THREE CHANNEL PULSE POWER SYSTEM FOR UNDERWATER ACOUSTIC SOURCE

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Abstract

A three channel pulsed power system has been developed at the U. S. Navy Coastal Systems Station in Panama City, Florida to provide power for underwater acoustic sources. In the present configuration, the system is capable of providing continuous operation at repetition rates up to 15 Hz and with energies up to 1.5 kJ per pulse per channel into a broad range of loads including spark-type underwater acoustic sources. The system includes three independent banks each of which contain two switcher-type power supplies, each capable of an energy output of 8 kJ/s at 3.2 kV. A highly flexible control system allows the construction of pulse trains with arbitrary trigger timings for each bank. High power silicon controlled rectifiers (SCRs) are used to form the pulse trains. The system is currently located on the deck of a remote controlled QST-35A U. S. Navy target drone boat and provides power for three underwater spark gap acoustic sources (sparkers). The system was recently demonstrated at an Advanced Concept Technology Demonstration (ACTD) military exercise in Newfoundland, Canada.

I. INTRODUCTION

Advances in computer technology have promoted the evolution of advances in naval sea mine technology. Microprocessors make it possible for sea mines to evaluate multiple sensor data and effectively determine how ship-like a potential target is. The mines can thereby discriminate against assets not of interest or, more importantly, discriminate against minesweepers. To counter this emerging threat, the U.S. Navy has undertaken a technology demonstration program to develop a new influence sweep system that will meet this challenge for the amphibious assault mission. The Advanced Lightweight Influence Sweep System (ALISS) program is developing new magnetic and acoustic sweep technologies with the high-speed capability (35 to 50 knots) to support in-stride clearance operations. Because the new technologies will be capable of emulating the magnetic and acoustic signatures of the assault craft, sophisticated "smart" mines will no longer be able to discriminate between the assault craft and the minesweeper. Thus, advances in sea mine evolution can be defeated.

For the acoustic portion of the system, the ALISS program has focused on plasma discharge, pulsed power technology. This approach was chosen for three reasons. First, high-speed transit and sweep capability is mandatory for the in-stride over-the-horizon mission, requiring low drag acoustic systems. The demonstration hardware has three 1-inch rods, 12 inches long, extending below the test platform. The loss associated with this drag is less than 0.5 knots at a speed of 20 knots [1]. Second, plasma discharge technology provides the ability to shape the acoustic spectrum, allowing emulation of the assault craft. The more closely the sweep resembles the assault craft, the harder it is for a "smart" mine to distinguish between the sweep and the target. This renders the mine's counter-countermeasures circuits useless. And third, plasma discharge efficiency is significantly higher than efficiencies of other technologies. Plasma discharge testing at Coastal Systems Station has shown efficiencies from 1 to 9 percent, depending on the transducer and pulsed power configuration. By comparison, other commonly used acoustic sweep systems have efficiencies that are less than 1 percent.

Figure 1 shows a picture of the ALISS equipment onboard the QST-35A. The QST-35A has an onboard remote control system that is connected to a satellite phone enabling unmanned remote control operation from virtually anywhere in the world. The pulsed power system is located on the aft end of the boat. A cryocooled, superconducting magnet is located directly behind the cabin. The magnet and pulsed power system are powered by two generators located between them. The three acoustic transducers are electrically connected to the pulsed power system on the deck between the two generators and are mounted on brass pipes, which extend below the hull of the boat.

Figure 1. ALISS equipment onboard the QST-35A.

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II. BACKGROUND

Operation of an underwater sparker is relatively straightforward. Initially, a capacitor is charged to a high voltage that can range from less than a kilovolt to several hundred kilovolts. Subsequently, a switch is activated, and the high voltage appears across the sparker. This high voltage breaks down the water gap, forming a plasma channel between the electrodes. The resistance in the channel drops rapidly (ranging from a few ohms to tens of milliohms), giving rise to high currents in the plasma that can range from several hundreds of A to tens of kA. This in turn causes the plasma temperature to increase to values on the order of 10^4 K.

Pressure in the channel rises, causing the channel to expand rapidly. Rising pressure in the channel can reach values on the order of 10^3 atm. Near the end of the discharge, pressure begins to fall off rapidly. The channel now assumes the shape of a spherical bubble. The inertia of the moving liquid causes the bubble to continue expanding until pressure in the bubble decreases below the ambient hydrostatic pressure. The bubble continues to grow, and the internal pressure continues to decrease for an extended period of time (relative to the discharge time). Eventually, the bubble reaches maximum size (maximum potential energy) and begins to collapse under the hydrostatic pressure, which is significantly larger than the bubble pressure. As the bubble collapses, the gas (steam) in the bubble is compressed, and the bubble pressure increases. This sequence of events is much like the expansion phase, except in reverse. As the bubble collapses to minimum size, pressure rapidly increases, eventually achieving a maximum value well above the hydrostatic pressure and in some cases significantly larger than the expansion peak, depending on the nature of the discharge. This cycle can repeat itself several times as the bubble rebounds from the collapse. Subsequent bubble periods will be progressively and significantly shorter than the previous cycle, and the pressure peaks will likewise be progressively smaller. The bubble may rebound several times before dissipating in the liquid. These large variations of the pressure in the bubble cause emission of compression and rarefaction waves in the surrounding liquid with the same characteristics as the bubble pressure. As shown in reference [2], it is the emission from the first bubble cycle that dominates the acoustic spectrum generated by the spark gap transducer.

III. SYSTEM DESCRIPTION

Extensive equipment testing and modification was conducted prior to the ACTD military exercise. The pulsed power system had to be modified from a shore-based, experimental system to a sea-based, operational system. The original intent for the pulsed power system was a spiker-sustainer concept [2]. The sparkers were to be housed in a pod, which would hold deionized water, underneath the boat. The transducer would be a point to point, wire feed system. The spiker circuit would provide a high voltage (~100kV) across the spark gap to initiate a plasma channel. Once started, the sustainer circuit would provide the high energy for the bubble formation. This concept was abandoned for the more practical system in which three coaxially configured sparkers were placed underneath the boat. It was determined that a spiker circuit was not needed when seawater was used as the fluid medium. Multiple sparkers were used to provide maximum fidelity over the desired frequency range.

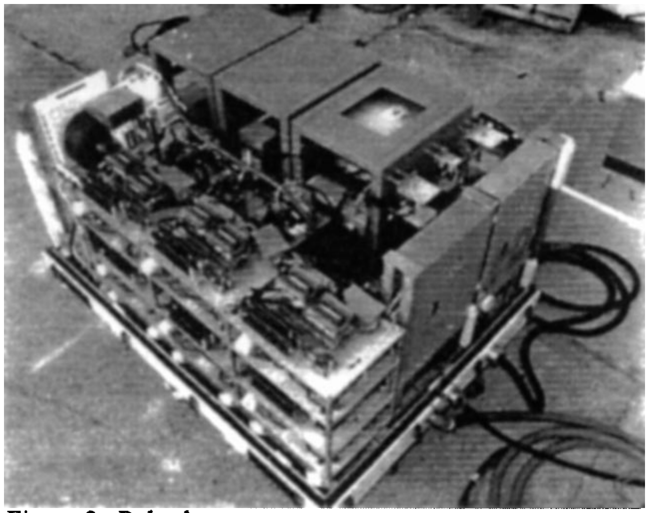

Figure 2. Pulsed power system.

Several modifications were made to achieve the final system. For example, the original test equipment was housed in a 40 foot connex box. The equipment was moved to a 2.6 by 2.0 by 1.4 meter marinized enclosure. The input power changed from shore-based to a 68 kW, 480 V, 3-phase diesel generator. The sparker lifetime increased from a few seconds to several hours of continuous operation.

The pulsed power system is housed in an enclosure to mitigate EMI as well as to shield it from the harsh marine environment. The enclosure houses the power distribution system, two 2-ton air-conditioners, the pulsed power system, and other ancillary equipment and weighs approximately 2,268 kilograms. The pulsed power system is divided into three identical banks that provide power to three separate underwater acoustic transducers, each of which can be controlled independently. Power is delivered to the transducers, which are located at the center of the boat, through high power coaxial cables. Figure 2 shows the inside of the enclosure with the top removed. The high voltage power supplies and control systems are housed in the racks shown at the top of the figure. The pulsed power circuit components are located at the bottom of the figure. The power distribution system is located on the right and the air conditioning system is located on the left.

Each of the three banks in the pulsed power system is separated into two "half" banks. The half banks are electrically connected together at the acoustic transducer. This allows for maximum flexibility in power delivery to the transducer. Figure 3 shows a simplified circuit diagram for a half bank.

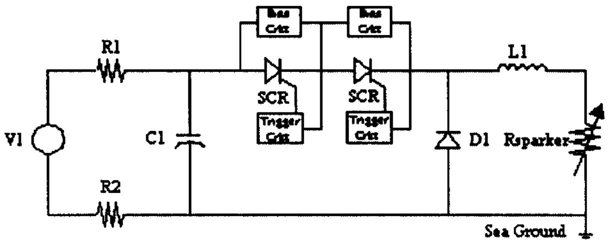

Figure 3. Pulsed power circuit.

Voltage, V1, is supplied by a Maxwell CCDS capacitor charging high voltage power supply. The power supply has a maximum output of 3.2 kV at 8 kJ/s. The power supply requires a 3 phase wye connected 480 V input. There is a 2 Ω/225 W charging resistor, R1, in series with the circuit. A 10 Ω/225 W resistor, R2, is on the negative side of the power supply. R2 is used to prevent grounding problems experienced with the floating ground of the power supply.

The circuit is arranged so that the power supply can charge up to three 50 µF/3.5 kV capacitors in parallel dependent upon the desired acoustic output. If a total bank output of 1.5 kJ per shot is desired, then all three capacitors would be placed in parallel in both half banks. A dump circuit, which is not shown, is located in parallel with the capacitors and contains a relay and a dump resistor. The relay is closed when the circuit is not energized.

The high voltage switches in this circuit are SCRs. The switches are Powerex C702CM SCRs. A voltage divider/bias circuit is used so that half of the full voltage will be dropped across the series connected SCRs. This is done for reliability. The failure mode for the SCR is a short-circuit. Therefore, if one fails, the other SCR will continue operation. Gas switches were considered but SCRs offer a considerable weight savings and proved to be reliable once certain circuit modifications were made.

The SCRs are switched by a trigger circuit. The trigger circuit is controlled by a fiber optic control signal. A 20 µH inductor, L1, is in series between the SCRs and the sparker.

The sparker, Rsparker, is represented by a variable resistor and its breakdown characteristics were described previously. The sparker is a coaxially configured electrode with a copper tungsten rod as the anode and a copper tube as the cathode. A fiberglass weave is used as the dielectric. A more detailed description is documented in reference [3]. A freewheeling diode, D1, is used to maintain current flow while the sparker discharges.

A Pearson Current Monitor Model 110 is used to measure the current flowing through the inductor and through the sparker. To calculate the voltage across the inductor and sparker, a known high impedance resistor is placed in parallel to D1 and the current measured passing through it. The current monitor output was recorded by an oscilloscope located in the cabin of the boat. In normal operation, the output is monitored to verify acoustic performance. A computer and control interface is also located in the cabin. The computer allows the construction of pulse trains with arbitrary trigger timings for each separate "half" bank. Fiber optics are used for voltage isolation between the pulsed power system and the control system in the cabin of the boat. The control system is used to control power to the systems, switch the dump relay, and control the high voltage. The control system is designed to be turned off and on remotely with the onboard remote control system.

IV. RESULTS

One goal of the ALISS project is to provide a lightweight acoustic system to the fleet. Therefore, an effort was made to reduce the weight by removing non-essential system components. One component believed to be non-essential was the inductor, L1. The inductor has a weight of 23 kg and since there were a total of six, removing these items along with the supporting hardware would achieve a considerable weight savings. Tests were performed to see the effect of the inductor on the electrical output of the circuit. Figure 4 shows the output with the inductors in the bank and Figure 5 shows the output without them. Both banks were charged to 3.2 kV and had a capacitance of 200 µF.

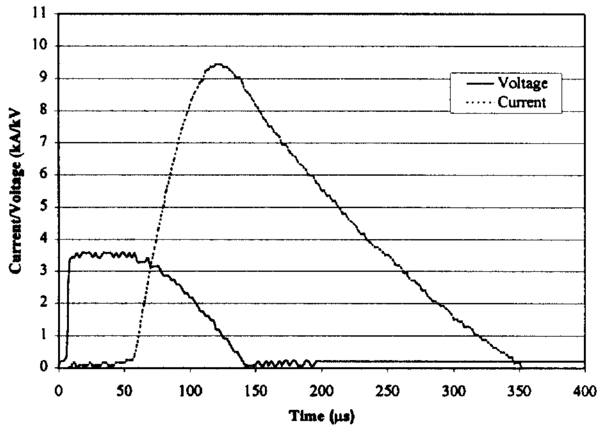

Figure 4. Current/Voltage output with inductor.

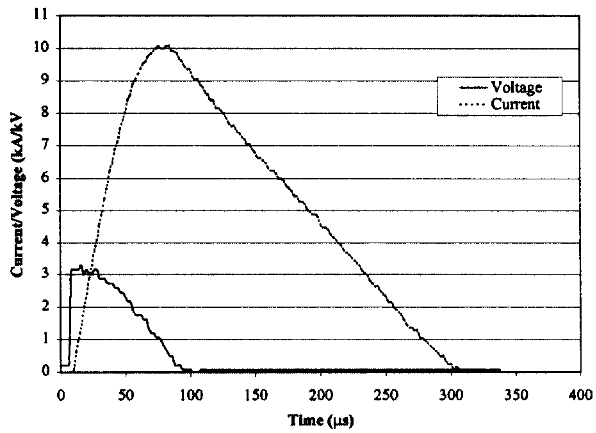

Figure 5. Current/Voltage output without inductor.

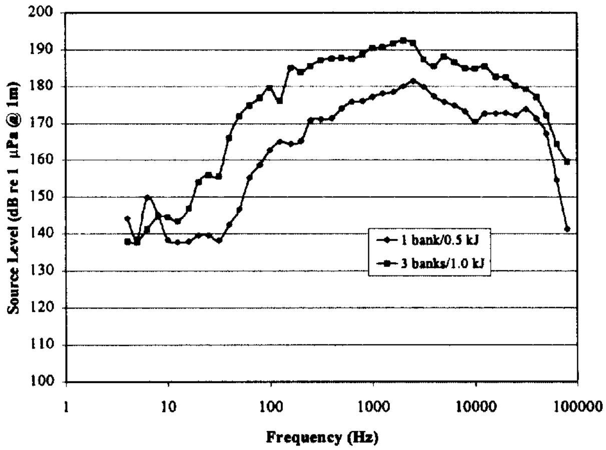

Figure 6. Acoustic output comparison.

As shown in the figures, the inductor acts like a choke on the output. The spark gap breaks down almost instantaneously when the inductor is removed from the circuit. There is also almost 1000 A more delivered to the sparker. Electric to acoustic efficiency tests indicate an improvement from 7% to 9% in efficiency without the inductors. The electric to acoustic efficiency was determined by calculating the ratio of the acoustic output energy in the frequency band of interest (8.9 to 5612 Hz) to the electrical input energy ($E = 1/2CV^2 = 1$ kJ). Unfortunately, the increased current forced the SCRs to operate near their maximum current threshold at the maximum acoustic output. This proved to be a reliability issue. Whenever a sparker failed to a short, the resultant current spike would also cause the SCRs to fail. Therefore, it was decided that the inductors would remain.

It was demonstrated during testing that the pulsed power system was capable of operation with an output of 1.5 kJ per shot with a repetition rate of 15 Hz. Due to the limited available peak current draw from the generator however, all three banks cannot operate continuously at a 15 Hz repetition rate. All three banks did operate continuously at a 10 Hz repetition rate each with an output of 1 kJ per shot for 90 minutes. The limiting factor was that the sparker life does not exceed this time at this output. The pulsed power system operated continuously for over two hours at a reduced output of 0.5 kJ per shot with a repetition rate of 10 Hz. Figure 6 compares the acoustic output of all three banks at 1.0 kJ output to that of one bank at 0.5 kJ output. As can be seen in the figure, the three bank, 1.0 kJ output is almost 10 dB greater than the one bank, 0.5 kJ output over most of the frequency range.

ALISS participated in the ACTD military exercise, MARCOT/Unified Spirit '98 in June, 1998. This was a joint mine countermeasures exercise to demonstrate novel systems that are currently being investigated for U.S. Navy fleet introduction. As an ALISS subsystem, the pulsed power system operated almost continuously, seven nights in a row with limited problems. ALISS also recently participated in a U.S. Navy fleet exercise, Kernel Blitz '99, in which the pulsed power system worked continuously without incident for four, six hour missions.

V. CONCLUSIONS

A pulsed power system has demonstrated continuous operation of three independent banks for over 1.5 hours with an electrical output of 1.0 kJ per shot at a repetition rate of 10 Hz. The pulsed power system provided electrical input to an underwater sparker, which was the limiting factor with continued operation. The system demonstrated successful operation in rugged, at-sea conditions during two military exercises. Additional experimentation should be performed to increase and optimize the electrical to acoustic efficiency between the pulsed power circuit and the sparker. The goal of which should be to maintain the system reliability and reduce the system weight.

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