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A PROPOSAL FOR THE CONSTRUCTION AND OPERATION OF AN INDUCTIVE STORE FOR 20 MEGAJOULES

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A PROPOSAL FOR THE CONSTRUCTION AND OPERATION OF AN INDUCTIVE STORE FOR 20 MEGAJOULES

by

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ABSTRACT

A proposal for coupling 20 MJ of energy initially stored in the Canberra homopolar generator, to a load in about 1.0 ms is described. The energy is first transferred to a coaxial inductor at a peak current and voltage of 1.5 MA and 190 V respectively. The opening of a fast mechanical switch which is being developed transfers the energy from the inductor to the load, producing a voltage of 1000 V across the latter. The system is intended for use with high energy lasers.

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C O N T E N T S

1. Introduction

Recent development in the design of lasers has led to the need for energy storage devices with a rating of some tens of megajoules and capable of discharging in about one millisecond, when using a laser material having a fluorescence lifetime of about this value. Capacitor banks of this rating are so large and expensive that several proposals have been made for the use of rotating machines to store the energy (Rioux 1967, Gauchon et al. 1968, Inall 1965). The homopolar generator at the A.N.U. in Canberra could supply 1.5×10^6 A at 800 V, that is 1.2 MJ ms^{-1}, and it could do this for more than 0.1 s. However, for many important applications of these lasers it is an advantage to increase the peak power and reduce the duration of the discharge.

This report deals with a proposal for coupling 20 MJ of energy, initially stored in the homopolar generator, into a load at a peak power of 15×10^9 W for about 1 ms. The generator is capable of storing 560 MJ, but for the operation discussed here it would be charged to only 81 MJ (i.e. a speed of 356 rpm giving a voltage of 190 V) before each pulse. During the discharge 22 MJ would be transferred to an intermediate storage inductor which would supply 15 MJ to the load in 1 ms. Between 8 and 15 MJ, depending on the operating sequence, would be lost in the resistance of the inductor, and an equal amount in the series control resistor and bus-bars. A further 8 to 10 MJ would be lost in a surge limiting resistor across the generator and between 18 and 40 MJ would remain in the generator at the end of the pulse. With the present generator drive, the system could supply a pulse every three minutes. The features of the possible operating sequences will be discussed later (see 2.3) and it will be shown that the sequence which takes 40 MJ from the generator and delivers 15 MJ to the load is possible if the switches, which are required for either sequence, can be made. It could be extended to higher energies with improved efficiency, and is superior to other arrangements suggested elsewhere (Rioux 1967, Gauchon et al. 1968, Salge and Brilka 1968).

2. Circuit Parameters and Current Waveforms

2.1 Circuit Components

The governing factors in the choice of the type of inductor to use for an energy store are:

(a) Inductance in relation to size is important because of the cost of copper required to make it and the building required to house it,

(b) Convenience of the output connections,

(c) Confinement of the associated magnetic field,

(d) Simplicity of construction,

(e) The configuration of the electromagnetic forces on it and the convenience of the constraints to oppose them.

An inductor consisting of coaxial conductors is larger than a coil of the same inductance and resistance, but it meets the other requirements so well that it has been chosen as the most suitable for use with the high currents available from the homopolar generator.

If the inductor is designed to carry 1.5×10^6 A, which is near the maximum current available from the generator, it would store 22 MJ if it had an inductance of 20 μH. Since about 15 MJ of this can be delivered to the load in 1 ms the power would be as high as one could consider using at this stage. Therefore, these values have been chosen for design purposes.

Of the possible charging and discharge circuits, the one shown in figure 1 was chosen because it best meets the requirements by providing:

(a) The voltage increase to couple the power into arrays of xenon arc lamps which require 1000 V to operate.

(b) Protection of the generator against production of transient high voltages on the terminals under normal or fault conditions.

(c) For the energy to be delivered to the load in about 1 ms.

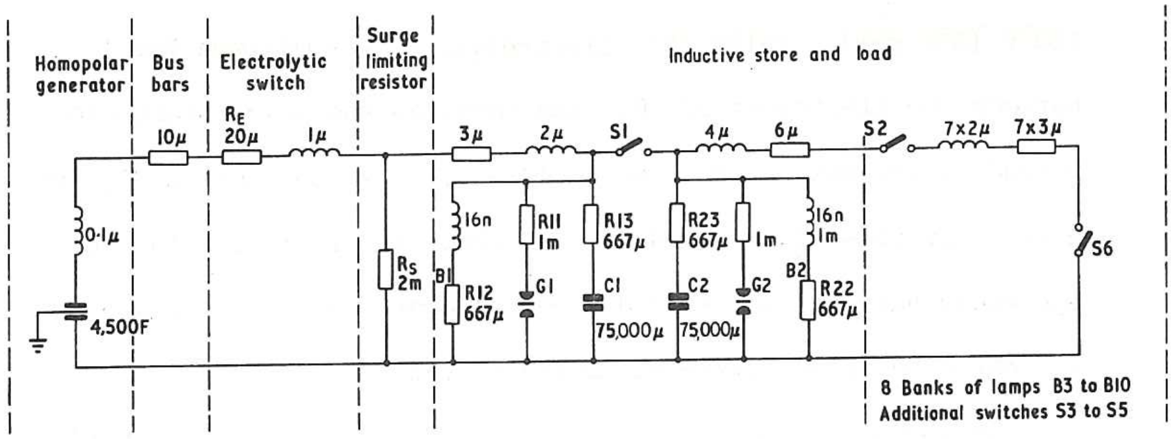

Figure 1. The charging circuit for the 20 μH coaxial inductor coupled to the homopolar generator via the electrolytic resistor. The discharge into the 10 banks of lamps, B1 to B10, occurs when S1 to S5 open simultaneously as the charging current reaches 1.5×10^6 A.

The circuit consists of the homopolar generator, using one disc of each rotor and full field excitation to give an equivalent capacity of 4,500 F, the electrolytic control resistor, R_E, (Blamey et al. 1962) with concentrated electrolyte to give a minimum resistance of 20 $\mu\Omega$, the 10 $\mu\Omega$ resistance of the bus-bars to the generator, the ten sections of the coaxial inductor, each with an inductance of 2 $\mu\Omega$ and having a resistance of 3 $\mu\Omega$. Switch S6 to start the charging cycle, switches S1 to S5 which control the discharge cycle, 10 banks of xenon arc lamps, B1 to B10, each containing 250 flash tubes, and a surge limiting shunt resistor, R_s, of 2 mΩ made up of 500 kg of aluminium strip, folded to keep the inductance below 10^{-7}H. R_s would dissipate all the energy in the generator if R_E failed to terminate the pulse according to its preset programme. The function of S6 could be performed by any one of S1 to S5 if this were convenient.

2.2 Peak Current Operating Cycle

One operating sequence could be to charge the generator to 190 V (356 rpm), raise the electrolyte to its maximum level between the electrodes of R_E and then, as the level starts to recede at the maximum rate of 80 cm s^{-1}, close the switch S6. The circuit at this stage would be that shown in figure 2. The voltage would have fallen to 178 V due to energy being dissipated in R_s while the electrolyte was being raised.

If the effect of R_s is neglected the current, i_1, would build up according to the following expression

$$i_1 = 2.96 \times 10^6 \text{ Exp } (-1.42t) \sin (2.93t) \qquad \ldots (1)$$

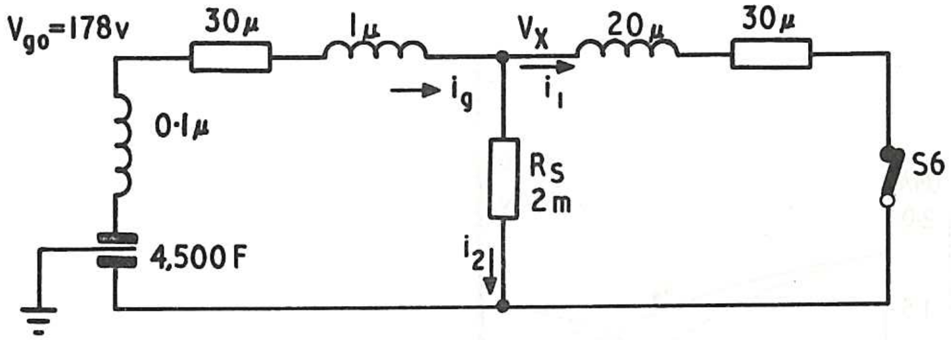

Figure 2. The circuit during the supply of current to the inductive store.

The maximum value of this expression is 1.55×10^6 A at t = 0.38 s. When the effect of R_S is taken into account the maximum value of i_g would be 1.6×10^6 A. The values of i_1, i_1, V_X and V_g shown in figure 2 are plotted in figure 3.

When the current reaches 1.5×10^6 A the switches S1 to S5 will open and the circuits will then become those shown in figures 4 and 6. Look first at figure 4; as the arc in S1 becomes a high resistance the current i_1 will flow into C1 via R13 and 1000 V will be developed across R13 and across R12, which will at that time be an open circuit. The trigger pulse will be applied to B1 at this instant and current will start to build up in R12 at a rate set by the 16 nH choke in series with it. The value of the inductance was chosen on the assumption that the voltage across the lamps would be about 500 V soon after the trigger and to ensure that the current rose to its full value in about 100 μs. If the current increases more rapidly than this

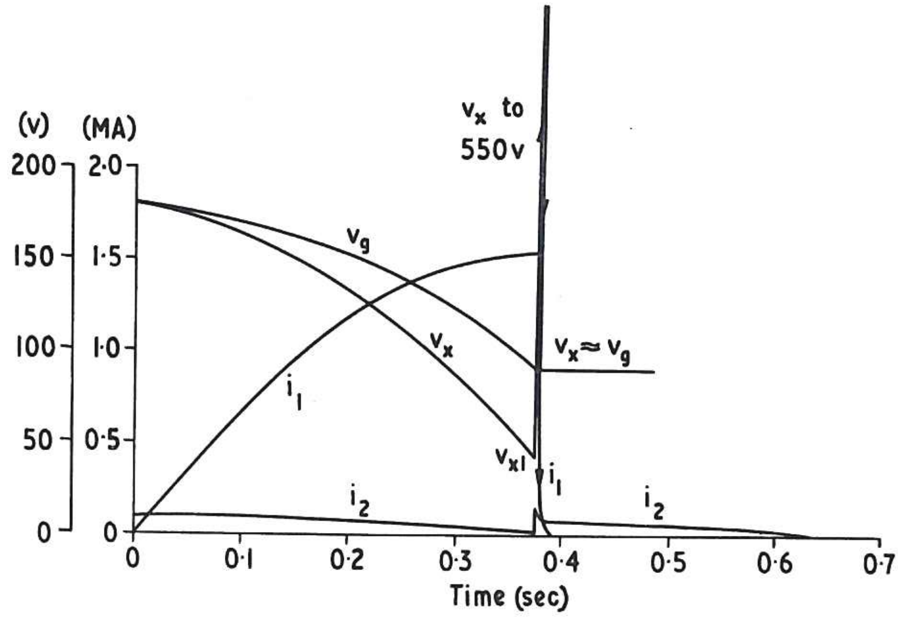

Figure 3. Current and voltage v. time. Switches S1 to S5 open at t = 0.38 s.

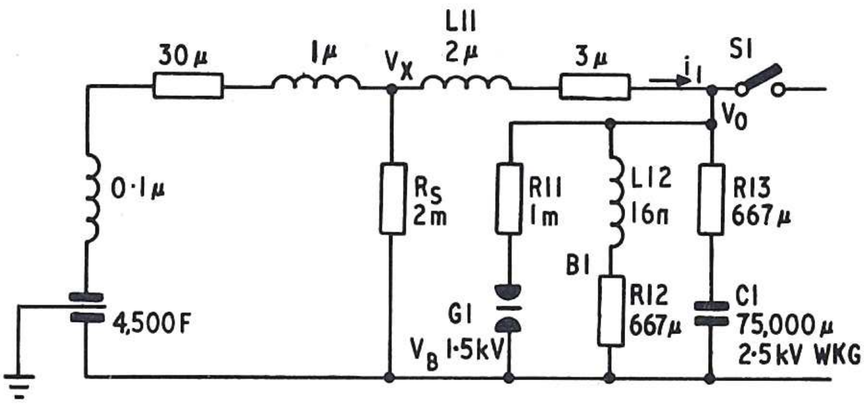

Figure 4. Circuit of the generator and the first bank of lamps, B1, after S1 has opened. $i_1 = 1.5 \times 10^6$ A.

the lamps are damaged. The resistor R13 and capacitor C1 would be necessary to allow current to transfer from the switch to the lamps at the required rate, when the arc voltage in the switch rises very rapidly. The transfer may be possible without C1, R13 or L12 if the arc voltage and current can be controlled to give the required values, or if the lamps can be preionized to enable current to rise more rapidly in them. A further alternative may be the use of an exploding foil in place of C1 and R13, designed to disintigrate when 0.150 MJ is dissipated in it. Possible developments along these lines will have to be verified by experiments.

The inductance of R13 must be made as low as possible, a value of 2 nH being an acceptable upper limit, but a value of less than 0.5 nH for R 13 plus the condenser connections can be made. Figure 5 shows the current and voltage waveforms calculated on the assumption that R12 assumes its value instantly. Since the xenon tubes would have a higher resistance for some tens of microseconds after the trigger pulse, the voltage, V_c, across C1 will rise higher than shown in figure 5. The current i_L in the lamps is shown rising to 1.5×10^6 A in about 100 μs. It will then decrease, reaching a value of 0.55×10^6 A in 3 ms. from the opening of S1.

Referring back to figure 3, the voltage, V_x, across the bus-bars at the terminals of R_s will rise when S1 opens. It will assume a value $V_o/3 + V_{x1}$, where V_{x1} and V_o are the voltages shown in figures 3 and 5 respectively. The peak value would reach 550 V if V_o reaches 1,500 V. Other conditions affecting this voltage will be examined later.

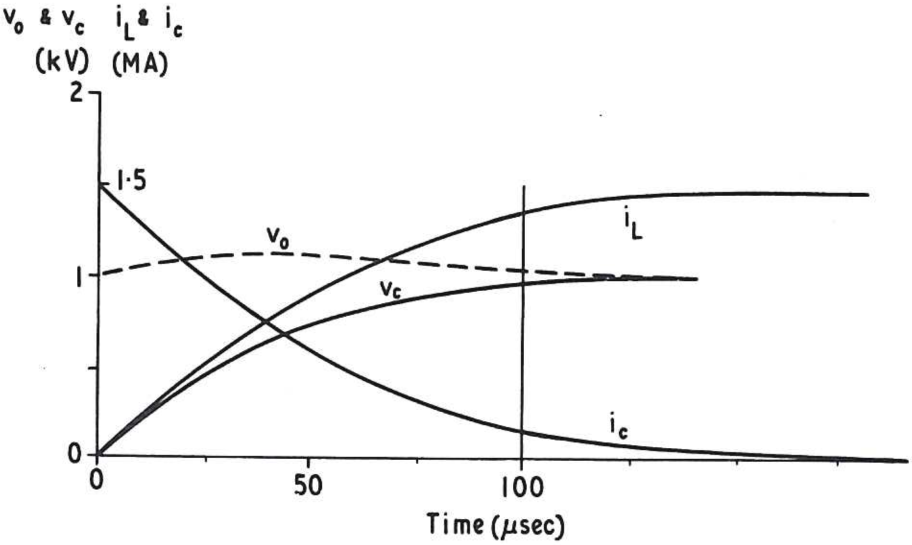

Figure 5. Output voltage from the inductor v_O, the voltage across C1, V_C, and the current into the lamp circuit, i_L.

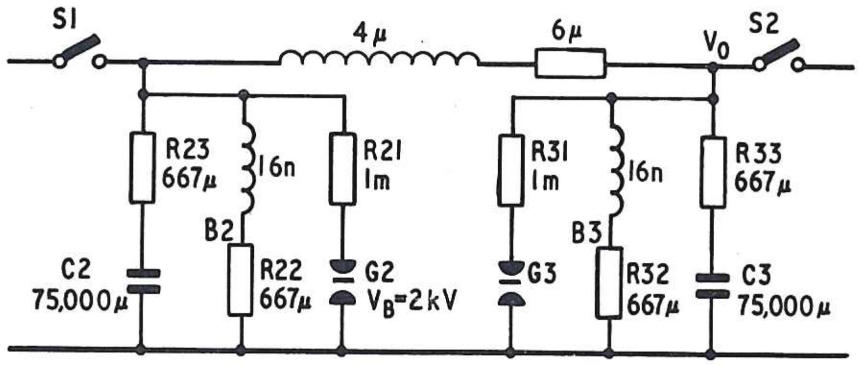

Figure 6. The circuit of each of the four sections between S1 and S5. The voltage V_O and current into C3, i_C, are as shown in figure 5, while for C2 the values are the same but of opposite polarity.

Four of the other five sections of the circuit formed when S1 to S5 open are as shown in figure 6. The current and voltage waveforms for B3 are similar to those shown in figure 5 for B1, while in the case of B2 the polarity is reversed. The extra inductance in the first section of the system, see figure 4, will not make any significant difference in the output of B1 compared to B2 etc., within the first millisecond of the discharge, which will be the only significant time when pumping a laser. The effect of the failure of the lamps to trigger and the need for the over-voltage gaps G1 - G10 is dealt with later.

Within 10 ms of S6 opening, the current in the xenon lamps will be zero, the current, i_2, through R_S will be 45,000 A and the voltage from the generator will be 90 V. At this time R_E will be about 30 $\mu\Omega$ and increasing until the electrolyte clears the electrodes and opens the circuit about 0.66 s. after S6 closed.

2.3 Short Duration Operating Cycle

The operating sequence just considered would result in the energy losses in the circuit resistance being the higher values quoted in the Introduction. If the starting voltage is increased so that the current rises more rapidly and the switches S1 to S5 are opened when the current reaches 1.5×10^6 A but is still increasing, considerably less energy is lost. The limit to this increase of voltage is set by the possibility that the switches may fail to open. In this case the current must not rise to a dangerous value. A conservative limit for the homopolar generator would be for the current not to exceed 1.75×10^6 A at a rotor speed of 300 rpm on the occasion of such a fault. This allows a starting voltage of 216 V and the current would reach 1.5×10^6 A in 0.25 s. at which time the switches would open. The losses would then be the lower values quoted in the Introduction. Further discussion will be based on the assumption that this short sequence will be used.

3. The Effect of Incorrect Functioning of the Circuit

In the event of faulty operation of the circuit shown in figure 1 the first requirement would be to avoid a voltage surge on the generator bus-bars of sufficient magnitude to break down the insulation, and secondly to avoid a short circuit which could carry an excessive current. Any protective device must be able to absorb all the energy stored in the generator without disintegrating or becoming a short circuit. When the generator is used with the inductive store, the rotor speed would be less than 450 rpm and so the maximum energy that could be delivered to R_S would be 130 MJ. By making R_S from 500 kg of aluminium the temperature rise would be limited to 300°C and would not damage glass and silicone varnish insulation. R_S would be connected to the bus-bars via conductors arranged to introduce the lowest possible series inductance, about 10^{-7} H. Details of the construction of R_S are given in section 4.4 and figure 8. If the current in R_S is assumed to rise in 10^{-4} s, the maximum voltage across the bus-bars would reach 3,700 V. The glass fibre and varnish insulation between the folds will have to withstand 120 V per fold. This resistor will limit the amplitude of a voltage surge due to the sudden reduction of current flowing into any load on the bus-bars or connected circuit. The other resistors, R11 etc, have a more specific and less arduous role. Referring to figure 4, R11 will carry current if G1 conducts due to a high voltage caused by the failure of the lamps to draw the correct current. Since it too is connected to the generator it could be required to dissipate 80 MJ. Therefore it must be similar in design to R11 and made from 330 kg of aluminium strip.

It is unlikely that one of R21, R31, R41, etc. could be the only load in parallel with Rs across the generator, but it is possible as the result of a series of components failing, therefore, all these resistors would be made the same as R11, to take 80 MJ. If R11 was connected to the junction of R13 and C1, R11 would absorb less of the energy from the generator during a fault and R11 could then be lighter. However, R13 would have to be more robust than is required in the circuit of figure 4. Because of the need for a very rapid rise of current in R13 during normal operation, it must be made of stainless steel strips, 0.028" thick. Further details of the design of these resistors are discussed in section 4.

4. Construction of the Circuit Components

4.1 Resistor R_E

The electrolytic resistor (Blamey et al. 1962), R_E, consists of 73 steel electrodes and a tank of sodium hydroxide solution which can be raised, by a hydraulic actuator, to immerse the electrodes to a depth of 50 cm in 0.6 s. As the drive continues its cycle the tank descends and the electrolyte clears the electrodes in a further 0.6 s. This machine has been used for more than six years and its performance under the conditions required for use with the inductive store is well known.

4.2 The Inductor

As explained in section 2, the inductor being proposed would consist of coaxial conductors, and the values shown in figure 1 for the inductance, 20 μH, and the resistance, 30 μΩ, were chosen to suit a moderate sized device, relatively simple to construct.

Because of the logarithmic relationship between the inductance and the ratio of the diameters of the outer and inner conductors, it is pointless to design for more than 0.33 μH per metre of coaxial conductor. Thus the 20 μH inductor will be 60 m long, and the ratio of diameters will be 4 to 1. The resistance of the inner conductor must be as low as possible and a value of 20 $\mu\Omega$ was chosen. This means that the diameter must be 25 cm if it is made from copper. The weight of copper would be 30 tons, and square bars 1.1" across are available to make an approximately circular bundle with an average diameter of 25 cm. The currents induced in such bars by the rising magnetic field will not significantly increase the effective resistance of the circuit.

The outer conductor can be made from 25 tons of aluminium bars to have a resistance of less than 10 $\mu\Omega$. The outward pressure on the outer conductors will be 20 psi of surface, which can be carried by steel bands at intervals along the outside. The switches S1 to S5 will be in series with the inner conductor and the coaxial assembly can be made in five sections each 12 m long with a switch at the centre of each section. These can be stacked side by side to give all the outputs in a central region or arranged in a line of one section, three sections and the remaining one to give an arrangement 40 m long with the outputs distributed along the length.

4.3 The Switches S1 to S5

The most difficult components to design and construct are the five switches S1 to S5, and the success of this inductive storage system will depend on their development. They will have to carry 1.5×10^6 A for about 0.2 s. and then open, taking less than 1 ms to increase the resistance of the breaking-arc to at least 20 $\mu\Omega$. Switches for 10^4 A have been built which rely on a stream of oil to open the contacts and cool the arc produced as the contacts separate (Salge and Brilka 1968, Kind et al. 1968). Voltage recovery across these switches as high as 1.7 kV μs^{-1} has been observed when a charged capacitor was used to cancel the current through the switch. This is much too rapid for use with xenon discharge tubes, in which it takes 100 μs for the discharge to spread correctly throughout the tube. The condensers C1 to C5 will be needed to control the voltage until the correct current flows through the lamps. The value, 75,000 μF, should limit the voltage to less than 1500 V, which is higher than the maximum value of V_c shown in figure 5 for the unachievable situation where the current in the xenon tubes assumes its correct value as soon as the tubes are triggered. The voltage limiting switched gaps G1 to G5 will be triggered at 1500 V. However, the inductance (33 nH) and skin effect in R11 would cause the voltage on the condenser to approach 2500 V before the current of 1.7×10^6 A could be established in R11 and G1. Therefore the condensers will have to be rated for a peak voltage of 2500 V. The maximum energy that could be stored in such condensers is 240 kJ, which is about one tenth of the energy which can be stored in the associated section of the inductance.

Figure 7 shows a drawing of a model switch with contacts 8.9 cm in diameter, which in the switches S1 to S5 would be 25 cm diameter. The contacts are closed by high pressure nitrogen in space A forcing the diaphragm, D, against the fixed contact F. The current flows from the diaphragm to the second electrode C

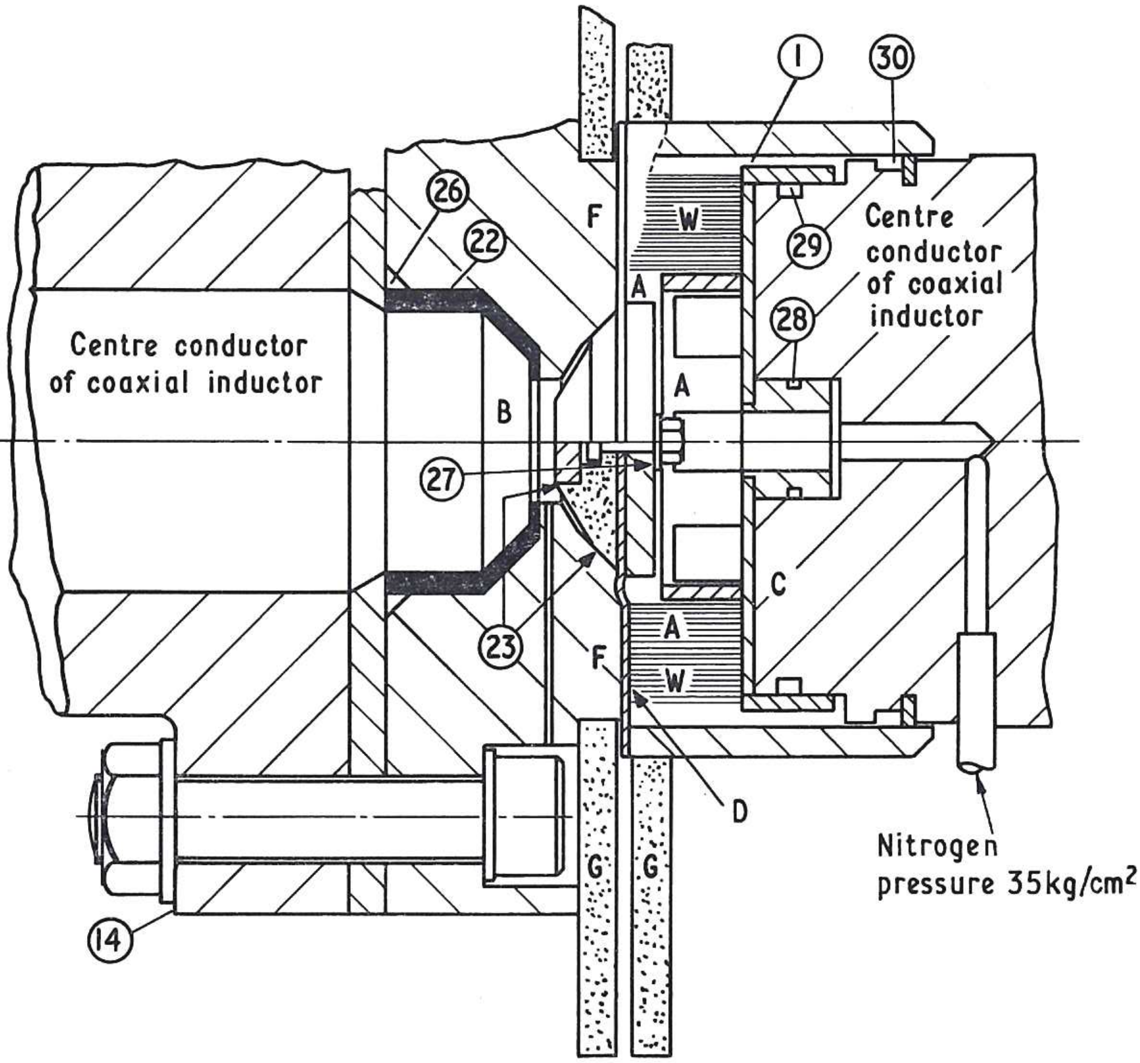

Figure 7. A sectioned view of part of a model of switch S1.

via an annular bundle of wires W which are inclined to the axis of the switch to allow axial movement of the diaphragm. The contacts are opened by releasing water at high pressure, and capable of rapid acceleration to high velocity, into the space B. The water pressure is much more than that required to force D away from F, the separation occurring as an expanding disc of water fills the region between D and F. When the arc occurs as the last areas of contact are broken, it will be deflected and cooled by the fast moving sheet of water which is confined with the arc by the discs of insulating material, G.

When the switches S1 to S5 are opened for a normal pulse they will have to hold off between 2000 and 4000 V for 3 ms, after which only one will be required to remain open to isolate the 100 V produced by the generator and connected via R_E for a further 0.3 s.

4.4 The Resistor R_S

In section 3 it was stated that R_S would be designed to absorb 130 MJ with a temperature rise of 300^oC. This would require 500 kg of aluminium or 1000 kg of mild steel. The purpose of this resistor is to prevent a high voltage surge on the generator terminals or bus-bars being induced by the stray inductance of the generator and R_E, if a circuit carrying 1.7×10^6 A suddenly became a high impedance. There is no data available to indicate how rapidly a fault could reduce a current of 1.7×10^6 A. Oil immersed switches can interrupt 10,000-20,000 A in about 1 ms and hold off some 10,000 V while doing so. Exploding foils in special enclosures and packing (Early and Martin 1965, Schenk 1968, Los Alamos 1968) have been used to interrupt currents of 800,000 A in

1 ms and while doing so have held off up to 50,000 V. But these interrupters which employ special features to terminate the arc cannot be taken as indicating the extinguishing rate which could occur due to a circuit failure in air. In fact the arc in air circuit breakers with special provisions to blow the arc out magnetically, does not extinguish until the current is less than 200 A. The voltage produced across the characteristic impedance of the generator system, due to the instantaneous interruption of a current of 500 A is not dangerous. Because stray inductance can never be completely eliminated from a resistor circuit, it is impossible to protect the generator against the instantaneous interruption of a current of 1.7×10^6 A. If it is assumed that an interruption cannot occur in less than 10^{-4} s, it is possible but difficult to limit the voltage to a safe value, that is less than 5000 V. This refers to an interruption due to the failure of some component, not to the opening of switches S1 to S5 which do not interrupt the current but divert it into the load consisting of the condensers and lamps or the triggered gaps.

With this limited aim defined, the necessary features of R_S can be considered. Firstly, the choice of material has to be made on the basis of the rate at which the current can penetrate to the full thickness of the conductor. The high magnetic permeability of steel is a handicap in this regard. Since the current must penetrate fully in 10^{-4} s, the skin depth, ε, at a frequency of 3 kHz would be an adequate indicator of the effectiveness of the conductor. If the permeability of steel is assumed to be 1000, the calculated value for $\varepsilon = 8.5 \times 10^{-3}$ cm. This sets an upper limit of about 1.5×10^{-2} cm for the thickness of steel sheets from which to construct R_S. When weight and resistance requirements are met it would be ne essary to use about 8 thin sheets of steel in parallel to make the resistor. If aluminium alloy with a permeability of 1 and an electrical resistivity of 5×10^{-6} Ω per cam cube is used $\varepsilon = 0.2$ cm, and a single sheet over 1 mm thick is satisfactory.

In this case the aluminium alloy resistor would have a weight of 500 kg, an area of cross section of 21.5 cm² and a length of 8,600 cm.

Since the inductance of R_S must be as low as possible, the most suitable cross section for the conductor would be a thin sheet folded into a flat "hair-pin" with the thinnest safe layer of insulation between the sheets. Such a "hair-pin" could be made of 16 SWG sheet. The thickness would then be 0.1626 cm so the sheet would be 133 cm wide, the hair-pin would be 4,300 cm long and the sheets thin enough for the "proximity-effect" not to cause any effective reduction in the current penetration. If the insulation thickness is 0.017 cm the spacing between the centres of the sheets would be 0.18 cm and the inductance would be 74 nH. The inductance will be the same, but the insulation requirements less everywhere except at the terminals if the strip is folded as a flattened Z with a span of about 150 cm and 58 layers (see figure 8). When the current is 1.7×10^6 A the layers will experience a bursting pressure of 10.4 kg per cm^{-2}. Since the current would drop to about 10^5 A in 0.5 ms the bursting force will give an impact of short duration which will be restrained by steel cover plates as shown in figure 8.

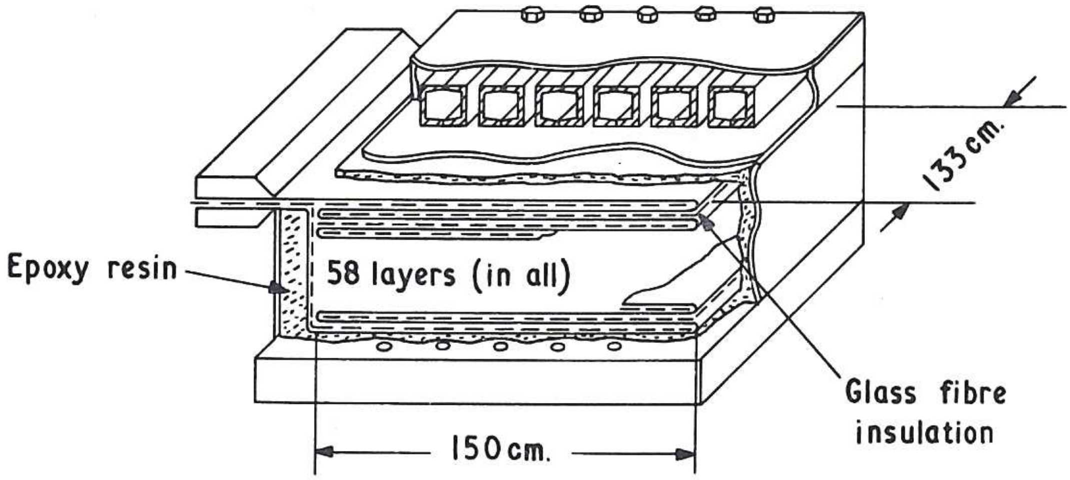

Figure 8. Resistor R_S constructed of Aluminium Alloy Sheet in a steel case.

During a normal pulse into the circuit shown in figure 1, R_S would dissipate about 10 MJ and the temperature would rise 30^o C. Between pulses it will be cooled by water passing through copper tubes fixed between 3 pairs of copper plates. These plates are not shown in figure 8, but they would be located between layers which form the sides of a "hair-pin" with the opening to the right of the drawing. In these locations the extra spacing required for the cooling structure will not cause an increase in the circuit inductance.

R_S is not only a component of an inductive energy storage system. It is a method of reducing the output impedance of the generator at moderately high frequencies, and it should be used whenever there is a possibility of a high current from the generator being interrupted very quickly. However, it cannot be used when the generator is storing more than 130 MJ, that is at a speed of 400 rpm, if there is any doubt about the electrolytic switch, R_E, being able to terminate the discharge before 130 MJ is delivered from the generator.

4.5 Resistors R11, R21, R31 etc.

In section 3 it was explained that R11 should be capable of dissipating 80 MJ. The other requirement of this resistor is that the current should rise as quickly as possible when G1 is triggered so that skin effect and inductance are more serious in R11, R21 etc, than in R_S. These resistors will therefore be made in the same way as R_S but will only require 340 kg of aluminium. The resistors will be 153 cm wide, folded with 150 cm span as for R_S, with a total length of 5,000 cm of sheet. The stray inductance will be 33 nH, which is rather high for this circuit, and results in condensers rated at 2,500 V being required for C1 etc.

4.6 Resistors R13, R23, etc.

The maximum energy to be dissipated in R13 would be 300 kJ. Since C1 will consist of 300 capacitors R13 can be made from 300 strips of 22 SWG stainless steel strip 1.23 cm wide and 25 cm long placed flat against the plate transmission line connecting back to the switch plate. Such resistors will introduce an inductance of 1/3 nH into the circuit, while the condensers themselves will contribute less than an extra 1/6 nH.

4.7 The Inductors L11, L21, etc.

About 250 xenon flash tubes will be used in each array of lamps such as B1. These will be supplied with current from the storage inductor via 250 separate coaxial cables. Each cable will connect to the switch terminals through a 4 μH choke. These 250 chokes

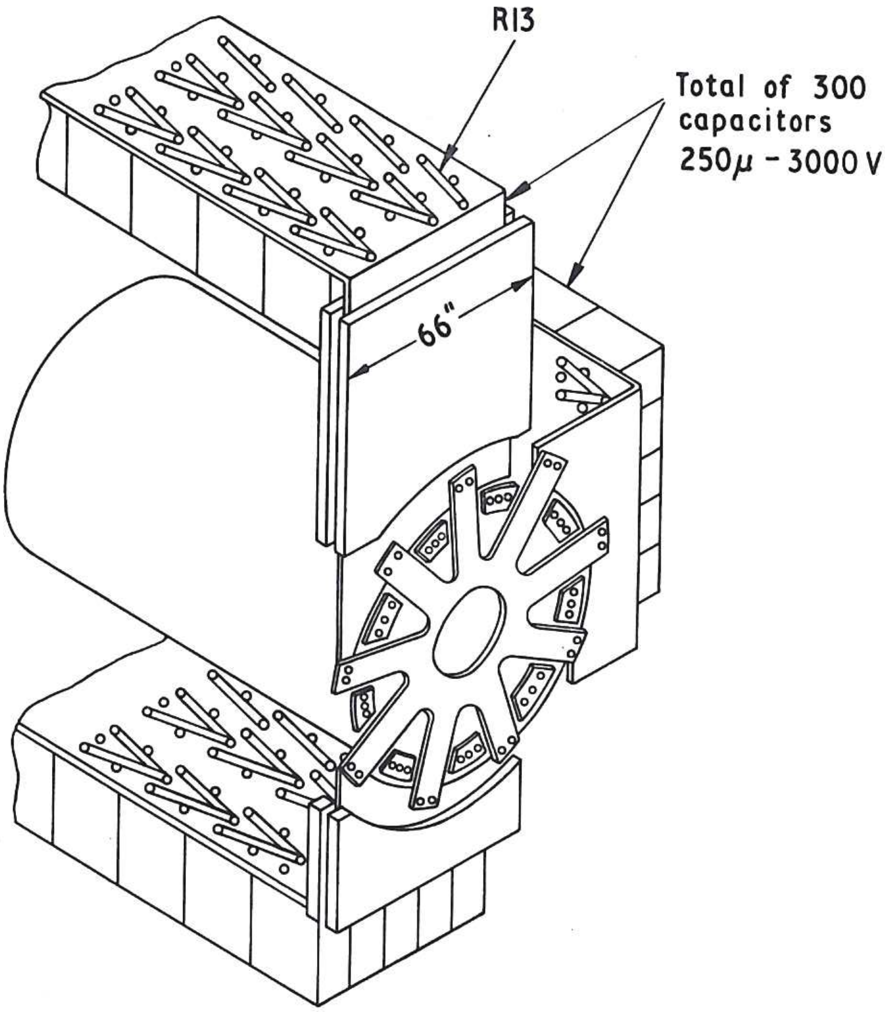

Figure 9. A sketch showing the type of arrangement for the connection to the fixed contact of S1, the 300 Capacitors required for the 75,000 μFd bank C1 and the stainless steel strips which would be used for R13. The connections for the 4 μH chokes and the coaxial cables to each xenon tube can be made using the terminal studs of the capacitors.

operate in parallel and form the 16 nH inductor L12 shown in figures 1 and 4. The chokes and cables will connect to the storage inductor by means of the terminal studs of the capacitors which form C1. The convenience of such an arrangement will be seen in figure 9.

5. The Efficiency of Energy Transfer and the Effect of Stray Inductance

A cycle of operation will start when S6 is closed and the current in the inductor will increase fairly slowly, as shown in figure 3. It will distribute uniformly over the cross section of the inner and outer conductors and energy will be stored in the magnetic field extending from the centre to the outer surface of the outer conductor as indicated in figure 10.

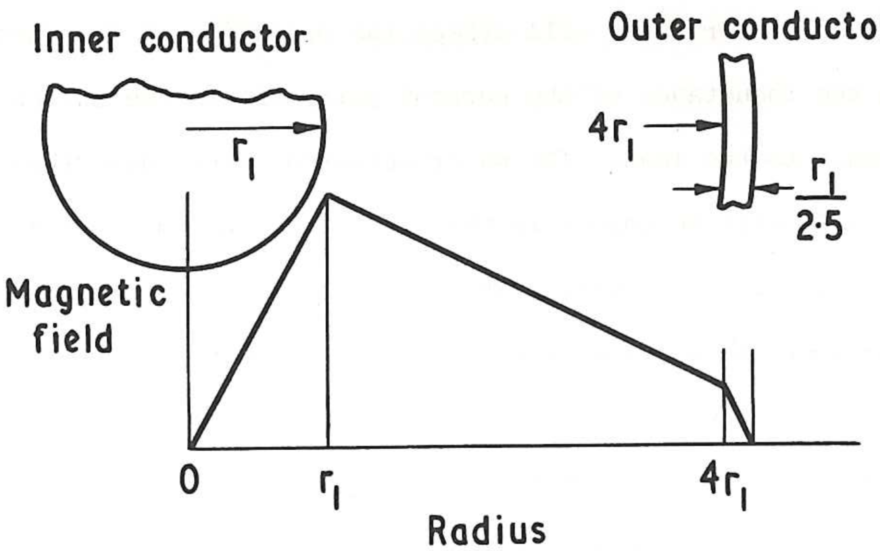

Figure 10. Diagram of magnetic field v. radius in the coaxial inductor.

When the circuit is interrupted, the current will transfer to the load and decrease to a low value in a few milliseconds. The energy in the air space will be delivered to the load, but the energy associated with the field in the conductors, regions A and B in figure 10, will produce eddy currents within the conductors themselves, and be dissipated there. The only contribution these circulating currents can make to the external circuit, is almost to compensate for the very small loss due to the resistance of the main conductors.

Since the radius of the outer conductor will be four times the radius r_1 of the inner, 15% of the total energy stored will be trapped in the inner conductor, and since the outer conductor will be $r_1/2.5$ thick 2.5% will be trapped in the outer conductor. Therefore, with the geometry proposed for the inductive store, 17.5% of the energy will be lost due to the field trapped within the thickness of the conductors.

Another factor which will affect the operation of the fast switches will be the inductance of the current paths within the switch and in the circuit to the load. The water-actuated switch described in section 4.3 will be unique in that it will open concentrically from the inner towards the outer edge. No field will be produced in the space between the opening contacts so that the voltage between the parting surfaces will be due to the small radial resistance only as the current is diverted towards the outer edge. When the contacts at the outer edge open the voltage will depend upon the impedance of the external circuit. The radial leads from each contact of the switch will pass through the outer conductor as close as possible to each other. However, the construction of the moving contact and the need for the water and the arc to miss the leads, will make it impossible to take the connections out without introducing an inductance of between 5 and 10 nH. If when the switches (S1 to S5) open the voltage across them can be made to rise very rapidly to 2000 V there will be 1000 V across each load circuit and it will occur initially across this stray inductance, but after 10^{-5} s the current into the capacitors will be about 7×10^{5} A and most of the voltage will be developed across R13 and the other branches of the load circuit. It is unlikely that the arc voltage could rise so rapidly or that the current transfer could occur in less than 5×10^{-5} s. This being so, the stray inductance will not be a determining factor in the operation of the switch and the current transfer to the load circuit. The more significant factor will be the lengthening, cooling, and quenching of the arc between the contacts which cannot move any effective distance in 5×10^{-5} s. If the arc persists for about 5×10^{-4} s with about 1000 V across it, some hundreds of kilojoules of energy will be dissipated in the water and could result in a serious loss of the stored energy.

This report has dealt with three reasons why much of the energy taken from the generator would not be delivered to the load. These are, losses in the resistive components of the circuit, eddy currents within the conductors, and losses due to the arc between the switch contacts. The overall effect of these would be that out of the 40 MJ delivered by the generator, only about 12-15 MJ would be dissipated in the load. This inefficient use of the stored energy is nevertheless tolerable for experimental equipment.

6. Conclusions

The system described appears to offer a practical way of extending the use of the Canberra Homopolar Generator to the supply of 12-15 MJ to a resistive load in about 1 ms, if the switches S1 to S5 can be developed to meet the required performance. A smaller generator, built for the energy range required, could also be used to advantage. The successful development of fast switches to break 1.5×10^6 A would also allow other applications of the Canberra generator, as well as being of wide general interest.

Acknowledgement

The model switch referred to in section 4.3 and figure 7, was made in the Culham Laboratory of the U.K.A.E.A., where it has been tested with currents up to 4000 A (reference 10). The design and the testing of the model switch has been carried out, and this report written, while the author was attached to the Culham Laboratory. The author wishes to thank Mr D.L. Smart and the many other people who provided facilities for, and helped with, this work.

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