STAGED EXPLOSIVELY DRIVEN OPENING SWITCH DEVELOPMENT FOR EXPLOSIVE FLUX COMPRESSION GENERATORS

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ABSTRACT

A staged opening switch employing both explosively driven, ruptured conductor and H.E.compressed exploding foil technology represents an attractive pulse shaping network for explosive flux compression generators (MCG). This staged system utilizes the low energy dissipation and high commandibility of an explosively ruptured cold conductor opening switch as a first stage and the fast opening time typical fuse switches as a second stage. Explosively driven ruptured conductor opening switches built and test by the AFWL have interrupted 185 KA in 4 micro seconds with .5 ohms peak resistance, and 12 KV per series channel voltage. The AFWL has previously demonstrated fuse switches at the terawatt level, and experiemnts show that improved fuse performance may be achieved by compressing the fuse vapor by such means as a high explosive. Staged opening switches permit the creation of a fast risetime, high final resistance, low energy dissipating pulse shaping network for simple, economical MCG systems.

I INTRODUCTION

Magnetic flux compression generators (MCG) powered by high explosives represent attractive electrical sources for a wide variety of experiments requiring large amounts of energy at very high currents. Flux compression generators which are relatively economical (for single shot applications), very compact, and which deliver energy at fractions of a terawatt are relatively routine. For applications requiring electrical power at the multi-terawatt level some form of power condition circuitry is required to compress the output pulse of most conventional MCG systems. Since the generators are fundamentally high current devices which operate most efficiently into matched inductive loads, the use of high current interrupting switches in power conditioning circuits is most attractive. However, the major limitation in performance when MCG systems are employed in circuits where time to peak current is relatively long, is circuit resistance which limits the energy multiplication and hence the energy delivered to the load. Conventional foil fuse opening switches, which have already been demonstrated at the terawatt level, would be likely candidates for use as power conditioners in MCG systems were it not for the very appreciable resistance which they introduce into the circuit as the fuse heats and melts prior to vaporization. The Air Force Weapons Laboratory is exploring opening switches, and combinations of opening switches which are characteristically low in resistance prior to activation, and which are capable of submicrosecond interruption of current. A relatively slow opening switch which displays very low resistance prior to current interruption is described in Section II of this paper. Section III describes efforts made to increase dR/dT, and final resistivity in conventional exploding foil opening switches. A conceptual approach to combining these two switches is described in Section IV.

II EXPLOSIVELY DRIVEN RUPTURED CONDUCTOR OPENING SWITCH

At the AFWL, an opening switch has been constructed and tested that maintains low resistance up to the time of current interruption. This switch, based on a concept described by R.D.Ford and Ihor M. Vitkovitsky of the NRL (ref.1), employs detonator cord to rupture an aluminum conductor whose cross-section is adequate to prevent significant heating prior to activation.

The switch consists of a conductor which is formed through a section as shown in Fig 1. Four such sections are joined in series, then the conductor is brought back under the sections a circuit shown in Fig 3. Current is delivered from a 300 microfarad capacitor bank charged to voltages up to 30 KV through a transmission line and a lumped storage inductor of 3.2 microhenries to the switch. A resistive load of approximately 80 milliohms, into which current is diverted when the switch is activated, is permanently connected in parallel with the switch. The conductor in the switch is sized so that the energy absorbed by the switch is well below that required to significantly heat or melt the conductor during the 60-80 microseconds required for the current to reach its peak value. At peak current, the detonator cords in all four sections are initiated simultaneously from the center by four conventional exploding bridge wire detonators, rupturing the conductor as the detonator cord burns outward from the center to the edge of the switch. The arc formed across the torn conductor edges is extinguished by the explosive products. Current measurements through the switch and voltage measurements across each section are made to characterize performance.

The circuit parameters varied, but best result were obtained for an opening switch using .010" aluminum sheet conductor in a four section switch. The switch was driven by four sections of 175 grain/ft detonator cord. As shown in Figure 4 currents of 185 KA peak were carried by the switch and subsequently interrupted, upon command, in 4 microseconds. Currents of 125 KA were delivered to the resistive load. Figure 5 shows the voltage measured across the parallel combination of switch and load. The switch experienced a peak voltage of 50 KV (12.5 KV per switch section). Voltage and current data were analyzed to produce information about the resistance of switch as a function of time. Resistance data, also presented in Figure 5, shows an initial resistance rise of 117 milliohms ohms/micro second and a leveling out of the resistance at 0.5 ohms between time of 75 to 85 microseconds. Comparison with the current information shown in Fig 4, shows that the switch reaches this plateau resistance shortly after the time of peak current and maintains this resistance while the current through the switch falls from 180 KA to about 30 KA. After 85 microseconds, the voltage across the switch has fallen to about 10 KV, by virtue of the fact that the current has almost completely transferred to the low resistance parallel load. The arc in the ruptured conductor is now extinguished by the expanding HE products and the resistance of the switch begins a second (slower) rise to virtually open

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circuit conditions. Experiments were also conducted in which the parallel path through the load resistor was broken -- thus requiring the switch to dissipate the full stored energy in the arc. As expected under such conditions, the resistance of the switch failed to rise to any significant value and the switch failed to "open" leading to very long "interrupt" times.

III HIGH EXPLOSIVE COMPRESSED FUSE

For compressing current risetimes to submicrosecond time scales and increasing available power, a fuse switch may be employed as the second stage of a multiple element power conditioning system. At the AFWL, fuse switches have been employed to interrupt currents in excess of 30MA in 100-200ns time frames. While suffering from the previously mentioned problem of high early time resistance when required to carry current for an extended period of time, the fuse represents the ideal companion to the ruptured conductor switch described in Section II because the fuse can represent a low (compared to numbers like 80 milliohms) initial parallel resistance into which a ruptured conductor switch can transfer current quite rapidly. The fuse can then rise very rapidly in resistance as it vaporizes, producing high voltages. The major limitation on the performance of fuse switches for some experimental applications stems, however, from their relatively low open circuit resistance, which frequently manifests itself in circuit performance that is limited by an L/R time, where L in the net circuit inductance and R is the fuse resistance, rather than by the rate of rise of resistance of the switch itself.

Laboratory experiments routinely show fuse open-circuit resistances that are a fraction (10% or less) of the resistance expected from a metal vapor just above vaporization temperatures. Laboratory experiments typically employ a porous medium around the fuse to cool and recondense the vapor and this discrepancy in resistance is conceptually explained by the expansion of the fuse vapor into the quench medium, thus allowing the fuse to present a larger cross-section to the current than that presented initially by the foil. The obvious suggestion is to surround the fuse with a nonporous, high temperature insulator to prevent such expansion. Such experiments have a poor history of performance, which is partially explainable by simple one dimensional MHD modeling of the geometry in which appropriate material properties for the surrounding medium are included. Upon vaporization, pressure in the fuse rises dramatically, and compresses any real medium (plastic,etc.) placed adjacent to the fuse to an extent which allows partial expansion of the vapor and formation of a volume of less dense vapor near the now moving interface. The lower density region of larger cross-section then conducts additional current, heats, and diminishes the apparent resistance of the fuse.

Obviously, to prevent such expansion requires either a truly incompressible medium (water is a candidate), or if the environment permits, the application of pressure from an external source whose value is higher than that of the vaporizing fuse, ie. that obtainable with simple HE configurations.

A diagram of such an experiment is shown in Fig. 6. A foil fuse is located between an insulating material and an HE charge. Current is delivered from a source similar to that employed in the circuit in Fig 2. The current melts, then vaporizes the fuse. HE detonation is timed to bring the burn front into contact with the fuse vapor just after the onset of vaporization. Measurements of current through, and voltage measurements across the fuse are made to characterize performance. No parallel load is employed placing relatively severe demands on fuse performance.

Results of an experiment which compared the performance of a conventional fuse with one employing HE compression are shown in Figure 7,8 and 9. For this experiment, the fuse consisted of aluminum foil .001 in. thick and 1.57 in. wide by 2.75 in. long. These dimensions were deliberately chosen to provide relatively slow cut off of current in the current when no HE compression was applied. The fuse conductor was in direct contact with a polyethylene insulator below for both experiments, and with polyethylene (for the uncompressed case) or HE (for the compressed case) on the top. For the conventional (uncompressed) case, Figure 7 shows the current rising to approximately 60 KA in 100 microseconds. Near the time of peak current, the fuse vaporizes giving rise to a slow interruption of the current. Figure 8 shows the voltage across the fuse rising to a very modest value of about 4 KV. and Figure 9 shows the resistance of the fuse rising to a maximum of just over 60 milliohms. For the given fuse dimensions and assuming no expansion of the vapor, this resistance suggests a fuse resistivity of less than 100 micro-ohm cm.

The results from the electrically and mechanically identical experiment when HE compression was employed are also shown in the Figures. The current rises to the same value but is qualitatively seen to be interrupted much more quickly. The voltage profile is seen to duplicate the voltage of the uncompressed fuse up to the time of arrival of the HE pressure pulse -- rising to virtually the identical 4 KV. However, upon arrival of the HE burn front, the voltage rises very quickly, achieving 12.5 KV at a time of 140 microseconds when the current has fallen to less than 35 KA. At this time the momentary fuse resistance is 360 milliohms-ohms or an implied fuse resistivity of in excess 600 micro-ohm cm. The current falls rapidly to zero and the implied resistance continues to rise to approximately 1 ohm at which point the uncertainty in the electrical measurements dominate. Figure 9 clearly demonstrates that the application of HE compression increased the observed resistance of the switch by a factor of more than 10 times. For confirmation, a similar experiment was also conducted using a .010" copper conductor in place of the fuse foil. The additional thickness of the more conductive copper made it impossible for the current to vaporize the fuse, but the action of the HE system was identical. Figure 10 shows the current trace that resulted. The figure shows that although the HE action alone was capable of eventually interrupting the current (as expected), no deviation from a short circuit current waveform was observed until 75 microseconds after arrival of the HE pressure pulse. Thus the less than 20 microsecond interruption time observed in the compressed fuse is not the result of catastrophic HE action alone.

IV PULSE SHAPING NETWORK

Optimal pulse shaping network design should minimize the shortcomings of the two switches while taking full advantage of their assets. The Explosively Driven Ruptured Conductor Opening Switches displays low early time resistivity and relatively fast current interruption. Fuses have previously displayed capability for fast interruption, and show potential of further improvement in performance when subjected to additional confining pressure.

Arranging the switches in parallel with the PLAN switch acting as the first stage and the HE compressed fuse as the second stage would serve several purposes. The initial resistance presented to the circuit would be negligible. As the EDRC switch is activated, the current is transferred from the first stage to the low initial resistance of the fuse second stage. The risetime of the current seen by the fuse is a function of the resistance rise of the first stage, not fundamental risetime of current for the source. This allows the geometry of the fuse second stage to be chosen for maximum speed of interruption (while still allowing sufficient "clearing time" for the first switch to achieve high voltage holdoff and high resistance.) By the time the fuse vaporizes, explosive gases in the first stage will have extinguished arcing in the EDRC switch, thereby increasing the ultimate resistance. The current is then transferred to the load at a rate proportional to the voltage generated by the fuse. The additional performance gained by employing HE compression of the fuse further improves the system resistance and the power delivered to the load. Tests of such parallel combinations are planned for the near future.

V CONCLUSIONS

Experimental data has been presented to show the performance of two opening switch techniques which are applicable to a staged power conditioning system appropriate for use in circuit employing an MCG as the prime energy source. The performance of the two switch types is seen to complement each other.

VI REFERENCES

1. Ford, R. D. and Vitkovitsky, I. M., High Recovery Voltage Switch for Interruption of Large Currents. Rev. Sci. Instrum. 53 (7), July 1982.

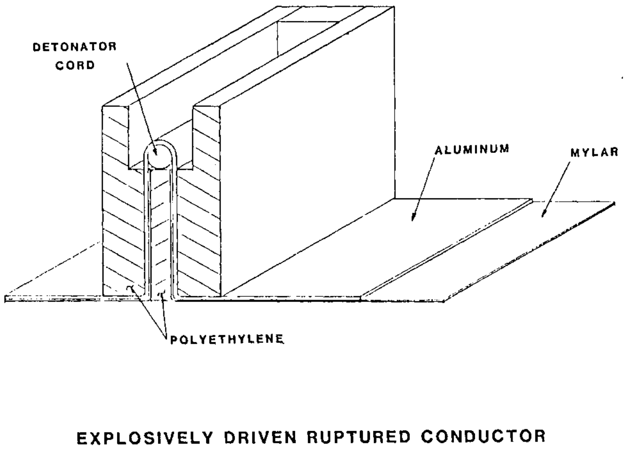


Figure 1. Single Channel EDRC

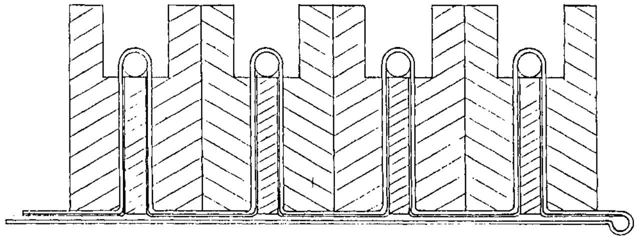


Figure 2. Multi-Channel EDRC

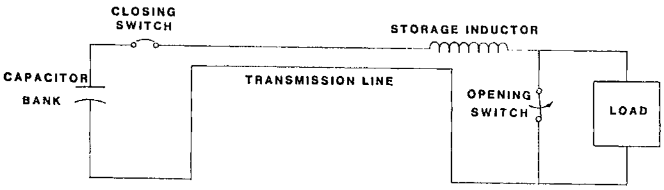


Figure 3. EDRC Circuit Schematic

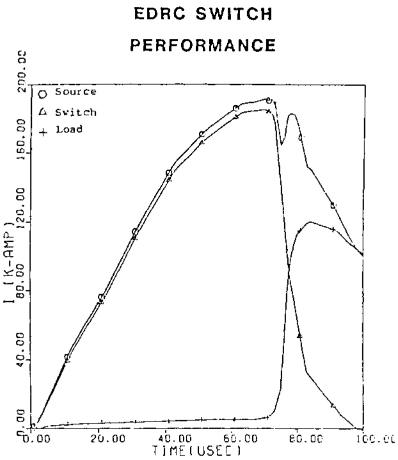


Figure 4. Source, Switch, and Load Currents Versus Time

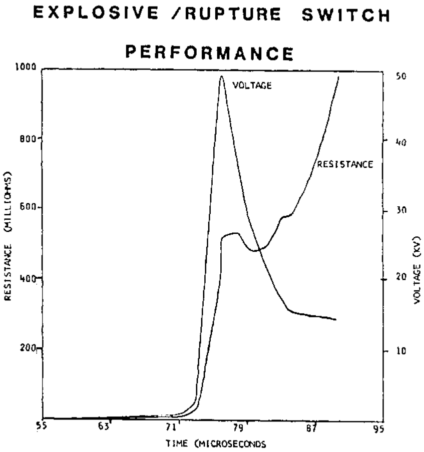
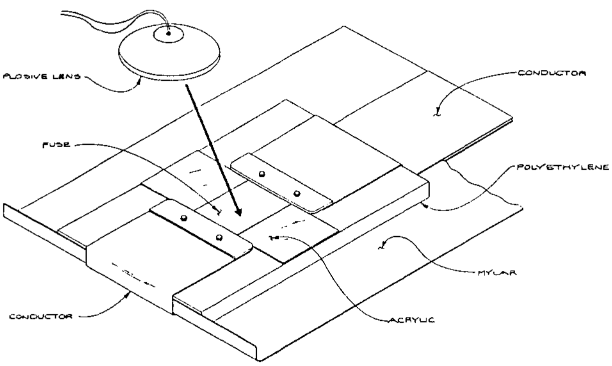


Figure 5. Voltage And Resistance Versus Time For 4 Channel EDRC



EXPLOSIVELY COMPRESSED FUSE

Figure 6. Explosively Compressed Fuse Assembly

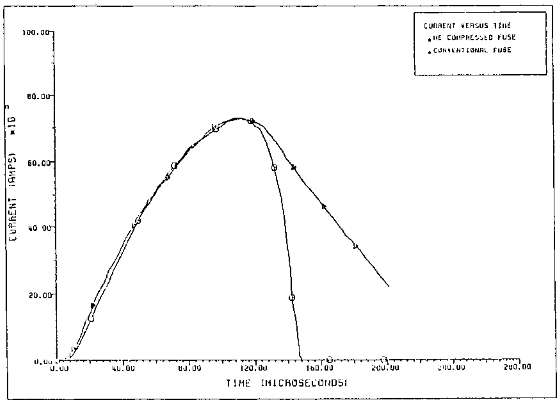


Figure 7. Current Versus Time For Conventional And Explosively Compressed Fuses

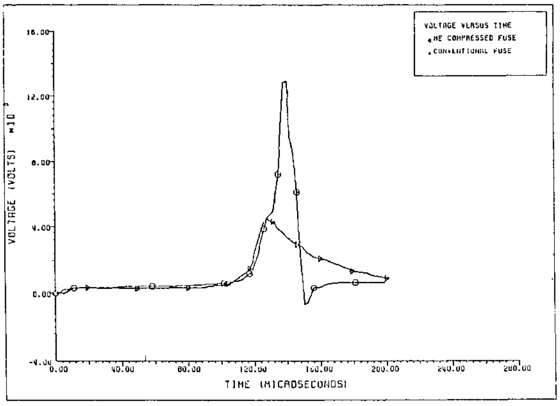


Figure 8. Voltage Versus Time For Conventional And Explosively Compressed Fuses

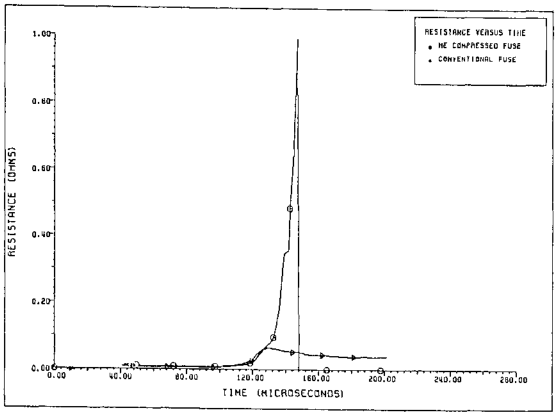


Figure 9. Resistance Versus Time for Conventional and Explosively Compressed Fuses

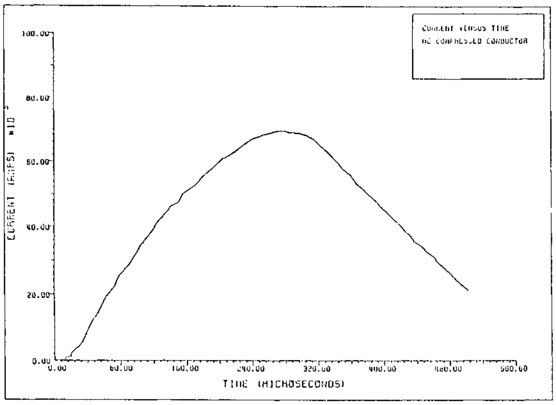


Figure 10. Current Versus Time for Explosively Compressed (non-fuse) Conductor