A test circuit for long distance directional plasma discharge using the exploding wire technique

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Abstract: With the use of high voltage impulse equipment and the exploding wire technique, long distance directional plasma discharges have been achieved. The methods described in this paper allows for such discharges in a relatively safe and dependable fashion. This paper comprehensively describes the equipment and circuits required to repeat these experiments. Equipment design considerations are also given in the paper. Special considerations to earthing are required for this method to ensure operator safety and that measurement equipment is not damaged. Voltage waveforms and other data have been collected via the experiments; the results and procedures are quite different to those found in the short distance exploding wire literature. The research conducted at UoC has allowed for discharges up to 70 meters in length using only 60kV DC. In these discharges the various high voltage switching mechanisms and high energy impulse generators that have been used will be described in this paper. The measurement instrumentation which is able to measure the large currents and voltages is described.

1 INTRODUCTION

It is well known that if a sufficiently large impulse current is applied to a thin metallic wire then the wire will fragment. Further; if the applied potential across this wire is great enough then the current will continue to flow over the gaps made by the fragmented wire giving a plasma arc. The exploding wire phenomena was initially brought forward by Nairne [1] as early as 1774. Nairnes' initial wire fragment experiment was used to prove that current is the same in all parts of a series circuit. From Nairnes' experiments to present, theory and experimentation in the exploding wire field continues[2-4]. Practical uses for exploding wires include fine particle production, x-ray production, explosive ignition, and circuit breaker applications. Experimental work into long exploding wire (over one meter in length) is lacking in the literature to date, as is explanations with regards to circuit configurations required for these experiments.

At the University of Canterbury experiments in exploding wire have been conducted since 1998. Initial experimentation investigated fragmentation of copper coils on magnetic accelerator guns. Investigation proved that this fragmentation was due to the wire explosion phenomena. These coils where fragmented by excitation from a 6.750kV, 17.1uF rated DC capacitor.

Later work using various testing circuit configurations and ignition mechanisms have allowed for full plasma shrouded wire discharges over 20m distances. Experiments producing partial plasma shrouded wire explosions have been conducted up to 70m in length.

2 EXPERIMENTAL CIRCUIT CONFIGURTION

Any research group embarking on the creation of long distance directional plasma arcs will need to build three circuit modules. The circuits are: the charging circuit, the detonation circuit and the safety discharge circuit. The circuit shown in Fig 1 allows for the high voltage capacitor banks to be charged.

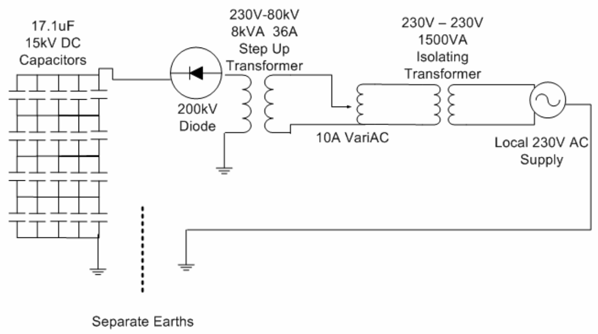

Fig. 1: Charging Circuit

It is important to note that the charging circuit contains two separate earths within the HV Laboratory: the local laboratory earth and the distribution board earth brought in via the power supplies. These two earths can experience a large potential difference during experimental detonation of wire. The detonation circuit is when the switch has been closed and the wire explodes (as shown in Fig 3).

There is commonly some charge remaining on the capacitors after detonation which requires discharging. This is more critical if the wire explosion fails possibly leaving fully charged capacitors. The discharging circuit is the same as the detonation circuit except the exploding wire has now vaporised. To deenergise the capacitors a water resistor is connected to the top of the capacitor stack. Hand earths are then applied to ensure the capacitors are safe to be worked on by personnel.

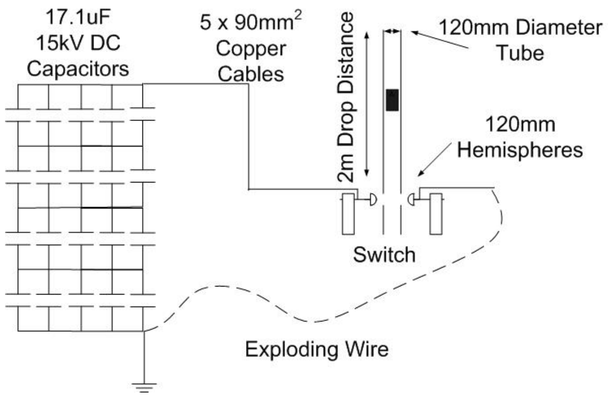

Fig 2 : Detonation circuit.

3 EXPERIMENTAL EQUIPMENT

The capacitors used for the University of Canterbury experiments are oil insulated and rated at 17.1uF, continuously at 6.675kV dc or 15kV for impulse loads. The capacitors where originally used on the 12th Harmonic filter of New Zealand's HVDC link. It has been found through testing that these capacitors are able to be charged up to 15kV without any known internal degradation when applied to impulse loads. While the capacitors are continuous rated, but in these experiments they are only energised for a short amount of time (three to five minutes per experiment).

The voltage on the capacitors is monitored via four Fluke 80k-40 40kV dc resistive dividers measured over the capacitor terminals. This measurement gives the operator an understanding of the initial charge of the capacitor layers and the ability to know what voltage remains after the wire detonation for deenergising. A 0.23MΩ water resistor is used to discharge any remaining energy from the capacitors after detonation. Water in the resistor is continuously flowing via the local water source to ensure that the water between the electrodes will not boil.

Fifteen 1.5m long wooden earthing and discharge sticks have been built for resistive de-energising and solid earthing of the capacitors between uses. The sticks were tested to the required International Standard IEEE STD - 978-1984 [5] to provide assurance of safety from flashover. The sticks allow the user to apply a water resistor load to the capacitors to de-energise them allowing the user to remain a safe distance from the high voltage terminals. Once the capacitors are de-energised the solid earth connections maybe applied in the same fashion via the earth sticks. These earth sticks must be rated to avoid flashover at full test voltage as instrumentation errors could lead the user to believe it is safe to apply them. Instrumentation errors or failures are common in this type of experimentation due to large electromagnetic emissions from the exploding wire.

The charging circuit for the capacitors uses an 80kV test transformer. This transformer is voltage controlled by a 10A, 240V ac variac on the low voltage side to ensure that the capacitors are not over charged. The high voltage of the transformer is connected to a diode giving a halfwave rectified dc input to the capacitors.

3.1. Capacitor Racking

The capacitors are mounted to steel racking to ensure they held firmly in place. Eight M8 bolts connect the capacitors to the racking. The capacitors are ganged in parallel in sets of five, and these gangs are layered in series connection. Crane lifting points are built into the racking so the gang of capacitors can be lifted. The gangs weigh around 320kg each. The capacitors in the gangs have a 100mm air gap between the casings so that if one fail s catastrophically then it will be less likely to fail the neighbouring capacitor or push the grouping over. In each gang the capacitors can be shorted to reduce the capacitance if the testing requires. Between the capacitors solid 40mm x 140mm x 1.6mm thick copper busbars ensure equipotential over the paralleled capacitors. 95mm^2 copper leads connect the gangs in series to ensure there is as little power loss as reasonably possible during discharge. By having capacitors organised in this modular fashion it allows the operator to change the configuration and capacitance of the circuit quickly.

1200mm diameter PVC culvert tubing cut into 100mm lengths are used as the insulators between the gangs of capacitors in series. The tubing is significantly less expensive than commercial insulators and capable of withstanding the static weight of several gangs on it. The insulation property of the tubing was Type Tested in its final configuration due to lack of available electrical information on the PVC material. The testing proved that the tubing is capable of 7kV per cm before surface breakdown occurs. The tubing length gives a safety factor of 4.5 for the maximum test voltage (15kV) between gangs. The between gang insulators are not outside rated due to their smooth surface, and can not be used in wet conditions.

The gangs are stropped to 3m steel outriggers to ensure that they are unable to topple over. Adjustable feet are installed at the end of the outriggers to ensure they are in contact with the ground providing support. The bottom gang of capacitors racking includes four 700kg rated solid steel wheels so that the whole unit may be moved by winch over hard level surfaces. The final configuration is shown in Fig 3.

Fig 3: HV capacitor bank with earth sticks attached. The height of the bank is 3 meters. Note the insulator tubes between the stages.

3.2. Switching Mechanisms

Four switching mechanisms have been used to ignite the exploding wire circuit. Originally a Circuit Breaker (CB) was used to switch the wire load onto the charged capacitors. While this mechanism allowed for safety of the user and ease of set up, the CB used was ac rated. It is expected that the dc current may be damaging the contactors within the CB so its use was discontinued.

The next switching mechanism was a high pressure air gun. The gun would fire an electrode projectile with a trailing wire attached. When the electrode hit an energized target the circuit would be complete and initiate wire detonation. This mechanism gave the operator electrical isolation. During testing, distances over 30 meters proved the gun to be inaccurate, and occasionally the wire trailing projectile missed the energised target. It was considered unacceptable to miss the target and with the aim for longer than 30m exploding wire experiments this mechanism was retired.

A HV sliding switch has been designed and manufactured to ignite the circuit as shown in Fig 4. When an electromagnetic trigger system is released a brass slider falls down a guide tube between two 12cm spheres. One of the spheres is connected to the charged capacitors and the other through the exploding wire to earth. The purpose of the slider is to break the air gap between the spheres creating an arc connection hence completing the exploding wire circuit. The air gap distance can be adjusted to what is required as the sphere stems are threaded through PVC insulators.

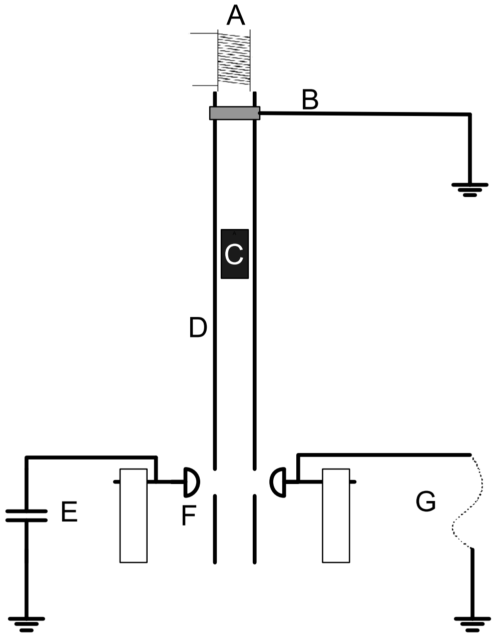

Fig 4: HV Switching Mechanism. A – 4V electromagnet to hold the slider in position pre-ignition. B – 12mm copper earth strap to ensure that the electromagnet potential may not rise in case of flashover up the guide tube. C – 115 mm diameter brass slider. D – 120mm PVC guide tube. E – Charged HV capacitor bank. F – adjustable 12cm Sphere gap. G – The exploding wire.

If a higher voltage is to be applied over the exploding wire, the air gap is increased so that the sphere gap will only ignite during firing of the switch. The distance set over the air gap can be closely approximated by 1.5 times the standard 12cm sphere break down voltage for the applied potential. The switch is triggered by turning off an electromagnet at the top of the guide tube which releases the slider. A copper earth strap has been placed around the top of the tube so that if the insulation of the guide tube were to break down no voltage can reach the electromagnet circuit which goes directly back to the personnel carrying out the test.

3.3. Measurements

Voltage measurements are obtained via a capacitive divider. The divider measures over the length of the exploding wire and none of the earth return path are included in this measurement. From the divider a coaxial cable takes the signal through a filter to a high speed oscilloscope.

The 500Ms/s oscilloscope is used to capture the waveform. The oscilloscope must be on an independent power supply (a inverted battery source) to avoid damage. It is also necessary to ensure that inductive loops are not present during measurement (the connection between the printer and the oscilloscope for example). Induced voltages in these loops following wire detonation damages equipment circuitry.

The potential rise of the laboratory during these experiments is considered significant. If the oscilloscope is connected to the local area supply the difference in earth potential between the measuring device earth and the local supply earth will cause damage to the oscilloscope. For this reason it is important that all measurement devices have the same neutral point in the circuit and that the oscilloscope earth is floating as the potential difference will cause damage. The neutral points must be the exact same physical connection because even the earth bond impedance is enough to give rise to a damaging potential difference. Waveforms are saved on the oscilloscopes internal memory and can then be transferred to computer after testing for analysis.

Current waveforms are currently obtained via a resistive shunt. The shunt is 50uOhm, 2000A continuously rated. Current can also be measured with the use of a rogowski coil.

3.4. Wire

The wire used throughout the experiments has been various sizes of copper magnet wire. The wire is polyester amide insulated. The wire is suspended from the ground plane by insulators. The wire orientation to the ground plane does not seem to affect the electrical characteristics of the circuit.

3.5. Earthing

Care must be taken when deciding the placing of protective and current carrying earths. There is also the complication of the HV Laboratory earth being remote to the distribution board earths brought in by the power supplies.

The bottom stage of the capacitor stack is connected to the laboratory earth to allow for charging. Current carrying connections which use the laboratory earth are the water resistor and return path of the exploding wire. Safety earths connected via a single bond to this point are all the equipment chassis earths excluding the oscilloscope and the copper straps on the switch.

An isolating transformer is provided between the distribution board power supply and the capacitor charging variac. It is not the isolation within the transformer itself that is relied upon because there is too much capacitive coupling between the primary and secondary windings. The isolation transformer has a 2 meter connection lead of the two pin type.

The variac has an insulated stand off from the control knob so that the user is sufficiently isolated from the metal chassis. If the hv diode were to fail whilst the capacitors were charged and the hv transformer flash between windings via physical breakdown or capacitive coupling then a high potential would be delivered to the variac putting the operator at risk; hence the hand isolation.

3.6. Safety Considerations

Due to the nature of the experiments safety measures are put into place for operators. The operator is positioned in a Faraday cage which is bonded to laboratory earth via a 20mm^2 copper lead. This ensures that the operators are safe from electric shock by eliminating touch potentials. The Faraday cage is covered with 1mm clear polycarbonate sheeting. This ensures that any projectiles produced via testing (commonly the case) or accidental explosion will not harm the operators. Eye protection is also worn at all times during testing. Audible noise from the detonation of the wire is such that hearing protection must also be worn.

4 RESULTS

4.1. Electrical Measurements

The University of Canterbury measurements are dissimilar to that presented in alternative exploding wire publications. Most papers describes a rise in voltage and then a damped sinusoidal response. Also descriptions mention dwells in voltage during the rise due to fragmentation [6]. Fig 5 shows a typical University of Canterbury voltage waveform. Note the ignition noise at time zero from the switching arc. The remaining voltage once the wire has detonated is attributed to charging of the capacitive voltage divider used for measurement. It is important to earth the capacitive voltage divider at the end of each detonation, as well as the HV capacitors

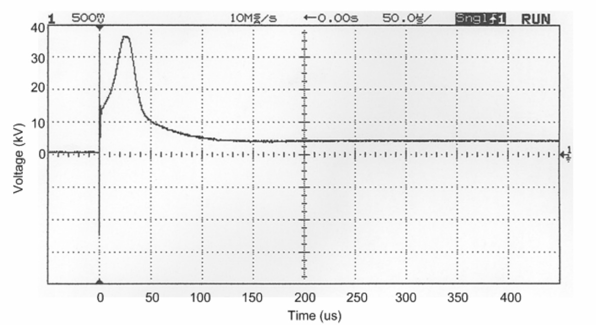

Fig 5: Typical voltage waveform for a 4.75mm diameter 5m polyester amide coated copper wire.

4.2. Photographic and Video Results

The use of long exposure photography has allowed for the capturing of images of long distance plasma paths. Both digital and traditional film camera photographs have been taken with no discernable difference in results. Examples of these photographs are shown in Fig 6 and 7.

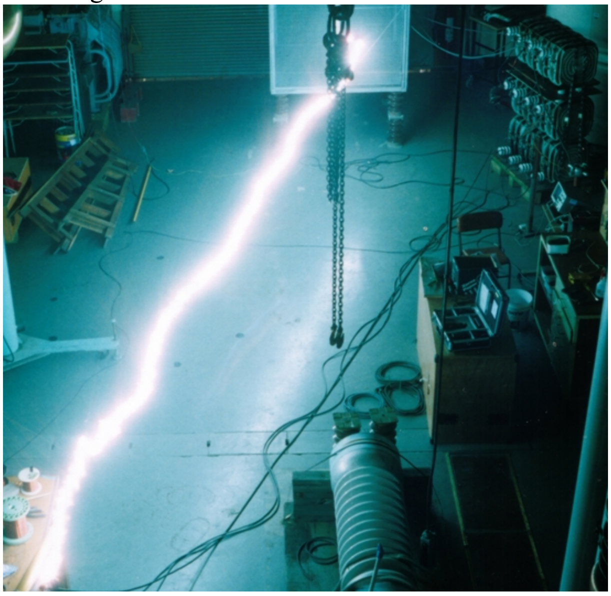

Fig 6: A 10m plasma discharge created using the exploding wire technique. This experiment up used the high pressure air gun switching system. A voltage of 60kV was used

Video captures have been made by the operators. The high speed of the wire explosions means that only 3 or 4 frames of the video contain useful frame images. With frame capture software it is possible to gain still images from the video with good results. An example of these frame captures is shown in Fig 8.

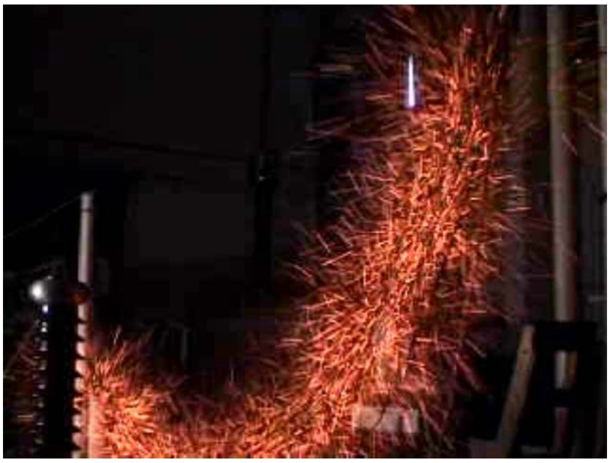

Fig 8: A 5m exploding wire created using the experimental equipment discussed in this paper. Note that there is no electrical conduction at this point only fragmented wire.

4.3. Wire Insulation

At the conclusion of a polyester amide insulated wire explosion experiment a curious outcome is noted. The wire explosion causes the wire to shed its insulation in tubes. Polyester amide tubes of up to 600mm in length have been found after detonation. On closer inspection of the tubes using a microscope it have been noted that the tubes are ripped along the length while the insulation is not thermally damaged [7]. Publications in the literature that discuss the use of insulated exploding wires are rare. The cold shedding of the polyester amide insulation skin via the precise and regular axial tearing has not been noted to date. This axial tearing is clearly shown in fig 8.

Fig 7: A 70m plasma discharge created using the exploding wire technique. 60kV was used to create this discharge. This experiment was conducted in a field site.

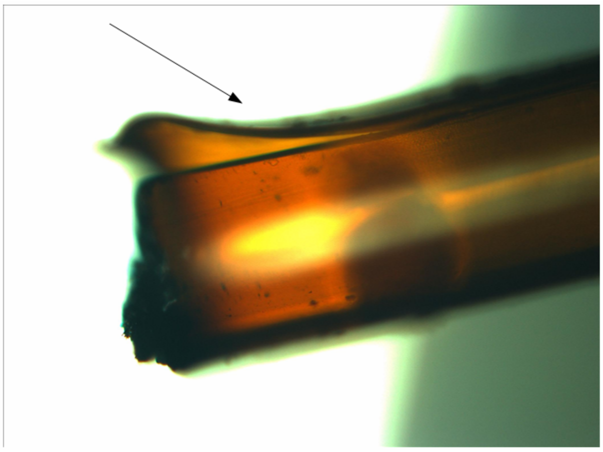

Fig 8: The end of a polyester amide tube with arrow indicating the beginning of the precision axial cold-tear in the insulation. This tear runs the length of this 120mm tube. The diameter of this tube is 4.75mm.

5 CONCULSIONS

Any high voltage engineering design is bounded by the formation of plasma arcs. While wire explosion is an intriguing means for the creation and study of plasma arcs, much of the available literature is directed towards research within the physical sciences. This paper described in detail how a high voltage engineering laboratory can set up reliable experiments of creating plasma arcs in the tens of meters. Numerous are the practical applications and implications of further understanding plasma arcs on this scale. Investigative experimental results can be taken in the form of: electrical transient recordings; still and video frame images; and careful examination of explosion remnants. Brief results have been given in this paper.

6 ACKNOWLEDGMENT

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