Title: AN IMPROVED, EXPLOSIONLY ACTUATED CLOSING SWITCH FOR PULSED POWER APPLICATIONS

Author(s): J. V. Parker, R. R. Bartsch, J. C. Cochrane, S. P. Marsh

Submitted to: IEEE/Pulsed Power Conf.
Albuquerque, NM
June 21-23/93

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
An Improved, Explosively Actuated Closing Switch for Pulsed Power Applications

V. Parker, R. R. Bartisch, J. C. Cochran, and S. P. Marsh
Las Alamos National Laboratory
Las Alamos, NM 87545

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 23 switches on Pegasus II has a resistance of less than 10 μΩ after 300 ns. Measured time behaviors include an intrinsic jitter of 50 μs 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 122 MA in 6 ps. 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 shot/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 200 kA. This arrangement worked with great reliability at voltages as high as ±1.8 kV. The explosive switches are essentially immune to many problems that plague gas switches, e.g., arcjet and arcing to media channels.

When we began planning for the upgrade of Pegasus I (12 MA) to Pegasus II (35 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 described 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 causes the delay in the switching, 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 layer 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 Princeton pulsed power system [4], but with a much larger explosive charge. To gain the 6 grams charge in the RP-1 detonator is more appropriate to 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 2D hydrodynamic code. The main design parameters were groove width and groove depth. In all cases, the jet material was aluminum and the normal jet form was used.
The 2-D code has a programmed-burn model for explosive detonation and the detonation was assumed to start as a flat 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.

The calculated and measured properties of the annular jet are summarized in Table 1. 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, c. The calculated jet velocity increased to 0.3 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 (AJ1) is 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 1. The measured time of first contact is about 0.5 µs later than expected from the calculations. The penetration time in also longer, leading to an average penetration velocity of about 1.6 km/s, substantially below the 3.37 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 AJ1 produced improved switching behavior and characterization testing was continued. The second phase of testing was done on a small capacitor bank that produces 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.
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 the 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 $E_c$, then the switching time should vary as

$$t_s = t_c + \frac{1}{V_p}$$

where $V_p$ is the applied voltage, $E_c$ is the breakdown field, $t_c$ is the jet velocity and $t_s$ is the closing time at zero applied voltage. The straight line in Fig. 5 is a fit of Eq. 11 to the mean delays. The best fit value of $V_p$ is 138 V/m in 11.7 kV/m. 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 intruder switch jitter, not including voltage dependent delay, was derived from the points at 90 kV. The jitter is 10 ms. Five measurements of the original switch design at 86 kV gave a jitter of 21 ms. The layout reduction in jitter achieved with the APS 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 1962. 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 7 MA/s. About 200 ns, dI/dt increases to 12 MA/s, the predicted value for the bank run initial current and change voltage. In contrast, the Pegasus I current waveform Fig. 3 begins with dI/dt = 18 MA/s and does not reach the constant limited dI/dt for 200 ns.

![Diagram of jet motion](image_url)

**Figure 4:** Predictions of jet motion from the AP hydrodynamics calculations. A thermal conjugation front as the jet begins to form. Shorter before switch closure.

Nine experiments were conducted at charge voltages from 20 kV to 90 kV and 1.5 to 1.5 MA. Switch voltage was measured with a capacitance voltage divider built into the switch mounting bracket. Only one of the tests at 50 kV charge gave evidence of early time resistance. The resistance decreased to less than the measurement accuracy of 0.25% at 900 ns. A parallel array of 10 switches would exhibit a resistance less than 0.25% at 900 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 about 0.25% or more than 5 min.

We attempted to measure the switch current at peak current with a megger on the voltage drops 1 MA current at 113 kV voltage an average bound on the switch resistance of 110 MΩ. The reason for the observed resistance at the metal jet neglecting finite e = 1 cm.

Measurements of the delay between triggering the RF and the beginning of current flow are presented in Fig. 5 as a function of the applied voltage. Although there are
Figure 5: Current waveform for the Pegasus II capacitor bank using similar jet switches.

Because of the improved switch characteristics measured in our development tests, we were not expecting the 390 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 100 ns the remaining switches begin to close, adding parallel paths and reducing the inductance. This process is essentially complete within an additional 100 ns, once the minimum jitter of the AJS switch is about 0.6 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 continued by reduced damage to the switch mounting hardware on Pegasus II, despite a 4 times increase in the amount (dI/dt)2tamed 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 microsecond of operation. The principal limitation to the AJS is a voltage-dependent closing delay that prevents true parallel operation during the first 400 ns of operation at 90 kV charge. An application requiring shorter delays, a burden charge could be added to the RP-1 detonator to increase the jet velocity.

References


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 1/4-13 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.