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Abstract: The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has accumulated a wealth of experience with regards to the unique conditions present during high current, pulse-power experiments. The successful completion of any experiment requires all data relevant to the test be accurately recorded and frequently requires event timing with microsecond resolution and jitter. Both tasks must be accomplished despite the presence of extreme pulsed noise sources. This paper will present the details of the control problems encountered during high current testing and the associated troubleshooting sequence which has eventually led to a working solution in all cases.

The primary area of focus will be the control problems experienced during the commissioning of the explosively operated opening and closing switches used at CEM-UT to sequentially stage the six Balcones homopolor generators (BHPGs) into any candidate load.[1] The reliable operation of both opening and closing switches at current levels in excess of 1.2 MA per generator is essential to the completion of several contracts at CEM-UT. Beyond the contractual obligations, a switch failure at these current levels can only lead to one of several very unattractive scenarios.

Failing to open a switch will result in excessive rotor reverse rotation, whereas opening at the incorrect time can result in up to 5 MJ being dissipated in an arc across the opening switch gap. Failing to operate a closing switch will result in the same condition of dissipating all inductor energy in an arc. In perhaps the worst-case scenario, the premature operation of a closing switch(es) can result in 7 MA, or greater, fault currents being delivered to the bus/gun system.

With these fault modes in mind, it was essential that the early control problems seen in the explosive firing channels be properly diagnosed and resolved. Towards this end, a series of tests was completed with the sole purpose of simulating the experimental conditions seen during high energy/current BHPG discharges and forcing misfires in the control circuits. These tests lead to several other spin-off tests and, eventually, a full understanding and solution for these problems.

Explosively Operated Switch Overview

The successful completion of the Task B 90 mm single shot gun contract goals is dependent on several critical sub-systems. However, even if all mechanical systems are properly designed and fabricated, the misoperation of any of the explosively operated switches can result in catastrophic failures of the bus/gun subsystems.

In order to provide the highest degree of personnel safety without sacrificing reliability, the FS-10 explosive initiator [2], manufactured by Reynolds Industries Systems Inc. (RISI), was selected to initiate the RISI RP-80 exploding bridgewire (EBW) detonator. This system was picked because of its inherent safety when compared to a standard low energy detonator (blasting cap).

This choice, in fact, represents a choice between primary and secondary explosives. Primary explosives are considered a sensitive explosive in that they will detonate when subjected to a spark, flame, or a hot wire, any of which causes a crystal to reach its ignition temperature. Secondary explosives are less sensitive to initiation than primary explosives. The detonation of secondary explosives require, in general, the shock wave energy from a primary explosive. Secondary explosives will not detonate when subjected to a spark, flame, or a hot wire.

While both an EBW and a standard detonator use a bridgewire, the difference between the two systems does not lie in the physical shape or geometry of the wire. In a standard detonator, a bridgewire is heated using a low current, normally only 1 to 10 A. The bridgewire is heated to the ignition temperature of the primary explosive next to the bridgewire (typically lead styphnate) which in turn ignites a secondary explosive.

In an EBW, a large amount of energy is applied in a very short time frame. Due to the small cross section of the bridgewire, the material is rapidly heated through the melting, boiling, and vaporization phases. For proper function, the input current must rise at such a fast rate that the wire's phase change is restricted due to inertia. When this inertia is overcome, vaporization occurs as an explosion. This explosive vaporization in turn ignites a secondary explosive, typically Pentaerythritol Tetranitrate (PETN) or Cyclothimethylenetrinitromine (RDX). The RP-80 EBWs used at CEM-UT require a rise of 1,000 A/μs and a minimum peak current of 200 A.

Firing Control Interface

After the FS-10 was selected as the initiator a printed circuit was designed to provide interface between the FS-10 and the BHPG controller and the fast sequence timers used to control staging times. The block diagram for the printed circuit card is shown in figure 1. This printed circuit (PC) card was used during all of the 45 mm commissioning shots and during the early testing of the 90 mm gun.

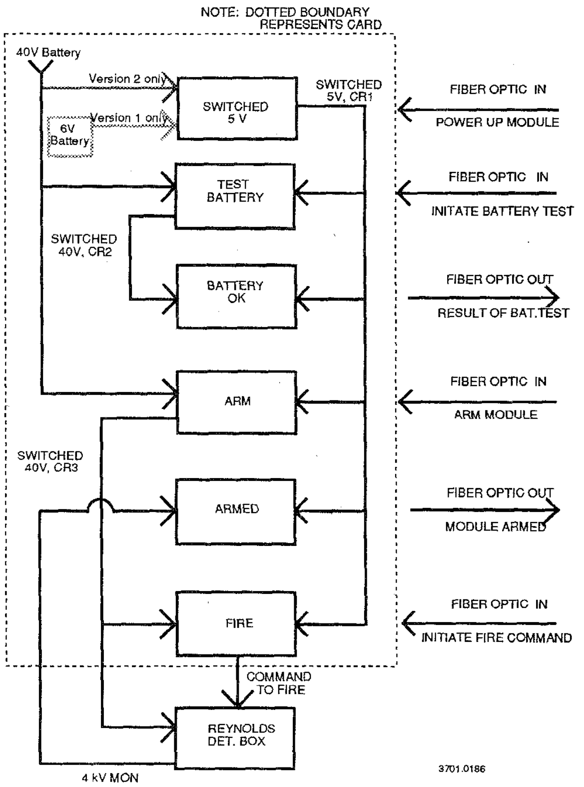

Figure 1. Firing module logic block diagram

Because of the failure of a firing module to initiate an explosive opening switch during shot #5 of the 90 mm single shot gun, a complete redesign of the printed circuit card used in the firing modules was undertaken. In order to facilitate use with the existing firing control system, it was decided to maintain the functional layout of the original PC card while attempting to increase the reliability of each subcircuit. The block diagram for the new card is identical to the one given for the original card.

The original design exhibited erratic behavior if the switched 5 V rail fell below 4.3 V. Two different solutions were used to correct for this problem. First, the switched 5 V is now supplied by a two stage linear dc voltage regulator which is driven from the main 40-V battery, rather than the independent 6-V battery used in the first card. Second, the firing pulse output circuit was redesigned to allow reliable operation with the 5 V rail as low as 3.0 V. To further decrease the possibility of any other misfires due to weak batteries, a new battery testing mode was used. The battery test now draws approximately 1.25 times the peak load current and watches battery voltage using a comparator for 3 s. If the voltage of the battery under test falls below 40 V for longer than 0.4 s during this test, then a "bad battery" condition is latched and the battery must be replaced.

Before the second generation cards were placed in service, the prototype card was installed into a firing box enclosure and cycled through several hundred test fires into a resistive load. This test was performed to demonstrate the reliability of the new design. One half of the available firing channels were then refitted with the new cards. These boxes were returned to service and the remaining boxes were refitted.

High Voltage Isolation of Explosive Switches

After installation of the new cards in all firing channels, the overall reliability of the firing control system increased dramatically during the remaining low energy checkout shots. However, while attempting to establish multi-generator staging capabilities, several high voltage isolation issues where discovered. It was found that under the proper conditions, high voltage transients could cause misfires in the FS-10 and/or the CEM-UT control card.

During multi-generator staging, the entire output bus/gun system experiences extremely high voltage transients because of the energy/voltage required to transfer current flow from one inductive path to another. Since the FS-10 firing box requires approximately 5 to 8 s to reach a full arm state and the staging of individual generators occur at intervals on the order of 1 ms, it is required that all firing boxes be fully armed before any staging may begin. If any or all of the firing channels have a sensitivity to high voltage transients then a condition exists where the staging of the first (or time zero generator) may in turn cause misfires of the remaining generators. This was in fact the failure mode seen on several Task B single shot 90 mm gun shots early in 1989.

Because the misfires had only occurred during staged generator switching transients it was felt that the problem would be found in one of two different areas. The opening of a switch, and subsequent staging of inductor current into the gun/bus system, generates both a large voltage transient and a large radio frequency (RF) noise spike. Since the exact nature of the noise/high voltage induced misfires were not known at the time, several first-pass tests were performed to attempt to isolated the problems.

One of the original tests performed was subjecting an RP-80 to a dc high voltage source after arming the FS-10 firing box. During this test, it was found that the triggered spark gap used as the final output switch in the FS-10 could be initiated at test voltages of 10 to 12 kV. In all test cases, this over-voltage initiation of the FS-10 resulted in firing the RP-80 detonator; furthermore, several of the FS-10's tested were damaged and would not function after this test. The triggered spark gap used has a maximum voltage standoff of 8 kV and is normally operated at 3.4 to 4.0 kV. In retrospect, this misfire mode could have been anticipated since the switching voltage transients typically range between 8 and 15 kV.

The firing modules and NEMA enclosures were originally at a common ground potential. This was redesigned to require a minimum standoff of 15 kV between the NEMA box and all firing components. Firing components were defined as the RISI FS-10, interface card, battery pack, and the battery cutoff key switch. A mockup was used to simulate this configuration so that initial hi-pot testing could be completed without further damage to the actual components.

Scrap aluminum cut to match the exterior dimensions of an FS-10 and a battery pack simulated these components. Each of the aluminum blocks were placed in the NEMA enclosure in the exact locations occupied by actual parts. The blocks are a good "worst case" approximation due to the sharp corners on these pieces which will tend to concentrate electrostatic stress. An unpopulated circuit card was used for the mockup and an insulating sleeve was fabricated for the battery cutoff switch which must penetrate the NEMA box.

Further modifications to the boxes included: a double coat of green epoxy insulating paint (1,900 V/mil dry standoff) was applied to the interior of the box and the box lid; a G-10 plate replaced the previous metal plate as the primary mounting surface inside the box; and all metal hold down screws were replaced with nylon screws.

All of the components inside the NEMA box were connected using 22 AWG wire and the high potential positive cable was connected to the block which simulated the FS-10. The NEMA box was connected to the ground leg of the hi-pot supply. The hi-pot test was performed by raising the voltage from 0 to 15 kV and holding at 15 kV for 1 min. With the final design, no current flow was measured and no arcs were seen.

Additional voltage isolation was provided for the system by modification of the RP-80 feed-through into the explosive containment. The original design had the body of the EBW, as well as the Teflon™ insulated input wires, in direct contact with the containment steel. In the event that high energy plasma from the switching event contacted the containment, the containment vessel could jump to some high potential. The feed-through was modified to allow use of a polyethylene sleeve. This was also designed to have a minimum voltage stand off of 15 kV from the EBW det wires to the containment steel.

While all of the above changes greatly enhanced the voltage isolation of the firing circuits, these revisions did nothing to address the additional concerns about RF noise. In an attempt to improve RF noise immunity, the lids to the NEMA boxes were modified to include a high conductivity copper finger stock which provided a current path between the box and its lid. This, together with single point grounding to a low impedance building ground plane, allowed the NEMA box to function as an excellent shielded enclosure.

At the same time the trigger circuitry internal to the RISI FS-10 was modified. RISI's stock FS-10 uses an SCR with the gate terminated at 27 Ω as a latching switch in the first stage input to the trigger network. This allows the stock unit to trigger reliably independent of trigger pulse width. When used in a pulse power environment however, the SCR can be triggered and latched by high magnitude, fast RF transients. In order to deal with this possible problem, all of the FS-10s used at CEM-UT have had the stock SCRs replaced with MOS-FETs. The modified units exhibit superior RF noise immunity, but not without a price. FS-10's with this change can display erratic behavior if proper pulse widths and rise times are not maintained at the input to the FS-10. All of the modifications were performed by RISI at their San Ramon, California repair office.

After all modifications were completed on one setup, the prototype firing set was subjected to a series of dc hi-pot tests identical to the initial tests described above. Next the box was subjected to transient RF noise bursts generated by discharging a capacitor into a spark-gap while simultaneously arming the fire set. Cross-talk noise tests were conducted by arming the prototype box and repeatedly firing another fire set whose output leads were tightly braided with the leads of the box being tested. The prototype fire set successfully passed all of these tests with no misfires. Optimism ran high in the lab.

The above modifications were incorporated into all of the firing channels and the system returned to service. Initial results were very positive as several successful shots followed the design changes. However, a misfire occurred again during test #14 of the 90 mm single shot gun. With the Balcones system about to see very heavy experimental usage, it became imperative that the misfire problems be solved.

A series of tests were performed using a transient high voltage source to simulate switching transients seen by the isolation switches. The setup included a firing box (which incorporated all of the above improvements) with its high voltage output leads connected to a detonator that was installed in a mockup isolation switch. The schematic for this test setup is shown in figure 2. This testing yielded a rather unexpected result, discharging the high voltage capacitor across the mockup switch at voltages less than the flashover threshold of the switch never produced a misfire. If the mockup isolation switch was forced to flash over by raising the test voltage, then FS-10 misfires occurred during approximately 50% of the tests.

During one series of tests, it was noticed that there was a sizable arc at the firing box grounding point during tests which produced misfires. It was hypothesized that the very fast dV/dt associated with a high voltage flashover at the isolation switch caused transient current to capacitively couple through the high voltage insulation of the firing box into the grounded enclosure. These tests where repeated without the grounding strap on the firing box enclosure and no misfires were generated.

Since the NEMA enclosures were originally grounded to provide RF shielding for the FS-10 and control card housed within, there was concern that simply ungrounding the boxes would solve one problem while creating an RF noise problem. Noise immunity testing was repeated without the grounding strap and despite very high noise levels, there was not a single misfire from any of the firing boxes tested.

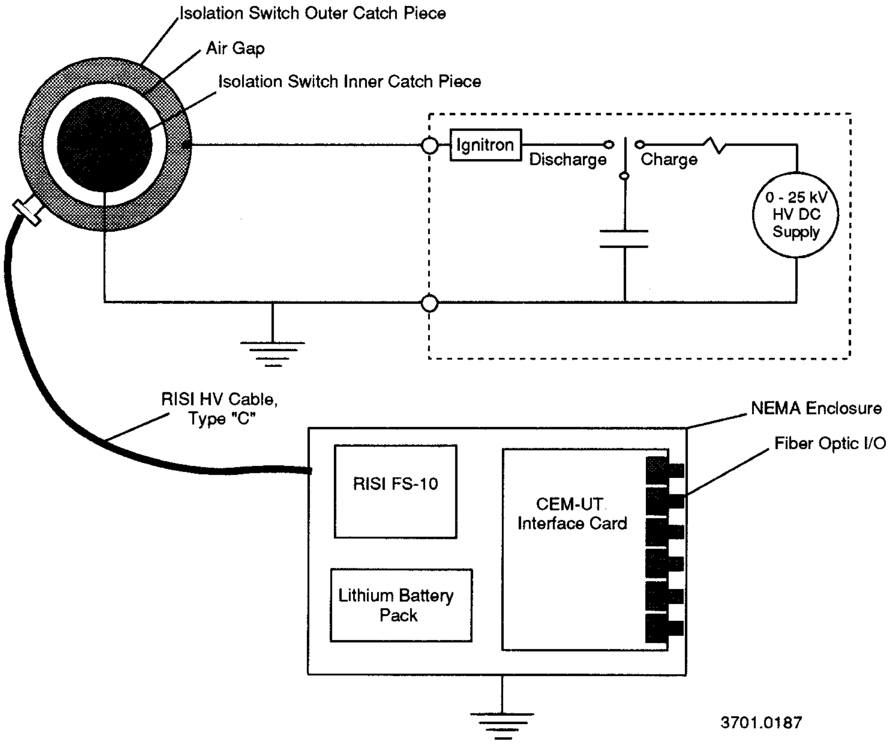

Figure 2. Schematic for transient high pot testing

The final solution to this problem required modification of the isolation switch to increase the flashover threshold to > 30 kV and removing the grounding straps on all of the NEMA enclosures. The ungrounded firing boxes were returned to service and no misfires have occurred since. This is the firing box/switch configuration currently in use at CEM-UT.

Summary

As a result of the experience gained during this testing, several baseline design points have been established at CEM-UT for further explosive interface circuits: The use of fiber optic channels for all triggering and digital I/O will avoid the possibility of ground loops and help minimize the chance of RF noise coupling into the system. Battery operation of all low-voltage control circuits can eliminate unwanted ground references, but the battery voltage must be tested at a current greater than normal load current. Use of a latching "no go" state is recommended.

If a grounded enclosure is to be used for RF shielding, then the magnitude of parasitic capacitive coupling between the control components and the box must be a design point. The high voltage isolation at all points in the fireset must exceed the predicted HV transients for the intended experiment. And finally, never assume that standard grounding and/or shielding is appropriate to a pulse power application without proper testing and verification.

Acknowledgments

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