A 2.5 GIGAWATT LIQUID DIELECTRIC COAXIAL PULSE FORMING LINE

T. L. Berger, V. H. Gehman, D. D. Lindberg
and R. J. Gripshover
Naval Surface Weapons Center
Dahlgren, Va. 22448

ABSTRACT

The pulse forming line (PFL) can store approximately 600 joules at 100 kilovolts. Line impedance is 0.86 ohm and discharge time into a matched load is 200 nanoseconds. The coaxial line is filled with a mixture of 60% ethylene glycol and 40% water, by weight, yielding the maximum freezing point depression. The dielectric liquid is dearated, deionized and cooled to subzero temperature in order to produce an intrinsic time constant of tens of milliseconds. A 50 kilovolt DC power supply with a current rating of 4 amperes is used to resonantly charge the PFL to 100 kilovolts in the millisecond time regime. A Marx generator is used for fast charging at high voltage. The PFL is being used for investigation of long term charging and breakdown statistics of water/glycol mixtures. It is also used for switch testing. In this paper, the PFL, charging systems, and liquid dielectric conditioning system are described. Experimental results of long term charging and breakdown statistics are also presented.

INTRODUCTION

Water, with its high dielectric constant and benign handling properties, is commonly used as the intermediate energy storage medium of pulsed power devices. Electrical energy is collected over a long period of time and subsequently discharged quickly into a load. Since power amplification is proportional to the ratio of charging time to discharge time, there is benefit in making the charging time as long as possible. Another benefit of long time charging is that it opens up the possibility of using new kinds of sources, such as the compulsator and other rotating machinery, to charge the line. The need for primary energy storage capacitors is thereby eliminated. To benefit from such new devices, it is necessary for the water to collect and store energy for times exceeding a millisecond, preferably tens of milliseconds. This is three orders of magnitude longer than the 5-10 microseconds typical of present high power devices and is a region which has received little experimental study.

Fenneman and Gripshover have shown that effective stress times of 250 microseconds are obtainable with pure, cold water [1]. This is still short of the milliseconds of time needed for rotating machines to discharge their energy . To obtain longer time constants, Gripshover and Fenneman suggested using mixtures of cooled water/glycol [2]. They showed that these mixtures retained the properties of pure water (high dielectric constant, high breakdown strength and benign handling characteristics) and increased the intrinsic time constant to nearly 100 milliseconds , thereby allowing tens of milliseconds charging time for the PFL. Their experiments, however, only involved small volumes of dielectric and small electrodes (80 sq. cm.). The purpose of this paper is to describe a large, full scale PFL and supporting systems to test these long charging time concepts.

DESCRIPTION OF THE PFL AND SUPPORT SYSTEMS

PFL

The PFL was initially designed to be a proof-of-principle device to demonstrate that full scale, low impedance, high dielectric, liquid filled pulse forming lines can be charged in the millisecond time regime. The design electrical parameters of the PFL are given in Table I.

Table I

PFL Design Parameters

Capacitance	116 nF
Impedance	0.86 ohm
Pulse Time	200 nsec
Inductance	863 nH
Maximum Voltage	100kV
Maximum Electric Field	61 kV/cm
Maximum Power	2.9 GW
Maximum Stored Charge	11.6 mC
Maximum Stored Energy	580 J

Fig. 1 is a schematic diagram of the PFL showing the overall dimensions. Fig. 2 shows how the center conductor is supported at the ends. The first end flanges, as shown in Fig. 2, were machined from 2 inch thick plexiglass. These have now been replaced with Lexan of the same thickness because shock waves generated by electrical breakdown within the PFL caused one of the plexiglass end flanges to fracture. The center conductor of the PFL is supported at the ends by 3 inch diameter end plugs which pass through the center holes in the end flanges. The diameter of these holes increases from 3 inches at the hole midpoint to 3.5 inches at the surfaces of the end flange. This was done in order to relieve stress at the triple junction which could initiate flashover across the end flanges. We also attempted to prevent flashover across the end plates by means of grooves (1/8 inch wide x 1/8 inch deep) which were machined on both sides of the end plates. Fig. 2 also shows

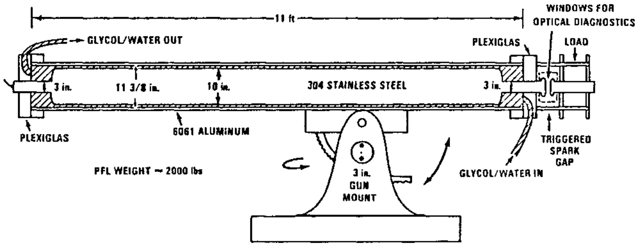

Figure 1. Pulse Forming Line

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14. ABSTRACT
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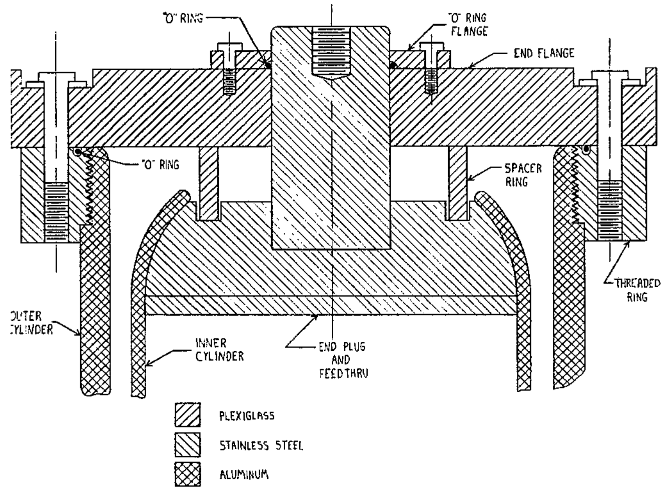

Figure 2. PFL End Details

that the diameter of the center conductor decreases near the ends of the PFL. It decreases from 10 inches to 7 inches over an axial length of 2 inches. This was also done to decrease field stresses at the ends of the PFL.

As shown in Fig. 2, the center conductor is stainless steel and the outer conductor is aluminum. Thus, by charging the center conductor positive with respect to the outer conductor, we are using steel as a positive charge injector and aluminum as a negative charge injector. According to Zahn, this biopolar injection should give the highest breakdown electric field [3]. In recent long term tests, however, aluminum has been found to be weaker so our choice of electrode materials may not be the best choice.

Although the PFL was initially designed and built to demonstrate long term charging of full scale, high dielectric, low imedance pulse forming lines, it also finds use as a source of well defined pulse power for single shot as well as repetitive switch experiments. The line impedance can be changed by changing the diameter of the inner cylinder. For example, a 3 inch diameter center conductor is available which will increase the line impedance by an order of magnitute(0.86 to 9 ohms).

Finally, we wish to point out that the 3 inch gun mount system (see Fig. 1) permits precise placement of the device. This feature is important for a number of reasons such as the capability of doing optical measurements on switch breakdown.

PFL CHARGING SYSTEMS

A block diagram of the resonant charging system is shown in Fig. 3. The fused

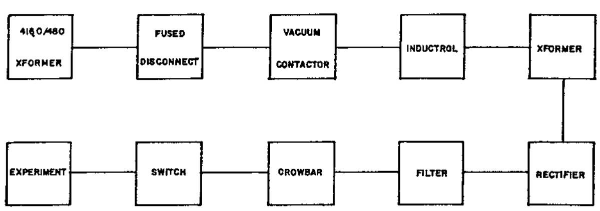

Figure 3. Block Diagram of Charging System

disconnect serves primarily as a protective device. It is padlocked in the OFF position when the system is not in operation. The fuses provide protection against long term faults. The 3 phase vacuum contactor is a convenient means of remotely applying or interrupting power to the system. It also provides fault protection. If a fault occurs and the input current exceeds a predetermined value, this condition is electronically sensed and the vacuum contactor opens thereby interrupting the input power. The opening time of the vacuum contactor is less than 2 cycles (60 HZ). The induction voltage regulator can raise the 480 V input voltage by 98% or lower it by 72%. The rectifier-filter converts the 3 phase high voltage transformer output to DC. In order to achieve less than 1% ripple, the value of the capacitor filter was chosen to be 10 microfarads. The function of the electronic crowbar is to limit the damage to sensitive and expensive equipment in the event of an electrical arc or fault. It does this by diverting the majority of available energy away from the fault. Essentially, this amounts to shorting the power supply at the filter bank terminals and maintaining this condition until the primary power has been removed from the circuit. In the event of a fault which causes the current to exceed a predetermined value, a sensor in the crowbar detects this condition and two 50 kV ignitrons in series are triggered. When the ignitrons fire, the energy stored in the filter bank as well as follow-on energy is dissipated in a 3 ohm resistor. Triggering occurs in less than 5 microseconds and at the same time a trigger signal is sent to the vacuum contactor which opens and interrupts the primary power.

The PFL is resonantly charged by inserting a switch, a high voltage diode and a 1 henry inductor in series with the PFL and the DC power supply described above. The switch is a high voltage vacuum contactor which is normally open. The resonant charge cycle is initiated by closing the vacuum contactor until the voltage on the PFL reaches its first maximum value and then opening it. For our inductor and PFL, the 1-cosωt waveform reaches a maximum value of 2V in approximately 1 millisecond, where V is the applied DC voltage.

A Marx generator is used when PFL voltages greater than 100 kV are required. The Marx generator contains 27 capacitors and 14 switches. Each capacitor is rated at 50 kV and 320 nanofarads. The switches are pressurized dry air insulated, mid-plane triggered spark gaps. The Marx is immersed in oil in a fully enclosed steel tank. The capacitance of the erected Marx is 12 nanofarads and the maximum voltage is 1.3 MV. From short circuit tests, the Marx inductance is 4.4 microhenries and the series resistance is 4.1 ohms. The maximum stored energy is 10 kJ. The maximum PFL voltage generated by discharging the Marx into the PFL is strongly dependent on the diameter of the PFL center conductor. For the 10 inch diameter center conductor, only about 16% of the Marx voltage appears on the PFL. This increases to 83% for the 3 inch diameter center conductor.

Liquid-Dielectric Conditioning System

A schematic of the liquid-dielectric conditioning system is shown in Fig. 4. The pump, heat exchanger, deionizers and storage tank are placed within a walk-in freezer that maintains a temperature below -10 degrees Celsius. A 15 horsepower, two-stage refrigeration compressor provides additional cooling to the liquid via the heat exchanger. The dielectric liquid is 60% ethylene glycol and 40% water. The liquid is pumped directly into the heat exchanger and then into the entry manifold for the three deionizers arranged in parallel. The manifold allows the transition from the 1 1/2 inch clear PVC pipe used in the system to the 1/2 inch entry ports of the deionizers. An optional bypass around

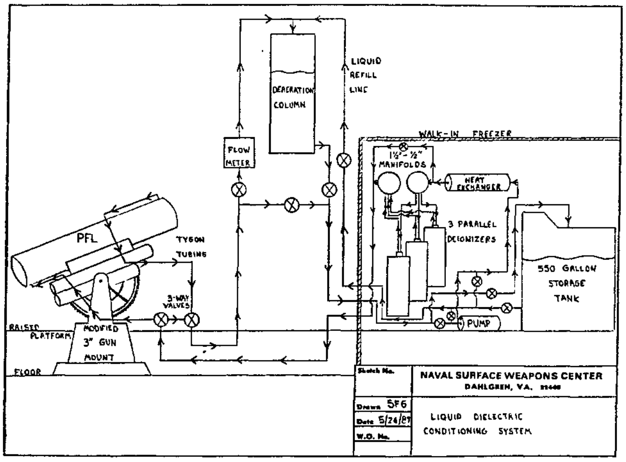

Figure 4. Liquid Dielectric Conditioning System

the deionizers is provided. Upon exiting the deionizers and the outlet manifold, the liquid is pumped directly to the PFL. The liquid transitions to flexible, 2 inch inner diameter, 1/2 inch wall Tygon tubing which forms the inlet and outlet connections to the PFL. This tubing allows rotation and elevation of the PFL by means of the modified 3 inch gun mount. An optional bypass around the PFL is provided. From the PFL, the liquid is pumped to the top of the deaeration column. It cascades down a series of plates designed to spread out the liquid and assist in deaeration to the exit port of the deaeration column. The deaeration column is maintained at a pressure near the vapor pressure of water by a vacuum pump in order to deaerate the liquid. The deaeration column is mounted six feet up the wall of the laboratory in order to provide sufficient net-positive-suction-head for the proper operation of the centrifugal pump. An optional bypass is provided around the dearation column. The liquid normally flows into the inlet of the pump, but an optional path (usable only when the deaeration column is bypassed) to the top of the storage tank and then out the bottom of the storage tank and into the inlet of the pump is provided. This optional path is used when mixing of the contents of the storage tank is required. Also, the pump can direct the flow of the liquid directly into the storage tank when the system needs to be emptied for maintenance. Finally, a fill-line is provided from the storage tank to the top of the deaeration column when liquid needs to be added to the system.

During the high voltage experiments, the liquid is continually cooled, deionized and deaered. Since the charging waveform requires about 1 millisecond to reach peak voltage, the intrinsic (RC) time constant of the liquid is maintained near ten milliseconds which corresponds to a temperature of about -20 degrees Celsius. Flow meters, pressure gauges, temperature sensors and a Tau meter are used to monitor the condition of the dielectric liquid. The Tau meter is a patented, NSWC invention designed to easily measure the RC intrinsic time constant of the dielectric fluid. Further details may be found in the references [4,5]

SYSTEM PERFORMANCE

Initial testing was performed on the PFL using the resonant charge system. The temperature of the dielectric liquid was maintained near -20 degrees Celsius which corresponds to an intrinsic time constant of approximately 10 milliseconds. The PFL voltage was measured at the input of the PFL with a resistor divider. Two TV cameras were used to monitor the ends of the PFL to determine if breakdown was internal or external. External breakdown at the output end of the PFL was observed when testing was initiated. Breakdown was caused by a large metal ring which was used to attach the load and spark gap to the PFL. This ring was attached to the end plate of the PFL and reduced the distance from the high voltage center conductor to the outer ground conductor by 2 inches. After the ring, load and spark gap were removed, neither external nor internal flashover across the end plates was observed.

The highest observed PFL voltage was 80 kV. Fig. 5 shows the charging waveform at this voltage. In attempting a series of 10 consecutive shots, however, the PFL always broke down before the 10th shot. The highest voltage applied to the electrodes for which there was no breakdown for 10 consecutive shots was 70 kV. By definition, this is the 10% threshold breakdown voltage. The 10% threshold breakdown field is 43 kV/cm. These results were obtained with the center conductor at positive high voltage and the outer conductor at ground potential. When the polarity was reversed, the same results were obtained.

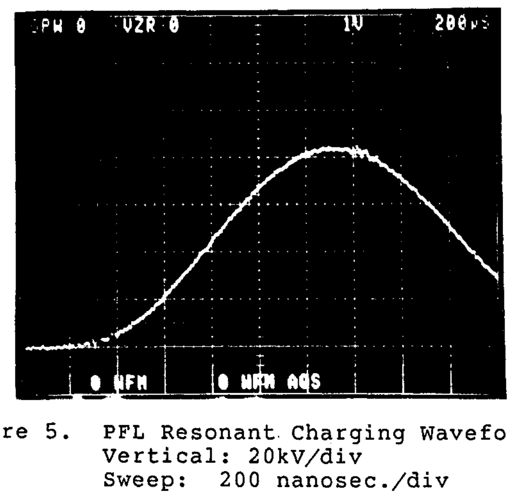

Figure 5. PFL Resonant Charging Waveform
Vertical: 20kV/div
Sweep: 200 nanosec./div

The PFL was also charged with the Marx generator. For these shots, the spark gap and load were connected to the PFL. The spark gap was adjusted such that it would not fire unless the PFL voltage was well in excess of 100 kV. The electrical connection from the Marx to the PFL was entirely coaxial. The only place we could connect a resistive divider voltage probe was at the Marx generator output. We could not do this, however, because there was too much inductance between the Marx generator and the PFL. In order to obtain PFL charging waveforms, we measured the current in the series circuit and integrated to get the charge on the PFL and then divided this charge by the known capacitance of the PFL to obtain the voltage. The results of one of these shots are shown in Fig. 6. This waveform shows that a PFL voltage slightly in excess of 100 kV was achieved. The time required to charge to 100 kV is about 700 nanoseconds. This is much faster than the 1 millisecond which characterizes the charging time of the resonant charge system described above. The Marx generator was adjusted to charge the PFL to about 110 kV for the next shot in this series. There was flashover in the vicinity of the load and some damage was done to the load. PFL charging with the Marx generator was terminated at this point but will be resumed in the future.

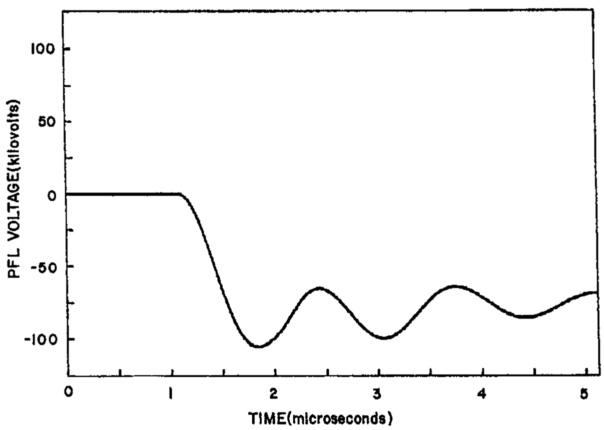

Figure 6. PFL Marx Generator Charging Waveform

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