Half-Megampere Magnetic-Energy-Storage Pulse Generator

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Energy is stored in the magnetic field of a large air-core transformer having a very low impedance, tightly coupled secondary winding. The energy can be effectively delivered in less than 5 msec to a noninductive load, having a resistance of less than 10^{-4} ohm.

INTRODUCTION

RESEARCH involving transient currents of the order of a million amperes requires very high peak power levels which are not ordinarily obtainable from a utility power line. It is usually advantageous to use an energy storage system which will permit taking energy from the power line over a period of seconds or minutes and then discharging the energy over a much shorter interval.[1] For certain applications, inductive storage has significant advantages over alternative methods such as capacitors or rotating machinery. The relative merits of several electrical storage methods have been discussed in a previous paper.[2] It was shown that magnetic storage is often economically advantageous in situations where the energy is in the megajoule range and the discharge time is several milliseconds.

The simplest form of inductive storage requires only a large reel of insulated cable, a source of dc charging power and the appropriate switching equipment. Current is built up in the inductance over an interval of several seconds, and then the load impedance is switched into the circuit so that the inductively stored energy is discharged in a few milliseconds. The single winding coil has the limitation that the maximum current delivered to the load cannot exceed the maximum current available from the dc supply. However, by adding a low-impedance, tightly coupled secondary winding to the inductance coil, the current to the load can be increased by transformer action.

A transformer-type storage coil has been built at the University of Michigan for studying transient electric arcs at currents of half a million amperes. This investigation is coordinated with the hypersonic wind tunnel program at the Arnold Engineering and Development Center, where a "Hotshot" type of transient wind tunnel uses an electric arc to heat the air supplied to the tunnel throat. An important objective of the University of Michigan program has been to obtain design information applicable to much larger installations. The maximum current obtainable from the transformer-type coil described in this paper is limited by the magnetic forces on the terminals of the secondary winding. However, with additional mechanical strength for withstanding these forces, operation at substantially higher energy and current levels would be possible.

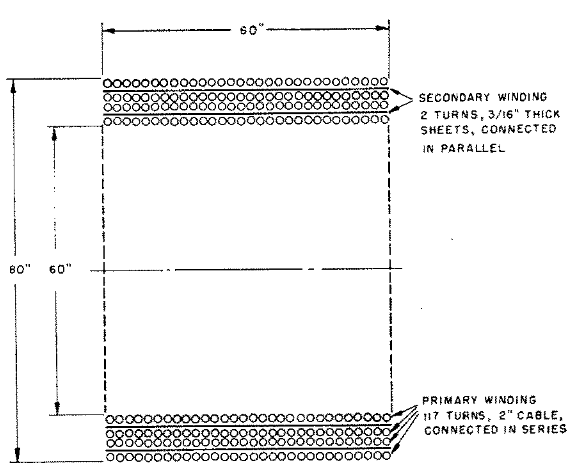

Fig. 1. Cross section of energy storage transformer.

DESCRIPTION OF THE COIL

Figure 1 is a drawing of the coil cross section showing the important dimensions, and Fig. 2 is a photograph of the completed unit. The specifications are as follows:

The primary winding has 117 turns of 3 000 000-circular-mil, 169-strand aluminum cable wound in 4 layers. The cable insulation consists of 2 half-lapped layers

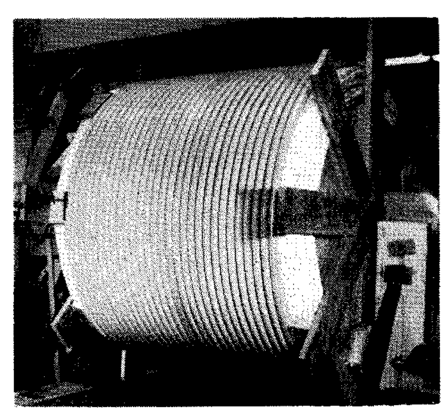

Fig. 2. Completed coil.

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[1] M. L. Oliphant, Proc. Roy. Soc. (London) A234, 441 (1956).
[2] H. C. Early and R. C. Walker, Commun. Electronics 31, 320 (1957).

of 5-mil Mylar and 2 half-lapped layers of 8-mil acetate fiber tape.

The secondary winding consists of 2 aluminum sheets, $\frac{3}{16}$ in. thick and 5 ft wide, which are interleaved between the layers of the primary winding so that each primary layer is adjacent to a secondary sheet. The ends of the sheets are overlapped as shown in Fig. 3 and insulated with Mylar insulation. The protruding tabs attached to the overlapped sections of the sheet are used for external connections. The 2 sheets can be connected either in series or in parallel, but most of the tests have been made with the parallel connection.

The interlayer insulation consists of 5 layers of 8-oz canvas for bedding, interleaved with 4 layers of 5-mil Mylar. The insulation extends about 5 in. out beyond the sides of the conductor layers in order to lengthen the insulation surface-breakdown path.

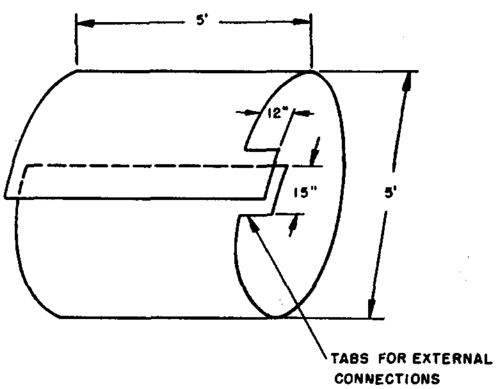

FIG. 3. Geometry of aluminum sheet used for secondary winding.

ELECTRICAL CHARACTERISTICS OF THE COIL

Standard open-circuit and short-circuit measurements were made to determine the primary and secondary self-inductances, the total leakage inductance, the mutual inductance, and the ac resistances at frequencies of 60, 120, 180, 300, and 420 cps. The values of the inductances are shown in Table I.

If it is assumed that the leakage inductance is divided between the primary and secondary, the primary leakage inductance is 0.275 mh. Since the primary leakage inductance equals $(1-k)L_p$, the coefficient of coupling, k, is greater than 0.98, which is unusually high for an air-core coil.

The ac resistance of the transformer is frequency dependent and is a function of the skin effect and the proximity effect in both windings. The measured ac resistance, referred to the primary, is plotted in Fig. 4, with the secondary (1) open-circuited and (2) short-circuited. In the tests with the secondary open, the measured values include the ac resistance of the primary plus the inductively coupled resistance due to eddy currents in the secondary sheets. Even with the secondary

TABLE I. Values of inductance.

Primary inductance	16.1 mh
Secondary inductance	0.00112 mh
Mutual inductance	0.133 mh
Total leakage inductance referred to the primary	0.55 mh

open-circuited, the Q of the primary is significantly less than if the sheets were not present.

The dc resistance of the primary is 15 milliohms; the computed dc resistance of the 2 secondary sheets in parallel (neglecting terminal resistance) is 10.5 μohms.

The self-resonant frequency of the primary (with the secondary open) is approximately 20 kc. At this resonant frequency, the distributed capacitance (referred to the primary) is about 0.006 μf. The capacitance between the primary and secondary (measured at very low frequency) s 0.06 μf.

POWER SUPPLY AND SWITCHING

The circuit switching arrangement is shown in Fig. 5. The power supply is a three-phase half-wave Ignitron rectifier which can deliver 5000 amp at 150 v. Since the duty cycle is short, the rectifier is operated at approximately 5 times the "normal" rating. Switch SW-1 is a commercial 400-amp circuit breaker, and switch SW-2 is a special fast acting switch described in the previous paper.[2]

The switching circuit has two special features:

1. To avoid the possibility of high-voltage transients causing trouble in the rectifier and power line circuits, the coil is completely disconnected from the rectifier before the discharge starts.

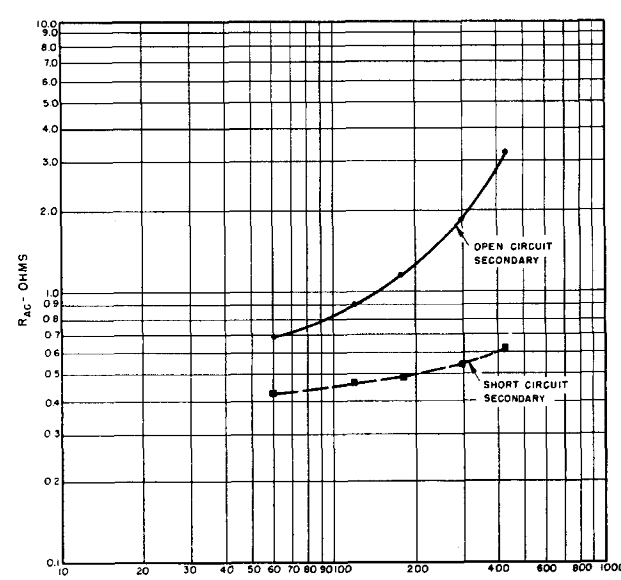

FIG. 4. R_{ac} vs frequency measured on primary winding.

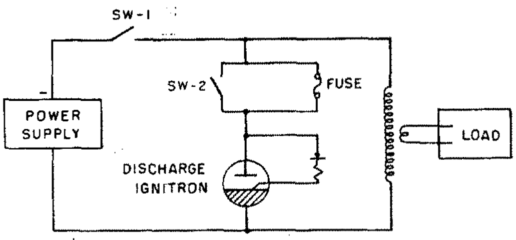

FIG. 5. Switching circuit.

2. In order to interrupt the primary circuit with a minimum of energy loss due to arcing across the switch, a by-pass fuse arrangement is provided as explained below.

The charge and discharge cycle is as follows: SW-2 is closed at the beginning of the test. SW-1 is then closed and the primary current rises exponentially to several thousand amperes in approximately one second. At a preset current level, SW-1 opens automatically, and the current which has been built up in the primary of the coil is diverted from the rectifier to the bypass circuit involving the auxiliary Ignitron. This Ignitron fires automatically as soon as the voltage across it reverses. SW-1 does not interrupt or withstand a high voltage, since the maximum voltage at this switch is limited to the approximate voltage of the dc power supply. Interruption of the current through SW-2 is more difficult primarily because the energy stored in the leakage reactance of the transformer must be dissipated. When SW-2 first opens, the current is bypassed through the high voltage fuse. The fuse carries the current for about 5 msec before blowing, thus providing time enough for SW-2 to be completely open and deionized. When the fuse blows, the current is interrupted in less than one millisecond and the secondary current is established at its peak value.

The expendable high-voltage fuse consists of a 12-in. length of #18 copper wire immersed in an oil-filled fiber tube. Experience with this switching arrangement indicates that it could be adapted to handle much higher voltages and currents and faster switching rates than have been required by the present installation.

TESTS WITH DUMMY LOAD

A series of tests was conducted in which the stored energy was discharged into noninductive resistors of 80 to 320 μohms. Exponential current discharges were produced with time constants of a few milliseconds. At energy levels of 150 000 j, about 70% of the original stored energy was transferred into the load. Ten percent of the energy was lost in the fuse during the switching, and approximately 20% was dissipated in the coil windings and the connections to the load resistor. Voltages and currents in the primary and secondary winding were oscillographically recorded. Data for a test at 525 000 peak amperes are given in Table II.

A typical dummy load resistance consisted of a folded flat copper strip, 5 in. wide, 25 to 100 in. long, and 0.02 or 0.04 in. thick. The magnetic force developed between the 2 adjacent sides of the folded load resistor was about 400 psi for a current of 500 000 amp. The length of the folded section at this current level was 45 in.; thus, the total force tending to separate the plates was 90 000 lb. The folded copper strip was clamped between two $\frac{1}{2}$-in. thick dural plates which were bolted along the edges. In one test, a row of $\frac{5}{16}$-in. bolts along the edges of the clamping plates were snapped, and the plates were bent apart.

SCALING CONSIDERATIONS

Present information indicates that the design of the storage transformer could be scaled up to much higher energy levels. In the present device, the high voltage insulation requirements have been easy to meet, but in an application requiring continuous repetitive operation, the insulation, heating and corona problems would require careful consideration. One method of reducing the maximum voltages induced in the primary would be to use multiple switches to open the primary winding at several different points.

The transformer type of coil design appears advantageous in situations where the turns ratio is relatively high. An alternative design is to use a single winding coil of very low impedance which is "charged" from a homopolar generator. Another alternative is to wind the coil in several sections which can be charged in series and discharged in parallel. Such a series-parallel arrangement requires a fairly elaborate switching procedure, but much of the switching could be done with Ignitrons. A design of this type would also help to minimize high-voltage insulation problems.

TABLE II. Discharge test measurements.

Load resistor	0.32 mohms
Time constant of load current $=T$	2.7 msec
Total secondary resistance $=L_s/T$	0.415 mohms
Ratio of load resistance to total secondary resistance	0.77
Secondary current	525 000 a
Primary current $=I_p$	4400 a
Total energy stored $=\frac{1}{2}L_pI_p^2$	155 000 j
Energy lost in fuse (measured)	14 000 j
Energy dissipated in load (measured)	105 000 j
Miscellaneous losses in coil windings, surrounding objects, etc.	26 000 j
Overall efficiency $=\frac{105\,000}{155\,000}\times 100$	68%