielectric and is essentially free of any external pressure. As a result of the initial stand off, only the jet has interacted with the dielectric at the time of switching.

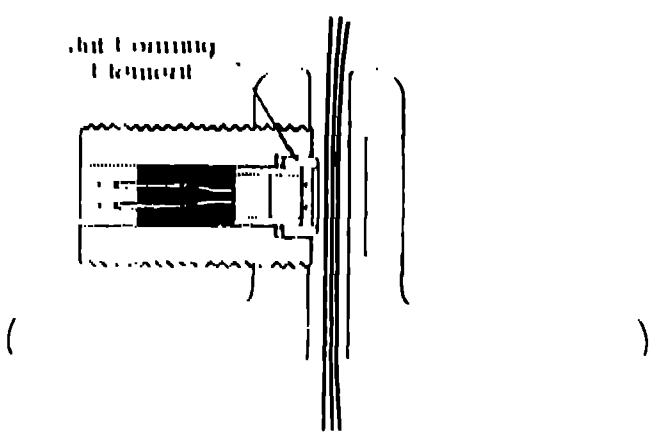

Figure 3. Improved switch design using a jet forming element. The

Table I

Comparison of calculated and measured performance of the explosive-driven aluminum jet

	Axial (calc.)	Annular (calc.)	Annular (exp.)
Free jet velocity	6.35 km/s	4.93 km/s	
First contact*	2.38 μs	2.54 μs	4.04 μs
Penetration*		3.10 μs	4.87 μs
Mean velocity in dielectric	·	2.27 km/s	1.46 km/s
Conducting area	0.09 mm²	2.28 mm²	

* Time relative to initiation of the explosive

The calculated and measured properties of the annular jet are summarized in Table I. The entry labeled "Conducting area" is the smallest cross-sectional area of the jet at the time it penetrates the 1.27 mm polyethylene dielectric. This area is sufficient to carry the Pegasus II current for about 4 μs before fusing. Taking into account the effect of jet motion, metallic conduction may last even longer.

A calculation was also performed for an axial jet, i.e., for a single hemispherical depression on the center, ie. The calculated jet velocity increased to 6.3 km/s for this case but the cross-sectional area was reduced to 0.09 mm², only 4.2% of the area of the annular jet. For this reason, axial jets were not investigated further.

Experimental Evaluation

Two sets of laboratory experiments were carried out to verify the predicted performance. In the first experiment, the annular jet switch (AJS) was fired through a dielectric consisting of three sheets of polyethylene (0.40 mm thick) with a thin layer of aluminum foil on the surface of each layer. Each aluminum foil layer was connected to an electrical circuit that sensed contact with the jet.

The results of this measurement are summarized in the last column of Table I. The measured time of first contact is about 1.5 μs later than expected from the calculations. The penetration time is also longer, leading to an average penetration velocity of only 1.46 km/s, substantially below the 2.27 km/s expected. We have not identified the source of this discrepancy but it may result from assuming prompt detonation of the explosive. In our calculations, the detonation wave reaches the face of the explosive in 1.8 μs. The manufacturer specifies this arrival time as 3.0 μs. This suggests that the explosive does not reach full detonation pressure immediately and, thus, may not provide the calculated driving pressure on the jet forming element.

Although jet velocity was lower than expected, the AJS produced improved switching behavior and characterization testing was continued. The second phase of testing was done on a small capacitor bank that provides current and voltage waveforms similar to those experienced by a single switch on the Pegasus II bank. These measurements addressed early time resistance and the switch jitter

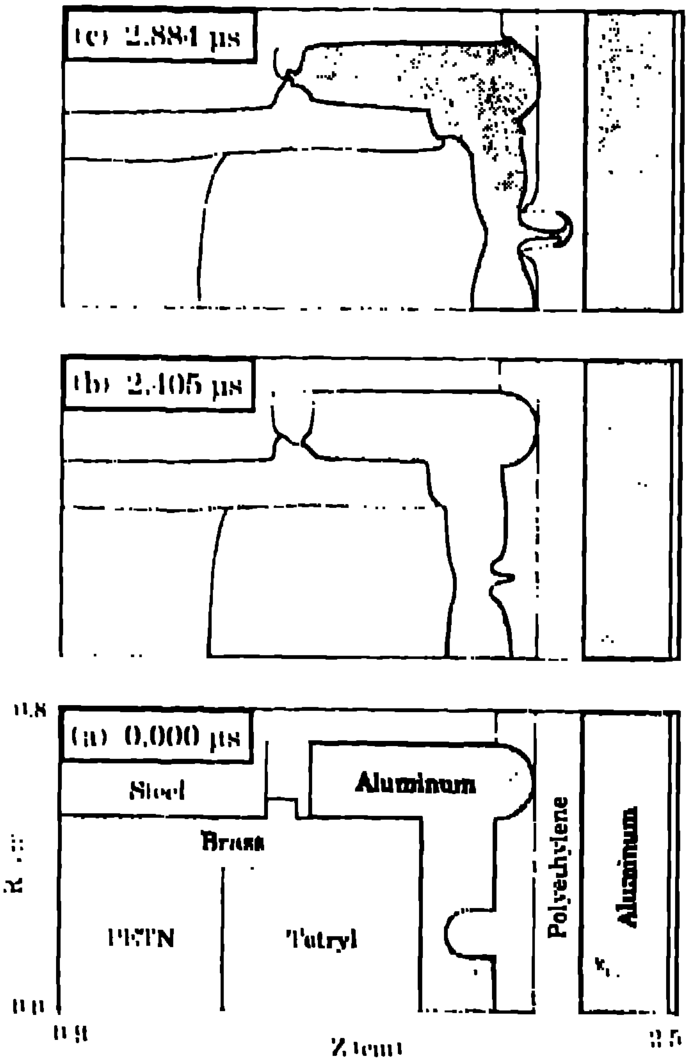

Figure 4. Predictions of jet motion from the 2-D hydrodynamics calculations: (a) initial configuration, (b) as the jet begins to form, (c) shortly before switch closure.

Nine experiments were conducted at charge voltages from [illegible] kV to 90 kV and İ dots from [illegible] × 10[10] A/s to [illegible] × 10[10] A/s. Switch voltage was measured with a capacitive voltage divider built into the switch mounting bracket. Only one of the tests, at 30 kV charge, gave evidence of early time resistance. The resistance decreased to less than the measurement accuracy of 0.25 Ω at 250 ns. A parallel array of 8 such switches would exhibit a resistance of less than 30 mΩ at 250 ns. We also conducted several tests of the original switch design. Resistance was measurable on every test, even at high charge voltage, and the resistance was above 0.2 Ω for more than 400 ns.

We also attempted to measure the switch resistance at peak current. There was no measurable voltage drop (< 1 kV) at a current of [illegible] kA, yielding an upper bound on the switch resistance of [illegible] mΩ. For comparison, the calculated resistance of the metal jet, neglecting the anode, is [illegible] mΩ.

Measurements of the delay between triggering the RF [illegible] detonator and the beginning of current flow are presented in Fig. 5 as a function of the applied voltage. Although there are a limited number of data points at 30 kV and 60 kV, Fig. 5 strongly suggests that the switching delay is a function of applied voltage. A possible explanation for this dependence is that the switch closes by dielectric breakdown as the jet approaches the opposite electrode. If one assumes that breakdown occurs at some critical field, E_b, then the switching time should vary as

$$t_s - t_0 = -\frac{V_a}{v E_b} \quad (1)$$

where V_a is the applied voltage, E_b is the breakdown field, v is the jet velocity and t_0 is the closing time at zero applied voltage. The straight line in Fig. 5 is a fit of (1) to the mean delays. The best fit value of E_b is 1.82 MV/cm (4.7 kV/mil). This is a large, but not unreasonable, breakdown field for a short duration voltage stress and lends credibility to this explanation of the delay.

The intrinsic switch jitter, not including voltage dependent delay, was derived from the 6 points at 90 kV. The 1σ jitter is 19 ns. Five measurements of the original switch design at 80 kV gave a 1σ jitter of 210 ns. The ten fold reduction in jitter achieved with the AJS is primarily attributable to the high velocity of the jet.

Pegasus II Operation

The annular jet switch has been in use on Pegasus II since the fall of 1992. Details of its design and use are given in the Appendix. The switch has performed reliably, producing the typical current waveform shown in Fig. 6. The current waveform begins to rise immediately with a dI/dt of 2 MA/μs. After about 380 ns, dI/dt increases to 3.85 MA/μs, the predicted value for the bank circuit inductance and charge voltage. In contrast, the Pegasus I current waveform (Fig. 2) begins with dI/dt [illegible] 0.8 MA/μs and does not reach the circuit limited dI/dt for 600 ns.

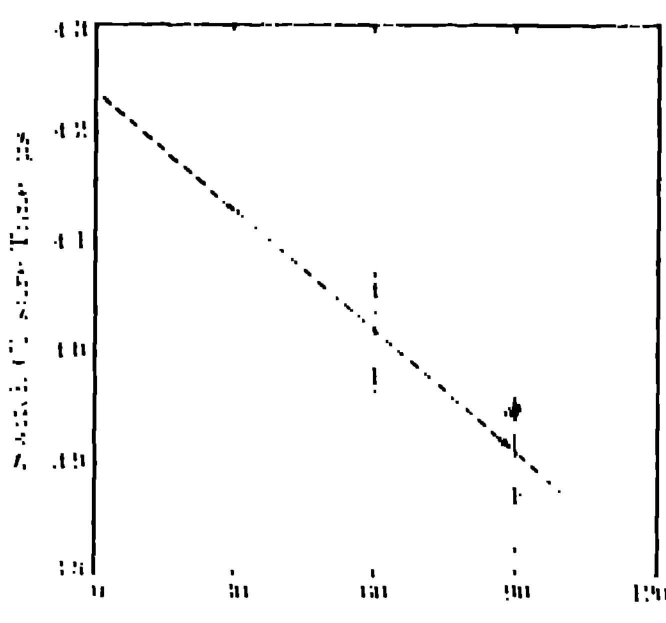

Figure 5. Measurement of switch closure time vs. applied voltage. The dashed line is the best fit to a simple model of switch delay assuming breakdown at a fixed electric field in the switch dielectric.

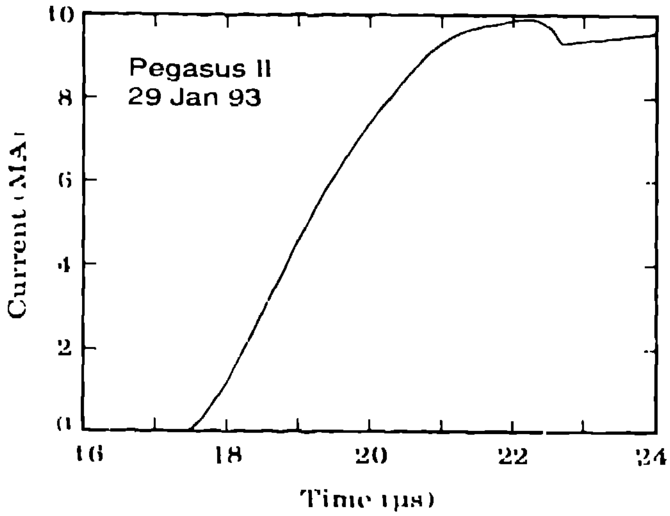

Figure 6 - Current waveform for the Pegasus II capacitor bank using annular jet switches.

Because of the improved switch characteristics measured in our development tests, we were not expecting the 380 ns period of low dI/dt at the beginning of current flow. Detailed modeling of the switching circuit established that this behavior is due to voltage-dependent switch delay rather than switch resistance or jitter.

From Fig. 5, we know that the AJS switch will close, on average, about 330 ns early at a charge voltage of 90 kV. However, only the first switch to close sees the full charge voltage. Within 30 ns after the first switch closes, the voltage on all of the other switches is reduced to approximately zero. The other switches, therefore, do not begin to close for an additional 300 ns.

The low inductance design of Pegasus II requires that the current flow be distributed uniformly among all 24 switches. During the interval when only one switch is closed, the total circuit inductance is substantially higher. After 300 ns the remaining switches begin to close, adding parallel paths and reducing the inductance. This process is essentially complete within an additional 100 ns, since the intrinsic jitter of the AJS switch is about 90 ns.

Because the low initial dI/dt is caused by inductance rather than switch resistance, there is no accompanying energy dissipation in the switches. This is confirmed by reduced damage to the switch mounting hardware on Pegasus II, despite a 4 times increase in the action ($\int I^2 dt$) carried by the switches.

Conclusions

An annular jet closing switch, driven by a commercial RP-1 detonator, provides lower resistance and a higher rate of rise of current during the first microseconds of operation. The principal limitation of the AJS is a voltage dependent closing delay that prevents true parallel operation during the first 300 ns of operation (at 90 kV charge). For applications requiring shorter delays, a booster charge could be added to the RP-1 detonator to increase the jet velocity.

References

[1] RP-1 EBW Detonators, P/N 167-4314, Reynolds Industries Systems Inc., Los Angeles, CA 90066

[2] J. H. Goforth, H. Oona, J. H. Brownell, A. E. Greene, H. W. Kruse, I. R. Lindemuth, S. P. Marsh, J. V. Parker, R. E. Reinovsky, D. G. Rickel and P. J. Turchi, "Procyon Experiments Utilizing Explosively-Formed Fuse Opening Switches," Proceedings of the 8th International Pulsed Power Conference, IEEE Catalog Number: 91CH3052-8, pp. 273-276

Appendix

Figure A.1 gives the dimensional specifications for the jet-forming element. This part was made from 6061 aluminum in our work, but any easily machined aluminum alloy should be satisfactory. The detonator holder, shown in Fig. A.2, is a modified 1"-13 x 2" steel set screw. The machined shoulder is designed to press on the detonator collar and not on the jet-forming element. This ensures that the face of the detonator is pressed firmly against the inside surface of the jet-forming element.

The mounting brackets shown in Fig. 3 are made from 2" aluminum angle with 3/8" thickness. The bracket facing the jet is machined on the back side to reduce the thickness to 3 millimeters. After switching, the jet blows through this thin area, relieving the pressure and reducing damage to adjacent parts. For example, the bracket holding the detonator can normally be reused several times.

Switch installation does not require any critical alignment. The mounting brackets should be parallel to ~1/32" over 2". The detonator holder should be screwed in finger-tight to compress, but not deform, the polyethylene dielectric.

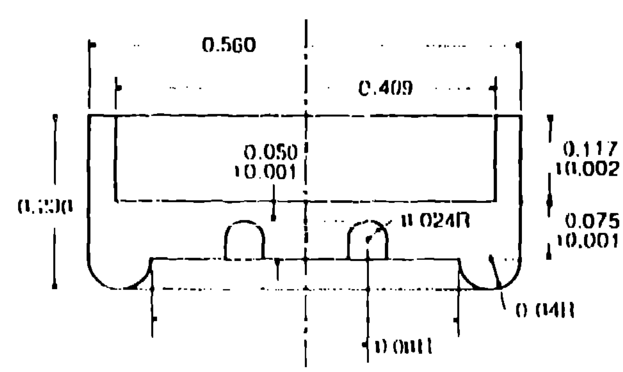

Figure A.1

Dimensions in inches

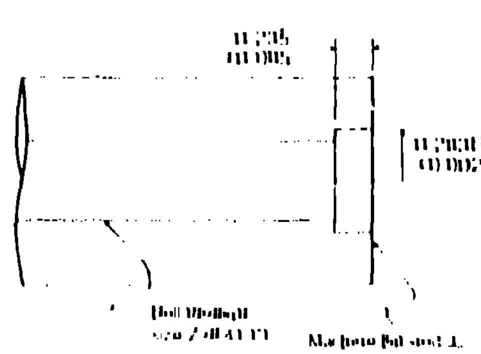

Figure A.2