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PULSED HIGH VOLTAGE AND HIGH CURRENT OUTPUTS FROM HOMOPOLAR ENE--ETC(U)
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Large energy storage capability of inertial-inductive systems provides an attractive option for satisfying the pulse power requirements associated with such applications as plasma confinement and heating, electromagnetic projectile acceleration and with production of intense radiation. These applications require high rate of energy delivery to the load at specific current and voltage levels. In conjunction with self-excited homopolar generator current source, an opening technology has been developed to provide up to 1 MJ output pulses, alternately, at hundreds of kilovolts or at megampere levels. The overall system efficiency, that depends sensitively on the load requirements, was measured over a range from 10% to more than 90% for different pulser-load circuit arrangements.

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PULSED HIGH VOLTAGE AND HIGH CURRENT OUTPUTS FROM HOMOPOLAR ENERGY STORAGE SYSTEM

I. INTRODUCTION

Energy-storage homopolar generators (HPG) are current sources characterized by their low voltage output and broad range of current outputs. Risetime of the current output varies from milliseconds[1] to seconds[2]. Because the energy stored in the inertia of the wheels can be very large (e.g. 500 MJ in the case of the Canberra HPG[3]) and is characterized by large energy density ($\gtrsim$ 10 MJ/m^3), their applications as a replacement for capacitor banks in large pulser systems has been suggested by a variety of authors[4,5]. The inherently low power output of an HPG can be augmented by a switched energy-storage inductor. In one such system a self-excited HPG[2] has been used with opening switches to produce 200-kV output at current level of 37 kA. The high voltage was achieved using a rapidly-opening (30 μsec), explosively-actuated circuit breaker (EACB) stage followed by a fuse stage[5,6]. The fuse stage was also used to commutate 35-kA current to a current step-up transformer, generating a 420-kA current with a 100 μsec risetime into a 10^{-3} Ohm dummy load. The power amplification, associated with the 200-kV output, is approximately a factor of 10^3. The high voltage allows the inductive energy to be transferred to a variety of loads such as flash lamps, magnet coils and, in conjunction with the current step-up transformer, to drive such devices as electromagnetic projectile accelerators.

II. HIGH VOLTAGE OUTPUT

In Fig. 1 the HPG-energized inductive storage system is represented as a current source and an inductor. The output current has the time

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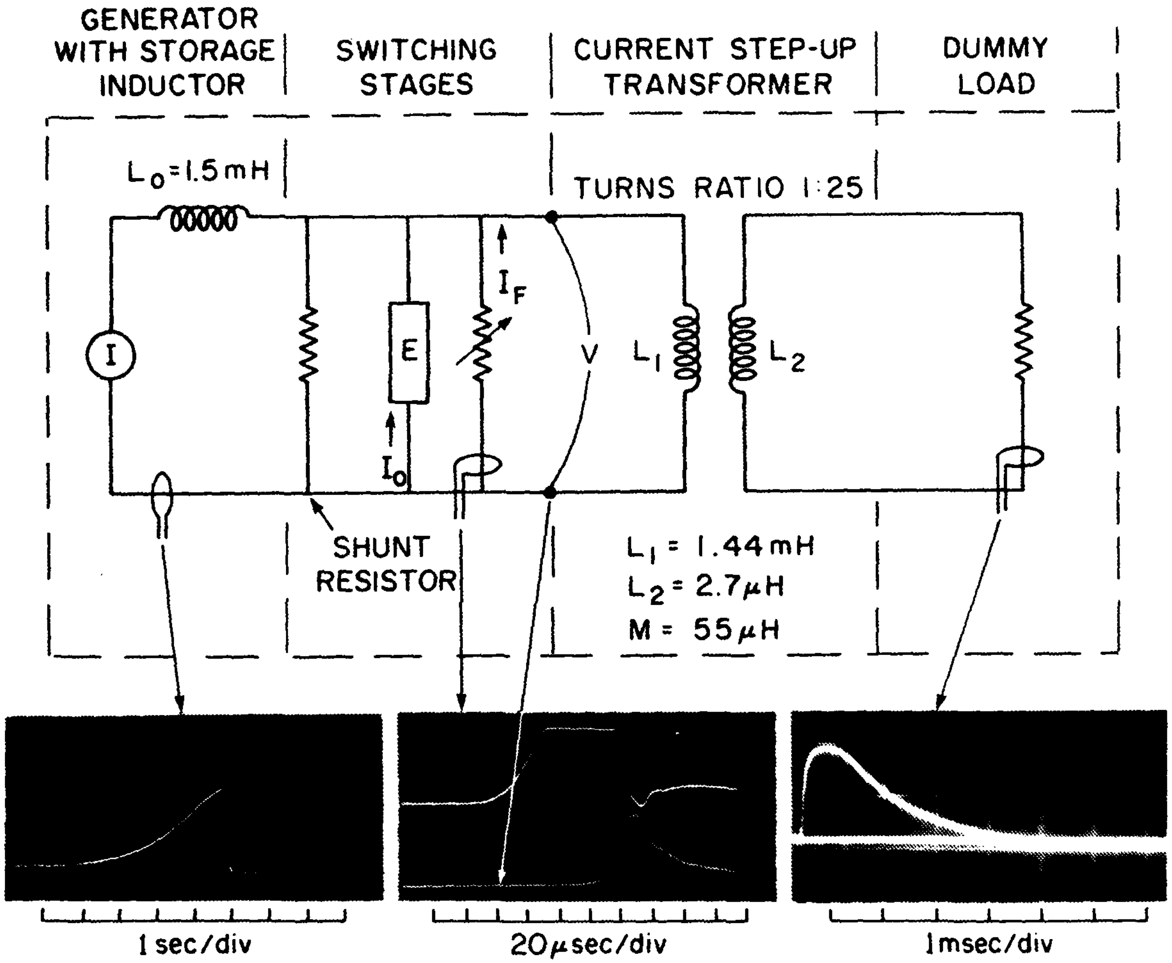

Fig. 1. Circuit diagram of the HPG and switching and transformation elements for high voltage and high current generation. Also shown are current and voltage traces. First trace shows the excitation current (36 kA). Next are shown fuse current (I_1=35 kA) and voltage (V-200kV) developed by the fuse. The last trace is the secondary current through $10^{-3}\ \Omega$ load with 420 kA peak amplitude.

dependence shown in the first oscillogram and initially flows through the EACB, denoted by letter E. If the initial resistance of the fuse or the resistive shunt is too high a closing switch (not shown in Fig. 1) is inserted in series with these elements to assure that the coil current is initially confined to the EACB leg of the circuit. If a low-value shunt resistor is the sole load for the EACB, then the efficiency of energy transfer is more than 98%.[7] This mode of operating, without the fuse, was studied earlier to determine the EACB performance in circumstances where it must carry the current for a period of seconds (e.g., shown in first trace of Fig. 1) and interrupt the current on command in tens of microseconds. When a fuse has been placed in parallel with EACB, it provides a short circuit path for the current at the time when EACB opens. The EACB arc voltage, V_A, of about 10 kV quickly commutates the current to the fuse. Fig. 1 traces show that the fuse current reaches a peak value I_F in about 30 μsec. The rapid transfer is possible because of the fast opening of the EACB and is consistent with the switch and connecting bus bar inductance, L, that determines the transfer time $T = I_F L/V_A$. The fuse cross section was selected, so that it would vaporize in 50 μsec to provide the required period for EACB recovery[5] to withstand the voltage of 200 kV generated by the fuse.

The voltage, V, generated by a fuse, shown in Fig. 1, has a typical risetime and amplitude associated with foil and wire fuses in high-resistivity water which serves as a tamper and as an insulator.[8] The maximum voltage was limited by the hold-off voltage of the insulation surfaces of the structural members of the HPG. Applied d.c. voltage tests have shown that the NRL HPG in air can support safely 200 kV. Modification of the HPG inductor coil, discussed in Ref. 9, could extend the safe operating voltage to 2 MV. The peak voltage obtained using the $CuSO_4$ shunt resistor alone as a load was 140 kV. The level was raised to 200 kV after the current step-up transformer was connected.

III. HIGH CURRENT OUTPUT

To generate high current output, a transformer was used to step-up the HPG current to 0.4-MA level. To obtain a large transformation ratio, the primary winding uses 48 turns. Its construction and its characteristics are discussed in Ref. 10. The layout of the energy storage system is shown in Fig. 2. The HPG generator and inductor coil is seen in the foreground. Output current bus-bars connect the generator with the explosive switch (in the first polyethelene box containing nitrogen atmosphere to prevent possible fire of the dispersed parafin that forms part of the switch). The connection to the fuse is made in the second container (filled with water). It continues to the third container filled with $CuSO_4$-water solution that provide easily variable shunt resistor. The large tank in the background contains the current step-up transformer (with connections not shown). Fig. 3 shows the version of the transformer with the two-turn secondary in the tank seen in Fig. 2. The secondary is constructed so that it can be easily connected in either a one- or two-turn configuration, with the latter extending the current capability to 1.0 MA with nominal inductor energy of 1 MJ*. The transformation of current, I_P, in the primary into the secondary short-circuited current, I_S, is

$$I_S = (M/L_2)I_P, \qquad (1)$$

where M and L_2 are values of mutual and secondary loop inductances, respectively, given in Fig. 1. The secondary current's peak value is independent

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*The HPG mechanical-to-electrical energy conversion efficiency[2] is about 23% at 1 MJ and 40% at maximum available stored energy (without cooling the storage coil) of 4 MJ.

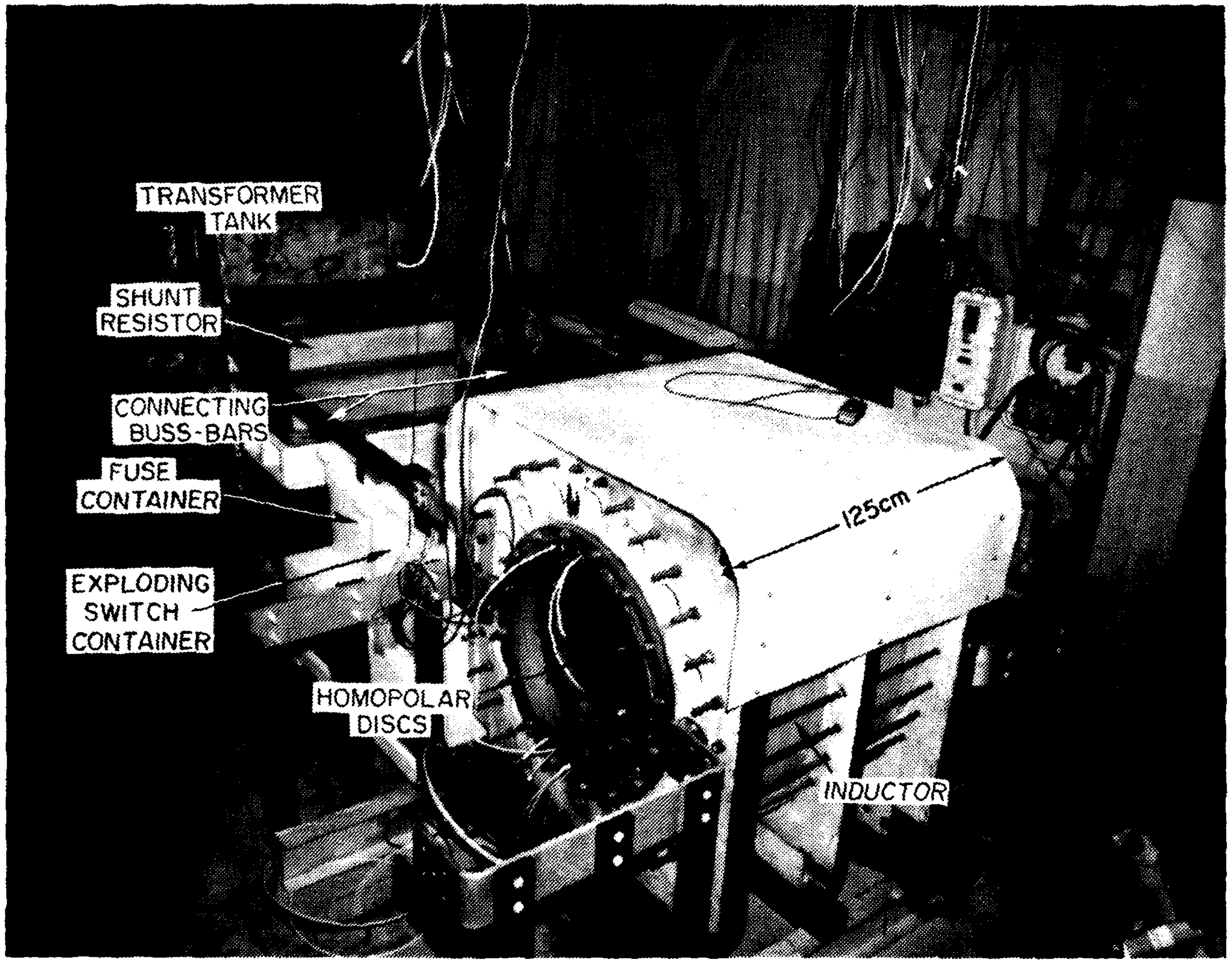

Fig. 2. Layout of the homopolar energy storage system showing the generator in the foreground. The remaining elements of the system, the switches, shunt resistor and the transformer, are seen in the background.

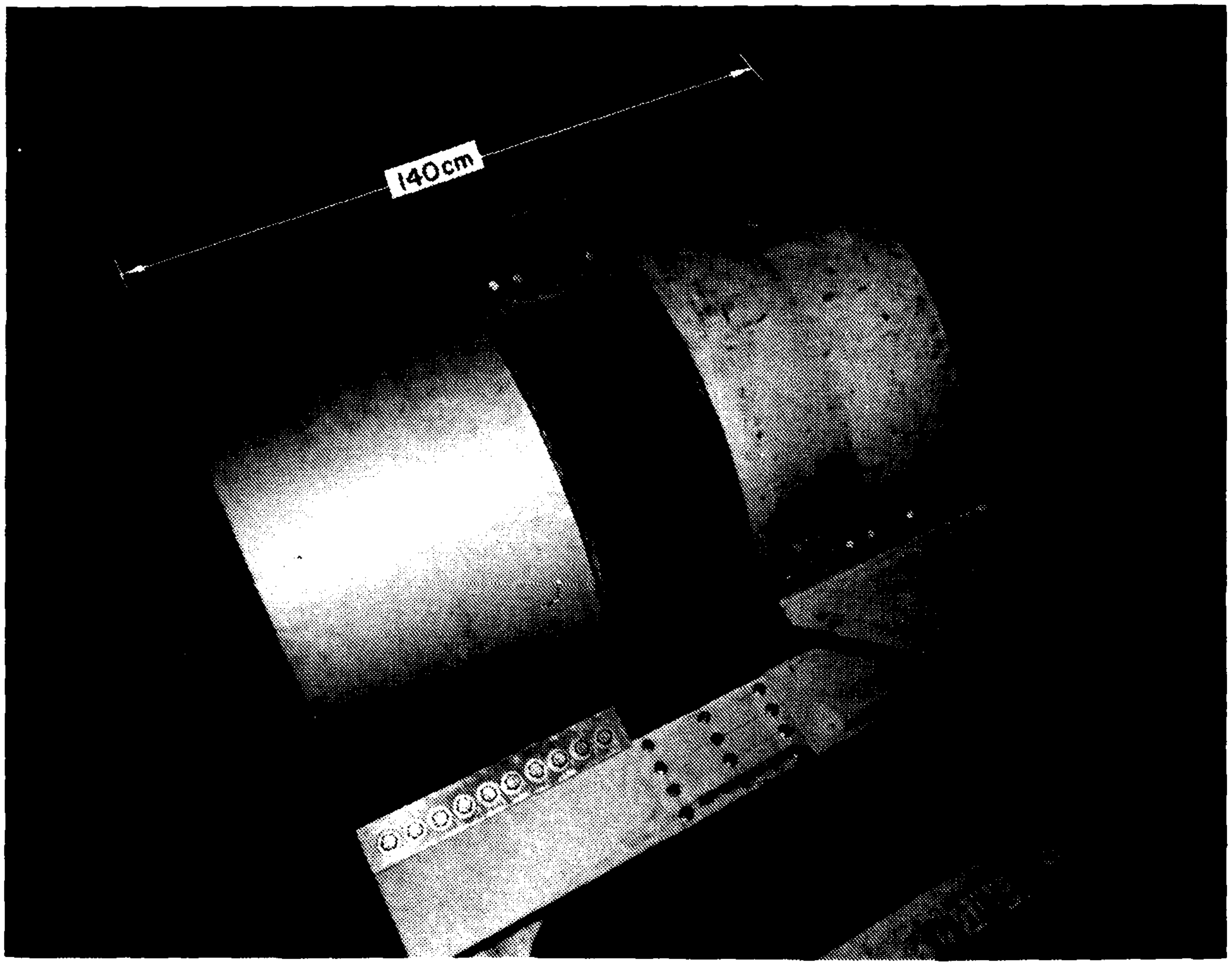

Fig. 3. Current step-up transformer with two-turn secondary. Primary turns formed by a single layer of RG-220 core are separated from the secondary by an additional layer of polyethelene insulation providing 1 MV hold-off capability needed in future applications of the pulser.

of the amplitude and shape of the switching voltage pulse provided only that the primary switching is fast enough. The peak current in the primary, I_1, is related to current in the storage inductor at the time of switching, I_o by the expression:

$$I_1 = \frac{I_0}{1 + (1-k^2)L_1/L_0} \quad , \qquad k^2 \equiv \frac{M^2}{L_1 L_2} \qquad (2)$$

as derived in Ref. 10, where the optimization of energy transfer using current step-up transformers is discussed.

The energy transferred by the transformer is:

$$W_S = \frac{k^2(1-k^2)L_1/L_0}{\left[1 + (1-k^2)L_1/L_0\right]^2} \; W_o \qquad (3)$$

where W_S is the inductive energy in the secondary loop and $W_o = \frac{1}{2} L_o I_o^2$ is the energy stored in the HPG inductor. The d.c. inductance of the storage coil is 1.46 mH, as indicated in Fig. 1. When this coil is discharged quickly, current induced in the wheel rims reduces the effective inductance to a somewhat lower value (1.0 mH). For purposes of specifying the electrical efficiency of the circuit in Fig. 1, $L_o = 1.0$ mH will be used. Typically[10], the ratio W_S/W_o is 10% for a broad range of transformer primary inductance to storage inductance ratios ($1 \leq L_1/L_o \leq 8$), for $k^2 = 0.4$. As k^2 increases, the efficiency becomes greater as L_1/L_o increases, reaching 22% level for $k^2 = 0.9$ and $L_1/L_o \geq 8$. The transformer design in this series of experiments uses a ratio of $L_1/L_o = 1.44$ and the value of k^2, as given in Eq. (2), depends on the choice of the load inductance in the secondary.

The transformer inductances L_1, L_2 and mutual inductance M were calculated and listed in Fig. 1. These and derived values of k^2 were checked using the measurements of I_P/I_S and I_1/I_O in conjunction with

Eq. (1) and (2), respectively. Both inductive and resistive (nearly short-circuit) loads were used. At $I_0 = 37$ kA, the peak value of I_S was calculated to be 265 kA for $L_2 = 4.4$ μH. This L_2 consists of the 2.7-μH transformer secondary in series with a 1.7- μH load inductance. The corresponding current for a negligible load inductance would be 500 kA. This value scales to 1000 kA for the single-turn secondary when the HPG stored energy is one quarter of the attainable stored energy level of 4 MJ, without cooling of the excitation-storage coil[2].

Using HPG output that ranged up to 36 kA (~ 1-MJ stored, low-frequency energy) the transformer step-up of the current, its risetime and decay time were measured using low inductance connection to 10^{-3} Ω load. At $I_o = 35.2$ kA, the peak primary current $I_1 = 25.0$ kA and load current $I_2 = 420$ kA, i.e. $I_p/I_S = 16.8$ and $I_S/I_0 = 12.0$. Having this resistive load causes the current to be about 15% less than that established from the short circuit formula in Eqs. (1) and (2). The time-dependent load current is shown in Fig. 1. Its risetime is approximately 100 μsec and is determined by the amplitude (130 kV) and shape of the switching voltage developed across the primary. The risetime is consistent with the transfer time, T, given in Section II. The decay time is approximately 0.8 msec corresponding to $L_2(1-k^2)/R$ time scale where R consists of the 10^{-3} Ω load resistance and the secondary coil resistance as well as the reflected primary circuit resistance. The decay time indicates that the load, rather than the circuit resistance, dominates the current time scale.

The observed energy transfer efficiency of almost 10% agrees, within measurement errors, with that calculated from Eq. (3). The calculated efficiency ranges from 10% to 13% for variation of L_2 from 5.0 μH (k^2=0.4) to 2.8 μH (k^2=0.7), respectively. The measured efficiency derived from the current and from the measurement of equivalent secondary inductance, was 9.5% for the large (4 μH) inductive load and 10.2% low inductance load.

IV. CONCLUSION

A key element in providing high-voltage or high-current output from an inductive storage system energized by relatively low-current homopolar-generator is the explosively actuated opening switch, EACB. Alone, it provides current pulse time compression of 10^3 and is more than 90% efficient[7] for an output current pulse duration of millisecond. The higher voltages resulting from the use of fuse stages in parallel with EACB permits an additional order of magnitude compression of the duration of the pulse and a corresponding power multiplication of $\geqslant 500$. Use of additional fuse stages (of the type developed in the large scale storage system, TRIDENT[6]), in the secondary circuit, suggests that very high power (10^{12} Watt) pulse generation is feasible[6]. The efficiency associated with the production of high power pulses is in the 10% to 20% range, in the case when current step-up is required.

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