RECENT RESULTS OF VACUUM-ARC SWITCHED* MULTI-MEGAWATT INVERTER TESTS

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ABSTRACT

Previous studies[1] have shown the possibility of using a vacuum arc switch (VAS) in high power force commutated or series commutated inverter circuits. One such application, discussed in this paper, is in the development of a 10,000 volt, multi-megawatt series capacitor inverter circuit. Initial testing has been performed on a 10 kHz series resonant L-C circuit using a VAS. Single pulse tests at 3000A peak and 5000 V have been very successful.

Extensive energy loss studies of the various circuit components result in predicted inverter efficiencies in excess of 95 percent. The tests show that these high efficiencies will be achievable if high quality circuit components are used. The inductors must be fabricated from Litz wire. Low loss materials must be used for the capacitors and distributed connections must be made to capacitor elements. The configuration and composition of the electrodes in the VAS must be such as to minimize the switch voltage drop.

INTRODUCTION

In the development of high frequency, multi-megawatt inverters for airborne applications, fast reliable, lightweight switching devices are required. Because thyristors are expected to be relatively heavy[2] a program for the development of vacuum arc switches is being supported at the State University of New York at Buffalo by the Air Force Aeropropulsion Laboratory. The results of preliminary tests on these devices and their application to inverter circuits have been described.[1] This paper presents the results of recent detailed energy loss measurements on vacuum arc switches and on other inverter circuit components.

The following paragraphs contain discussions concerning vacuum arc switches and the series-capacitor inverter circuit. Then, the components selected for use in the circuit are described. Finally, the details of the energy loss study are presented along with initial results of tests of the inverter circuit.

BASIC DESCRIPTION OF VACUUM ARC SWITCH

Vacuum arc switches(VAS) have been described in detail elsewhere.[3,4] A brief description is given here to orient the reader who is not familiar with these devices.

The basic configuration of a VAS capable of being turned off as well as on is shown in Figure 1. A vacuum-arc discharge between the cathode and anode is initiated by the use of an igniter electrode. The igniter is separated from the cathode by an insulator on which the metallic vapor from the arc can deposit forming a conductive thin film. To ignite the arc, a current pulse is passed through this film causing a portion of it to vaporize. The resulting plasma burst quickly fills the interelectrode space allowing the main arc current to pass between the anode and cathode with a rise time on the order of one microsecond. During the ensuing discharge the metallic film is regenerated, preparing the system for the next ignition pulse.

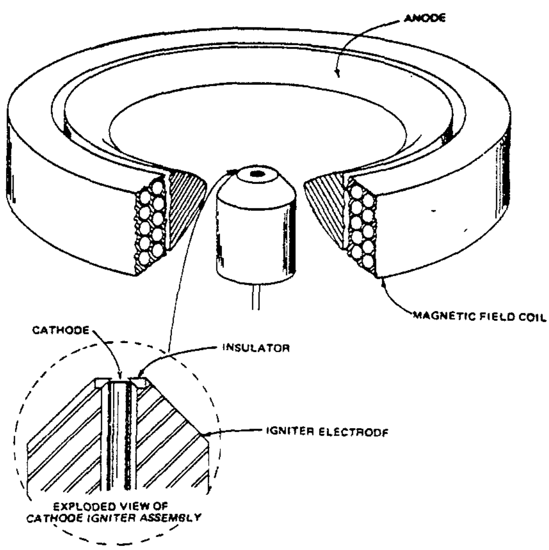

Fig. 1. Configuration of vacuum arc switch

For arc interruption to occur, the electrodes must be of a coaxial geometry. The cathode is a small electrode placed on the axis and the anode is an annular surrounding the cathode. The arc is extinguished by applying a coaxial magnetic field to the device in such a way that the field lines are essentially perpendicular to the paths of the electron current from the cathode to the anode. The effect of the field is to increase the voltage drop across the arc and thereby decrease the discharge current. The arc is extinguished when the current is reduced to a value where the average lifetime of the arc becomes very short compared to the duration of the magnetic field pulse. When conduction ceases, metallic vapor is no longer emitted by the cathode. The vapor in the interelectrode space rapidly condenses and the switch returns to the high-vacuum state and remains off when the magnetic field is removed.

In some switch applications a significant voltage may exist between the field coil and the anode and this can lead to malfunctions resulting form arcing between the anode and the field coil. For these applications,

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it is possible to use an induction coil with only one or two turns in place of the anode/field coil arrangement shown in Figure 1. By driving the induction coil with a pulse transformer it is possible to use the coil as an anode as well as for arc interruption purposes.

Of course, in circuits where natural commutation of the switches occurs, there may be no requirement for magnetic interruption. In this case the anode can be a cup shaped electrode facing the cathode igniter assembly.

BASIC SERIES CAPACITOR INVERTER CIRCUIT

The basic inverter circuit presently being considered for use with vacuum arc switches in the multi-megawatt power range is shown in Figure 2. The primary features of this series capacitor inverter circuit that make it attractive for lightweight high power applications are:

1. Natural commutation of the switches occurs.
2. High frequency operation is possible and this leads to the use of lightweight inductors, capacitors and transformers.

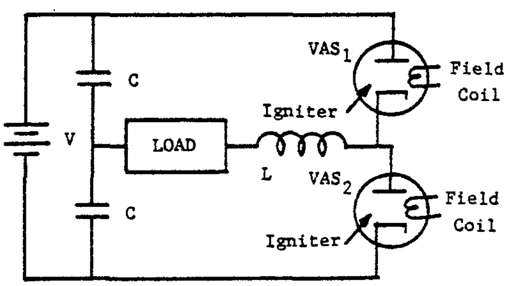

Fig. 2. Basic inverter circuit

In the series capacitor inverter circuit, when one of the vacuum-arc switches is turned on, a half-sinusoidal current pulse is passed through the load. At the end of a current pulse, conduction through the switch ceases and the arc is extinguished. The field coil is not used for current interruption. Instead, it may be used to insure that arc reignition doesn't occur during the non conducting half cycle. The current waveform applied to the load can be very nearly sinusoidal if the delay time between the end of the conduction period for one switch and the ignition of the other switch is limited to a few microseconds. This does indeed appear to be possible with the vacuum arc switches because tests have demonstrated that the switches become non conducting in a fraction of a microsecond after current zero has occurred. The results of virtually eliminating the nonconducting delay between the operation of the switches are that high efficiency and a high operating frequency can be attained.

During each half cycle of operation, the equivalent circuit for the series capacitor inverter is simply the series L-C circuit shown in Figure 3. This is the basic circuit that was used for determining the energy loss characteristics of the vacuum arc switch.

It was necessary to provide test data for the vacuum arc switch under multimegawatt-level operating conditions. To do this, it was assumed that a circuit Q on the order of two would be required for inverter operation. A load resistance on the order of one ohm was chosen and this resulted in the selection of a capacitance of 10uf and an inductance of 40μH for operation at approximately 8 kHz. The current in the circuit was chosen to be 2000 A so that the power delivered to the load would be at least 4 MW.

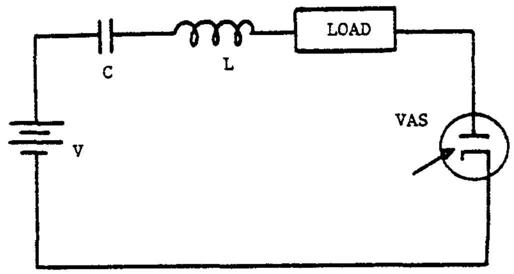

Fig. 3. Equivalent circuit for series capacitor inverter.

During energy loss tests, the load was eliminated so that the only losses in the circuit were those in the components and in the switch. The current level was maintained at approximately 2000 A to provide realistic tests of the switch. The voltage source, V, for these tests was a large (1000μF) capacitor charged to approximately 5000 V. Thus, the actual test circuit was that shown in Figure 4.

LOSS TESTS

The primary testing technique used was as follows. Capacitor C_o was initially charged to the desired voltage. Capacitor C was initially completely discharged. Then, the VAS was operated, causing a half-sinusoid of current to flow in the circuit as is shown in Figure 5. During conduction of the switch, energy was transferred from capacitor C_o to capacitor C. By subtracting the energy transferred to C from that removed from C_o, the energy dissipated in the circuit elements and in the switch was determined.

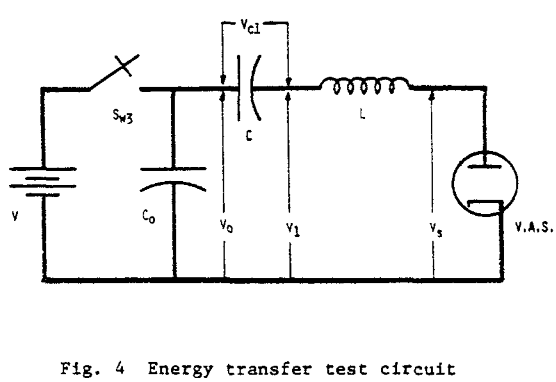

Fig. 4 Energy transfer test circuit

To separate the switch losses from the circuit losses, additional tests of the circuit elements were performed. Basically, these tests consisted of replacing the VAS with a lossless closing switch. When this switch was closed, causing the L-C circuit to resonate, the time constant of the resulting damped sine wave was measured. From this time constant the resistance of the circuit elements was calculated.

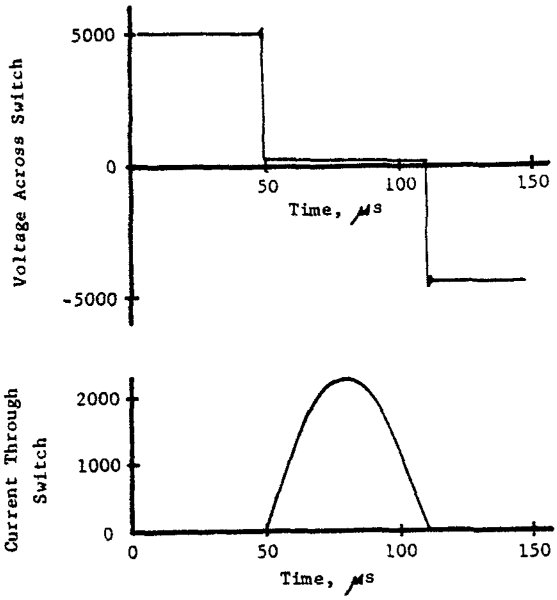

Fig. 5 Waveforms of switch voltage and current

There are several factors that made the time constant measurements far from trivial. The first and most important was that of devising a lossless closing switch for operation at the currents (kiloamperes) and voltages (kilovolts) of interest. It was necessary for the switch to be lossless, of course, so that only the circuit losses would be measured. The problem with a standard knife switch, which is essentially lossless during conduction, is that it is far from lossless during the closing process. Energy is dissipated in the arc formed as the switch closes. In addition; in the knife switches tested, there was always some bouncing of the contacts during closure which resulted in losses and in interruptions in the oscillation of the circuit.

To eliminate the switching problems, the switch pictured in Figure 6 was devised. This switch consisted of a cone-shaped brass contact that was driven through a .005 in (.0125 cm) thick teflon sheet into a lead pad with a hammer. This switch closed in a microsecond or less and the energy loss due to any arcing that may have occurred during the closing process was insignificant. The use of the lead pad eliminated contact bouncing. A typical current waveform that resulted from the use of this switch and the circuit in Figure 6 is shown in Figure 7.

Using the hammer actuated switch, extensive tests were performed to reduce circuit losses as much as possible. The capacitors finally selected were six each, 1.68 μF, 40 kV, rated GE pyranol units in parallel. These were the best capacitors readily available in the laboratory. Capacitors manufactured from polypropelene and silicone oil would be significantly better. The inductor was made from Litz wire produced by the New England Wire Company. Two conductors, each 0.375 in (.95 cm) in diameter and consisting of approximately 2000 strands, were wound in parallel in a solenoidal configuration. Interconnecting conductors were fabricated from Litz wire or flat strap and were minimized in length. The end result of these tests is that a circuit resistance value of 21 milliohms at 8 kHz was achieved. It is estimated that approximately one third of this resistance was in the capacitors and that two thirds was in the inductor. This resistance could be further reduced by using additional Litz wire conductors in parallel with the two in use and by using polypropelene-silicone oil capacitors.

It should be pointed out that measurements were performed over a wide range of currents to determine whether or not nonlinear effects were occurring at any point in the circuit. None were found.

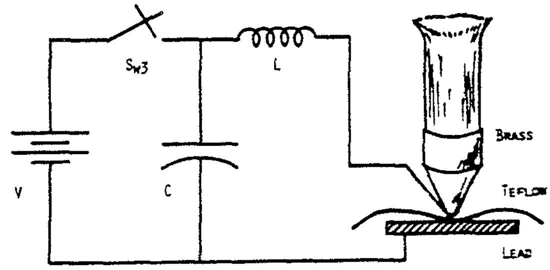

Fig. 6 Resonance test circuit including hammer actuated switch

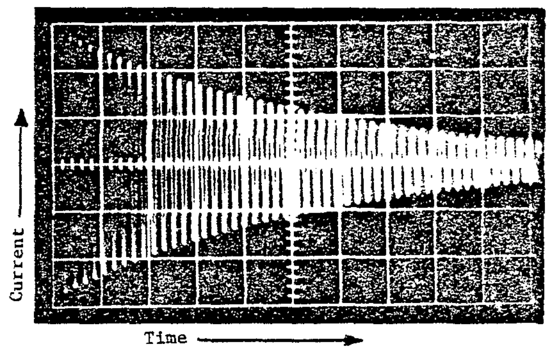

Fig. 7. Current waveform resulting from use of hammer actuated switch and series resonant circuit.

Using the circuit resistance measurements obtained from the loss tests, it was possible in the energy transfer experiments to separate the circuit losses from the switch losses. Before discussing these results, however, the energy measurement techniques should be described.

The initial energy contained in C_o was, of course, given by

$$\frac{1}{2} C_o V_o^2.$$

After the operation of the VAS and the transfer of energy to C, the energy in C_o was reduced. It is important to realize that because C_o was two orders of magnitude larger than C, the actual change in the energy content and of the voltage V_o was relatively small In order to accurately determine the change in energy level of C_o, therefore, extremely accurate measurements in the value of V_o were necessary. These measurements were complicated by the fact that leakage paths within the capacitors (both C_o and C) as well as those provided by the voltage measuring instrumentation caused the capacitors to discharge very slowly. The result was that all voltages changed with time so that measurements had to be performed very rapidly before and after an energy transfer cycle.

To provide rapid and accurate voltage measurements digital voltmeters having an accuracy of .01 per cent or better were used. The maximum input voltage capability of the digital voltmeters was 1000 V. To make possible voltage measurements at the 5000 volt level and higher, voltage dividers consisting of the 10 MΩ input resistance of the digital voltmeters and a 90 MΩ series resistance were used. The 90 MΩ series resistance was provided by 14 each 7.5 MΩ metal film resistors in series. Metal film resistors were used because they were linear over the voltage range of interest.

To make the voltage measurements rapidly, the sample and hold features of the meters were used. Thus, for example, the meter measuring V_1 was triggered at the end of the energy transfer cycle to take and hold the voltage reading at that time.

RESULTS

The circuit elements and the vacuum arc switches are being continually refined. The following results, while they are very good, are representative of the type of results that can be achieved however they are in the process of being improved. These results were obtained with an inductor having a resistance somewhat above that of the Litz wire inductor described previously in this paper. In addition the VAS used had a resistance somewhat above that currently achievable.

The voltage change occurring on capacitor C_o during the transfer of energy to C was

$$\Delta V_{co} = 91.5 \text{ V.}$$

Thus the energy removed from C_o was

$$\Delta E_{co} = \frac{1}{2} C_o V_o^2 \Big|_{t_o} - \frac{1}{2} C_o V_o^2 \Big|_{t_1}$$

$$= 469.2 \text{ J}$$

where t_o = time at beginning of cycle

t_1 = time at end of cycle

$V_o\Big|_{t_o}$ = 5000 V.

The energy transferred to C was

$$E_c = \frac{1}{2} C \left[V_o^2\Big|_{t_1} + V_1^2\Big|_{t_1} \right].$$

$$= 448.1 \text{ J.}$$

The energy lost to the circuit elements and to the switch was therefore

$$E_{loss} = 469.2 - 448.1$$

$$= 21.1 \text{ J.}$$

Now, if the individual component losses are tallied, they should agree with the above calculated total loss The energy loss, E_R, in the resistance of the circuit components and of the switch was

$$E_R = \frac{1}{2} I_{peak}^2 Rt$$

$$= 19.1 \text{ J}$$

The energy loss, E_A, due to the fixed switch arc drop of 21 volts was

$$E_A = \frac{2}{\pi} I_{peak} (21)$$

$$= 2.0 \text{ J}$$

Therefore the total loss is computed to be

$$E_{loss} = 19.1 + 2.0$$

$$= 21.1 \text{ J}$$

and this agrees with the result from the energy transfer test.

For the test described above the total loss was 4.5 per cent of the energy removed from C_o. Approximately two thirds of this (2.9 per cent) was lost in the switch.

Switch improvements already made as well as those being made should reduce the switch loss to well below two per cent. Also, circuit improvements already made have reduced the circuit losses to well below 1 per cent.

SUMMARY

In summary detailed loss measurements have been performed on vacuum arc switches and on associated components of the type that would be used in a series-capacitor inverter circuit at megawatt power levels. The tests performed in making these measurements have demonstrated that attention to detail in all aspects of the measurements is necessary to obtain valid results. Techniques have been developed for making accurate loss measurements on all circuit components under high power operating conditions. The results given in this paper show that the energy loss in a vacuum arc switch operating in a series L-C circuit is less than three percent of the energy transferred by the switch. Recent switch improvements should reduce this loss to well below two per cent.

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