DESIGN PRINCIPLE AND CHARACTERISTICS OF THE G.E. FLUX PUMP

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INTRODUCTION

There have been several methods proposed for generating or otherwise creating a large direct current in a low temperature environment to avoid the losses associated with conducting high current to a low temperature region from a room temperature source. If such a device is operated in conjunction with a superconducting magnet system, it is desirable that the current source also be superconducting, and be constructed so that flux is introduced within a closed superconducting circuit. These devices can then be considered as flux pumps.

One of the methods for accomplishing this is to use a transformer-rectifier circuit, made from superconductive components, to transform a small alternating current input into the high level current required, which can then be rectified to obtain a large direct current. The transformer can be fabricated in a conventional manner using superconductive windings, but novel methods are required to achieve the rectification function with superconductive components. The situation is further complicated in that, in the case of energy storage systems such a superconducting magnets, phase-controlled rectification is desired so that energy can be removed from as well as added to the load.

The flux pump to be discussed here was invented and developed by T.A. Buchhold and uses a transformer-controlled rectifier configuration to convert a small alternating current input to the output characteristics needed for energizing superconductive magnet systems. This device operates with very high efficiency and is capable of producing sufficient output power for practical use in many magnet applications. As this concept has undergone considerable improvement and refinement over the past several years, an up-to-date summary of the characteristics of this type of flux pump and its capabilities will be given.

FLUX PUMP OPERATION

The key concept introduced by Buchhold is a unique combination of magnetically-controlled, cryotron-like switches used in conjunction with saturable core reactors to achieve phase-controlled rectification. Figure 1 shows the low temperature portion of his flux pump circuit and the arrangement of the various components.

The input transformer has superconductive windings on an iron core and is excited by a square wave, room temperature voltage source. As the transformer has a high primary to secondary turns ratio, the input current requirement is low and, therefore, small cross-section input leads may be used to connect to the room temperature source.

The secondary circuit is connected in a two-phase arrangement which requires two sets of the cryotron-reactor "rectifiers." The load is connected between the cryotrons and the center tap of the transformer secondary winding. The primary winding of the saturable reactor, the gate of the cryotron switch and all interconnecting leads are made from superconductive material, usually niobium. Thus, in the absence of cryotron excitation, the entire secondary circuit is superconducting.

Ideally, of course, the cryotron switches would have zero resistance in the "on" state and infinite resistance in the "off" state. The former condition is met by the use of a superconductive cryotron gate material, but the finite resistance of the gate in the off state is one of the primary factors limiting the efficiency of the flux pump. This will be discussed more fully later. The cryotron is switched between the on, or superconducting state, and the off, or normal state, by means of a superconducting magnetic control winding. This is excited by an external, room temperature, source.

The saturable core reactors consist of three windings on a torroidal core of Deltamax. The primary winding is connected in series with the gate of the cryotron switch, the retarding winding is connected in series with the cryotron control, and the signal winding is wound from a normal metal and extends to the room temperature control circuit. The functions performed by these windings are best shown by a description of the circuit operation, but it is pointed out that the reactor core is normally in saturation except during short periods in the switching cycle. Thus the impedance of the reactors is usually negligible except for short periods when the core leaves saturation. It will be shown that this characteristic is a key factor in the high efficiencies obtained with this concept.

Figure 2a shows some of the wave forms which illustrate the circuit operation in a simple rectification cycle, that is, rectification without phase control. For this operation the retarding windings on the saturable core and the phase shifting circuit may be ignored. To follow the action of the circuit throughout a basic rectification cycle, first assume that the upper cryotron in Fig. 1 is superconducting or on, while the lower cryotron is off. At this point, both saturable reactor cores are in saturation and the load sees the voltage across one half of the transformer secondary, e_1, and the load current increases according to the relation:

$$\frac{dI_L}{dt} = \frac{e_1}{L} ,$$

where L is the load inductance.

At the end of the positive cycle, the transformer voltage reverses polarity and it becomes necessary to switch both cryotrons in order to achieve rectification. To do this, an external circuit detects the change in polarity of the primary voltage and produces a signal which interrupts the control current flow in the lower cryotron. Thus the control field goes to zero. The cryotron gate tries to revert to the superconducting state, but, as the gate resistance decreases, the current tends to increase. This would cause large losses and inhibit the switching process if it were not for the reactor in series with the gate. The rectangular hysteresis loop characteristics of the saturable reactor core prevents a rapid build-up of the gate current as is shown in Fig. 2b.

Point A in Fig. 2b shows the position on the hysteresis loop of the core before the change in polarity of the input voltage. The core is in saturation with a current, I_b, flowing through the primary winding. The current, I_b, is determined by the voltage across the full transformer secondary and the resistance of the lower cryotron in the off state. When the voltage reverses polarity and the cryotron switches to the on state, the current through the core primary tends to build up toward the value it will conduct when on. However, as the current goes through zero, the core leaves saturation and the current is limited to a low value, i_o, determined by the width of the hysteresis loop. The time for which the current is limited depends on the design of the circuit and is set to give the gate of the cryotron sufficient time to complete its normal to superconducting transition at the low current level.

The upper saturable core reactor also performs an important function at this time. As the lower cryotron is switched to the on state and the lower reactor goes into saturation, the entire secondary circuit is of very low impedance. Thus, the current in the secondary is commutated very quickly from the upper half of the circuit to the lower half by the transformer voltage. As the current in the upper half is driven through zero, the core of the upper reactor comes out of saturation and the changing flux in the core induces a voltage in the signal winding. This signal is then used to trigger current flow in the upper cryotron control from the room temperature circuit which switches the upper cryotron gate to the normal state. By repeating this process with the polarity changes in the input voltage, it is seen that rectification is achieved and energy can be fed into an inductive load.

In order to change the rate at which energy is fed into the load or to remove energy from the load, a means for phase shifting the rectification cycle with respect to the input voltage is required. This is accomplished with two modifications to the circuit.

The first is the addition of a means for delaying the signal derived from the input voltage reversals which is used to switch the appropriate cryotron to the on state. This is easily accomplished in the room temperature electronic circuit by conventional circuit techniques. The second change is the addition of the retarding winding to the cores of the saturable reactors. As stated before, this winding is connected in series with the cryotron control coils so that the cryotron control signal also passes through the retarding winding.

The wave forms of Fig. 3 show the operation of the circuit with phase shift α. Again assume a point in the positive half cycle where both cores are in saturation, the upper cryotron is on, and the lower is off. When the voltage reverses polarity, there is now no switching action because of the signal delay, α. There are two changes, however.

First the current through the off lower cryotron reverses due to the input voltage polarity change. With no retarding winding, this would cause the lower core to come out of saturation. However, as the core action is needed only when the cryotron is to be switched on, a means must be provided to hold the core in saturation until the proper time. This is accomplished by connecting the retarding winding in series with the cryotron control so that the control current creates sufficient mmf to overcome that of the primary winding and keep the core in saturation.

The second effect is that, because neither cryotron has been switched, the load current decreases due to the reversed input voltage polarity.

After the delay, α, a signal is produced to turn the lower cryotron on. This signal now interrupts the cryotron control current and removes the retarding winding mmf from the core. The cryotron gate then returns to the superconducting state and the bottom core leaves saturation at the proper time to allow the gate to switch on at a low current. When this is completed, the secondary current commutates and the upper cryotron is switched off by the means described previously. The output voltage is thus again positive up to the next reversal in the input square wave.

It is seen that the phase delay, α, provides a means for controlling the fraction of a period for which the load is exposed to a positive or a negative voltage. The load charging rate can then be easily adjusted in the room temperature circuit for adding or removing energy. It is also clear that the electronic circuit can be de-energized at any time to leave a persistent current in the magnet circuit.

FLUX PUMP CHARACTERISTICS AND APPLICATION

If one considers the application of this flux pump concept in conjunction with a superconductive magnet system, the performance of the system can be summarized by a few simple equations.

First, the load current is given as:

$$I_L = \int_o^t \frac{V}{L} \, dt \quad ,$$

where V is the effective output voltage of the flux pump, and L is the inductance of the load.

As the inductance of a superconducting coil is normally a function of the field, it has been included under the integral sign, but in a simplified analysis it will be assumed that L is constant.

The maximum output voltage is shown as a function of current for a typical flux pump in Fig. 4. It is seen that the voltage decreases somewhat with current, the decrease depending mainly on the output impedance of the square wave source exciting the transformer primary. If this decrease is also neglected, the load current can be approximately expressed as:

$$I_L = \frac{V}{L} t \quad .$$

With these conditions, the total load charging time is then:

$$t = \frac{2 \, W_s}{P_M} \quad ,$$

where W_s is the energy stored in the magnet system, and $P_M = V \, I_{max}$, the flux pump output power at the maximum current.

In turn one can define a maximum efficiency factor as:

$$\eta_m = \frac{P_M}{P_M + P_L} \quad ,$$

where P_L is the loss in the low temperature section of the flux pump.

Because the efficiency of the flux pump determines to a main extent whether or not the device can provide an economic savings in a given application, this definition deserves further clarification. It is found that the predominant flux pump losses are nearly independent of the output current. Thus if one plots the efficiency as a function of output current, the curve in Fig. 5 results. This shows that the efficiency is zero, by this definition, at zero current, but rises rapidly with the current to approach its maximum value at the full output. It should also be pointed out that the losses are nearly independent of the phase shift in the rectification cycle, so that the definition assumes the maximum output voltage with no phase delay.

Further rearrangement of these equations shows that the instantaneous power loss is related to the efficiency and maximum power output as:

$$P_L = \left(\frac{1 - \eta_m}{\eta_m}\right) P_M \approx (1 - \eta_m)\ P_M \quad .$$

The energy lost in charging a coil system to its final energy at the maximum charging rate is:

$$Q_L = 2\left(\frac{1 - \eta_m}{\eta_m}\right) W_s \approx 2\ (1 - \eta_m)\ W_s \quad .$$

That is, the inefficiency on an energy basis is twice that found from the power equation.

These equations show that the energy lost in energizing a magnet system is related only to the efficiency of the flux pump, while the charging time is a function of the power capability of the pump. The instantaneous power loss, on the other hand, is affected both by the efficiency and power capability of the device.

If some typical flux pump parameters are assumed, the following values can be found for a representative application. Consider a 50 W, 98% efficient flux pump designed to energize a magnet system storing 50 000 J of energy. The time required to energize the magnet at the maximum pumping rate will be about 33 minutes, and approximately 2000 J will be dissipated in the liquid helium. The instantaneous power dissipation will be about 1 W, which is equivalent to a liquid helium boil-off rate of 1.4 ℓ per hour, and total helium consumption is about 0.75 ℓ. This example illustrates that very high flux pump efficiencies are desirable to achieve low system losses, and the power range which must be considered to achieve practical charging rates is also indicated.

FLUX PUMP DESIGN AND CAPABILITIES

As with many engineering devices, careful optimization procedures must be followed to maximize the efficiency of a flux pump unit for a specific application. This optimization process generally defines the maximum efficiency that can be attained in practice while the power capabilities are defined by the physical size of the unit or by practical fabrication constraints. Usually it is possible to design for given power levels with any combination of current and voltage so that a design can be matched to the load with little effect on the efficiency characteristics of the device.

The limit on flux pump efficiency is set by the properties of the cryotron switches. Table I shows the various components of flux pump loss and gives the percentage of the total loss attributed to each component in a typical design. This clearly shows the dominant effect of the cryotron loss in present flux pumps.

TABLE I. Distribution of Flux Pump Losses

1. Input Transformer	- 15%
a. Winding loss	
b. Core loss	
2. Saturable Reactor	- 5%
a. Winding loss	
b. Core loss	
3. Cryotron	- 80%
a. Gate ohmic loss	
b. Gate hysteresis loss	
c. Control winding loss	
d. Iron loss	

An analysis of the losses occurring in the cryotrons shows that the total loss and, thus, the ultimate efficiency of a flux pump depends mainly on the superconductive properties of the gate material. This is due to the fact that the ohmic cryotron loss is inversely proportional to the length of the gate in the cryotron, or to the volume of the cryotron, while hysteresis loss increases directly with the volume. Thus, there is an optimum design which makes the two loss components equal, the optimized loss then depending on the properties of the gate material.

Recent development programs have devoted a significant effort toward the development of new cryotron gate materials so that the device efficiency can be improved. This has resulted in the use of certain niobium alloys which display characteristics particularly suited for use in construction of the cryotron gates.

The design of the remaining flux pump components follows from rather conventional considerations to attain the desired operational characteristics. Every component must, however, be carefully designed and constructed to avoid needless loss and to maximize the output characteristics for a given size.

Over the past several years improvements in the design and fabrication procedures has resulted in continually improved flux pump models for practical use. Several flux pump units have been built and used with superconductive magnets. These have ranged from an original 3 W feasibility model having a maximum efficiency of about 90%, to more recent models in the 50-60 W range, having maximum efficiencies of almost 98%. The current ratings of these units has ranged from about 300 A to more than 1700 A at approximately constant power output. However, there appears to be no serious technological barrier to further increases in flux pump power levels if the need should arise. There is always, however, a need to improve efficiency which could result from further improvements related to high current cryotrons.

In applying flux pumps to systems, several problems had to be solved which were not directly related to the flux pump itself. One of these was the need to shield the flux pump when used in close proximity to a high field magnet. Use of static superconductive shields was found to be only partially effective but active shield concepts have been used successfully in several cases. For a simple solenoid an active shield can consist of a superconductive winding placed between the magnet and the flux pump and connected in series with the main coil, but with the opposite field sense.

Another problem was the possibility that the flux pump could be driven normal during a coil quench with the energy of the load being dumped into the flux pump components. This, of course, overheats and damages the flux pump components. This problem was overcome with the development of special semiconductive "avalanche breakdown" devices which operate reliably at liquid helium temperatures. These units can be custom fabricated to break down at low voltage and pass high currents and are connected directly across the flux pump output to limit the energy which can be dumped back into the flux pump from the load.

Figure 6 shows a typical flux pump-magnet system which includes these features. This figure shows a shield winding between a 100 kG Nb_3Sn magnet and the flux pump, which is enclosed in a niobium housing. The copper heat sink in which the protective semiconductor is mounted is also visible.

Figure 7 shows a typical 300 A, 50 W flux pump. The efficiency of this unit is close to 98% and is similar to that in Fig. 6. For comparison another 50 W flux pump designed for 1700 A is shown in Fig. 8.

The flux pump control unit shown in Fig. 9 is relatively compact and has several features useful in system applications. These include automatic selection of field level, protective discharge in case of low helium levels, two pumping voltages to minimize losses at low pumping rates, and continuous rate control between maximum charge and discharge. In addition, of course, persistent current operation is possible by simply de-energizing the control unit.

In summary it can be said that this flux pump concept has been developed to a point where flux pumps are considered as a commercial item rather than a research device. Present applications have been in association with research type, superconductive magnet systems where only modest power requirements exist. It is still true that flux pumps only become competitive with conventional systems for loads requiring relatively high currents, and low inductance loads are desirable to achieve rapid charging rates. As for magnet systems storing many megajoules of energy, where a conventional power system is used, the use of a flux pump can still be considered to supply the energy dissipated in the resistive joints of the load, or to attain fine field adjustment.

ACKNOWLEDGEMENTS

The flux pump concepts described here were originally conceived and developed by Dr. T.A. Buchhold of the General Electric Research & Development Center. R.K. Terbush has also made many significant contributions throughout the development program.

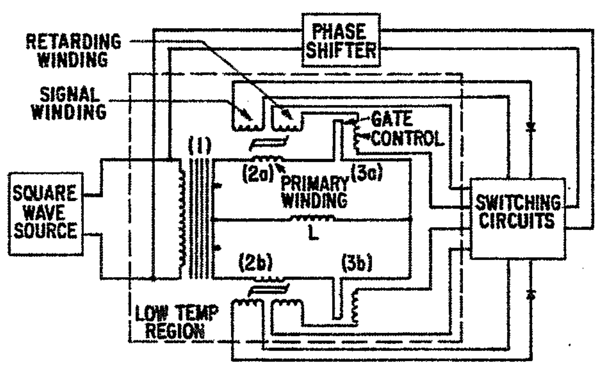

Fig. 1. Schematic of the flux pump with phase shifting.

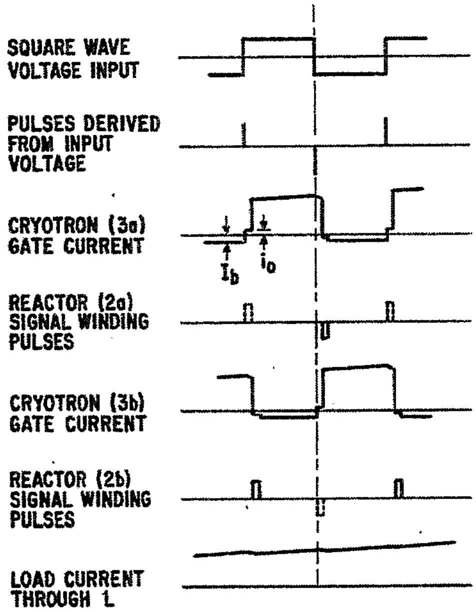

Fig. 2a. Wave forms in simple rectification cycle.

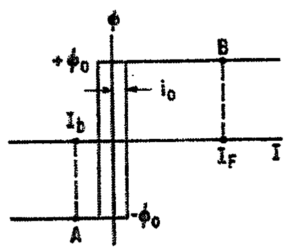

Fig. 2b. Loop characteristics of the saturable core reactor.

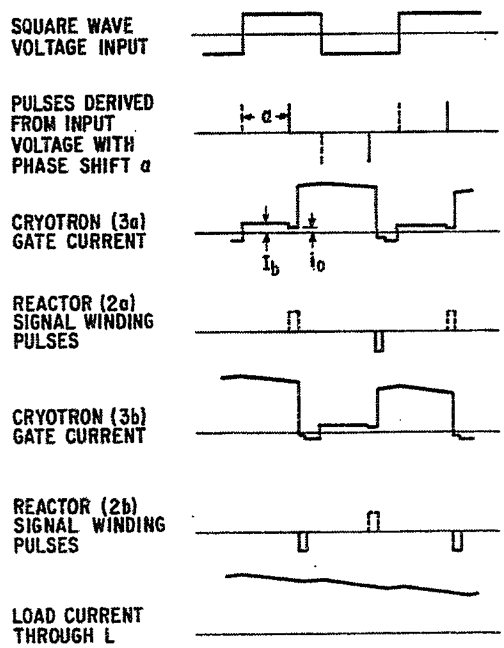

Fig. 3. Wave forms for rectification with phase shift.

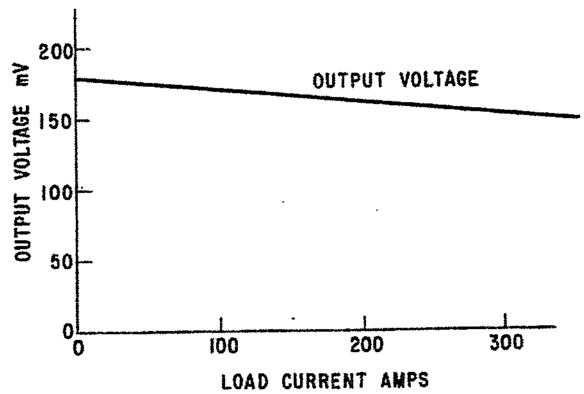

Fig. 4. G.E. superconductive flux pump characteristics.

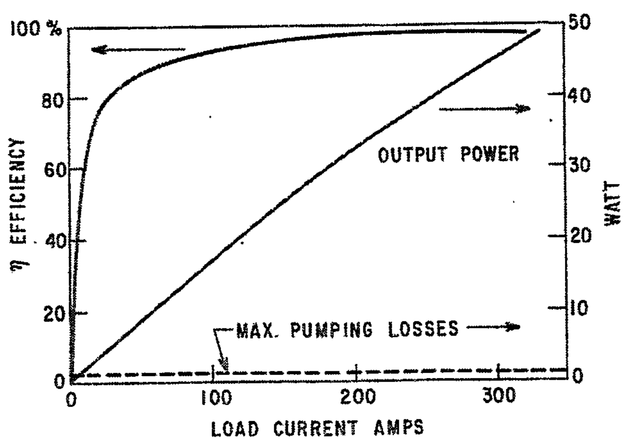

Fig. 5. G.E. superconductive flux pump characteristics.

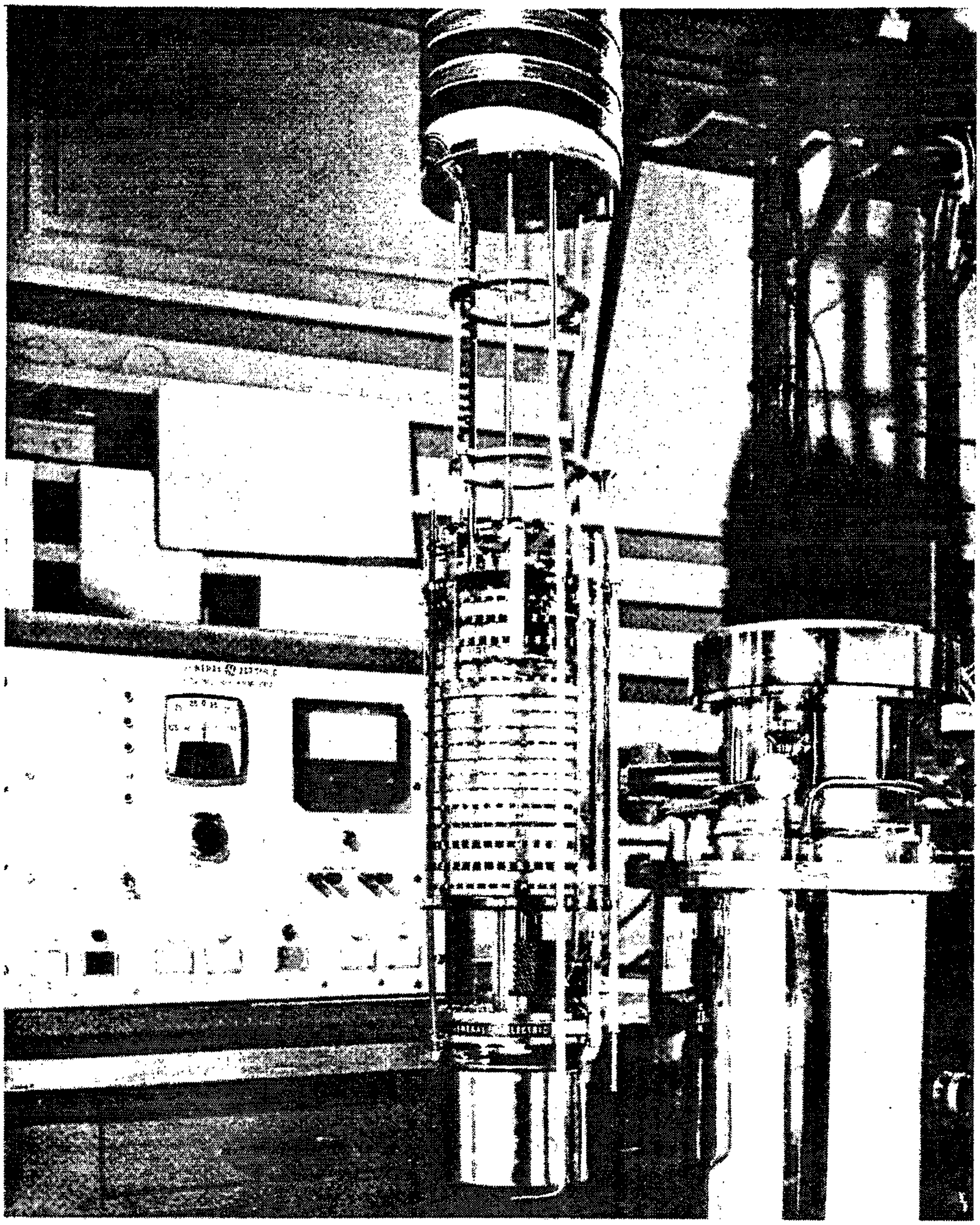

Fig. 6. 100 kG magnet system with flux pump.

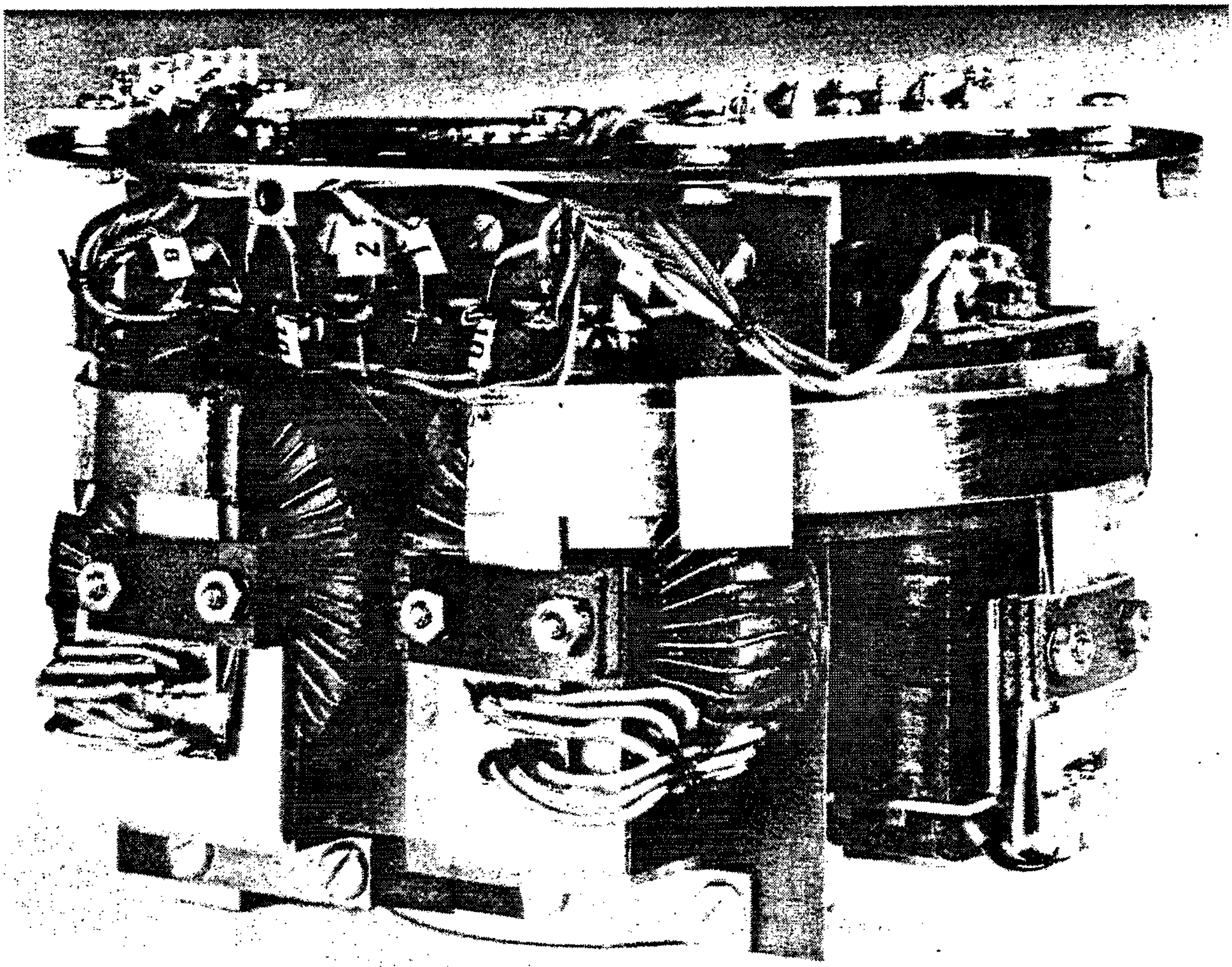

Fig. 7. 300 A, 50 W flux pump.

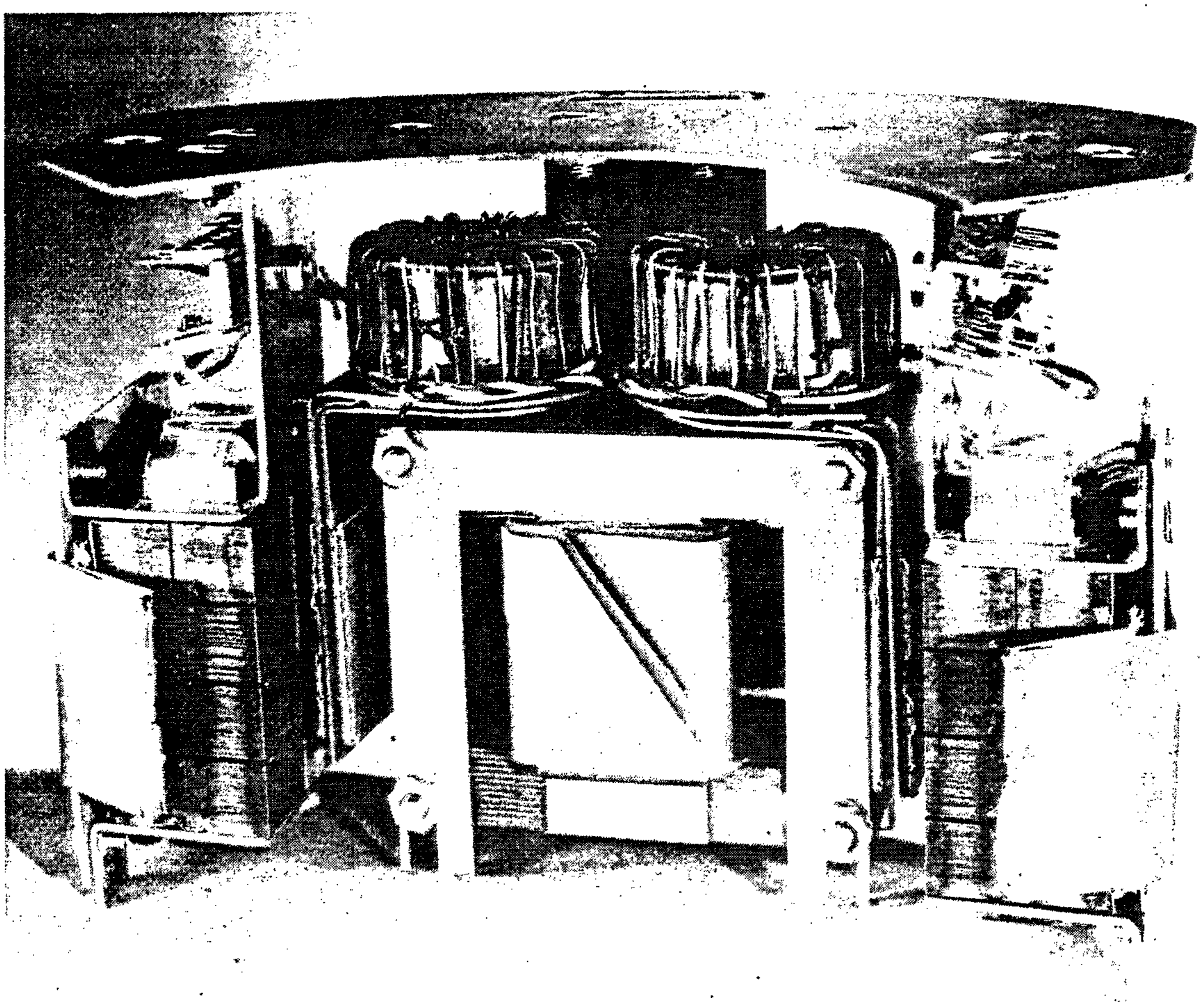

Fig. 8. 1700 A, 50 W flux pump.

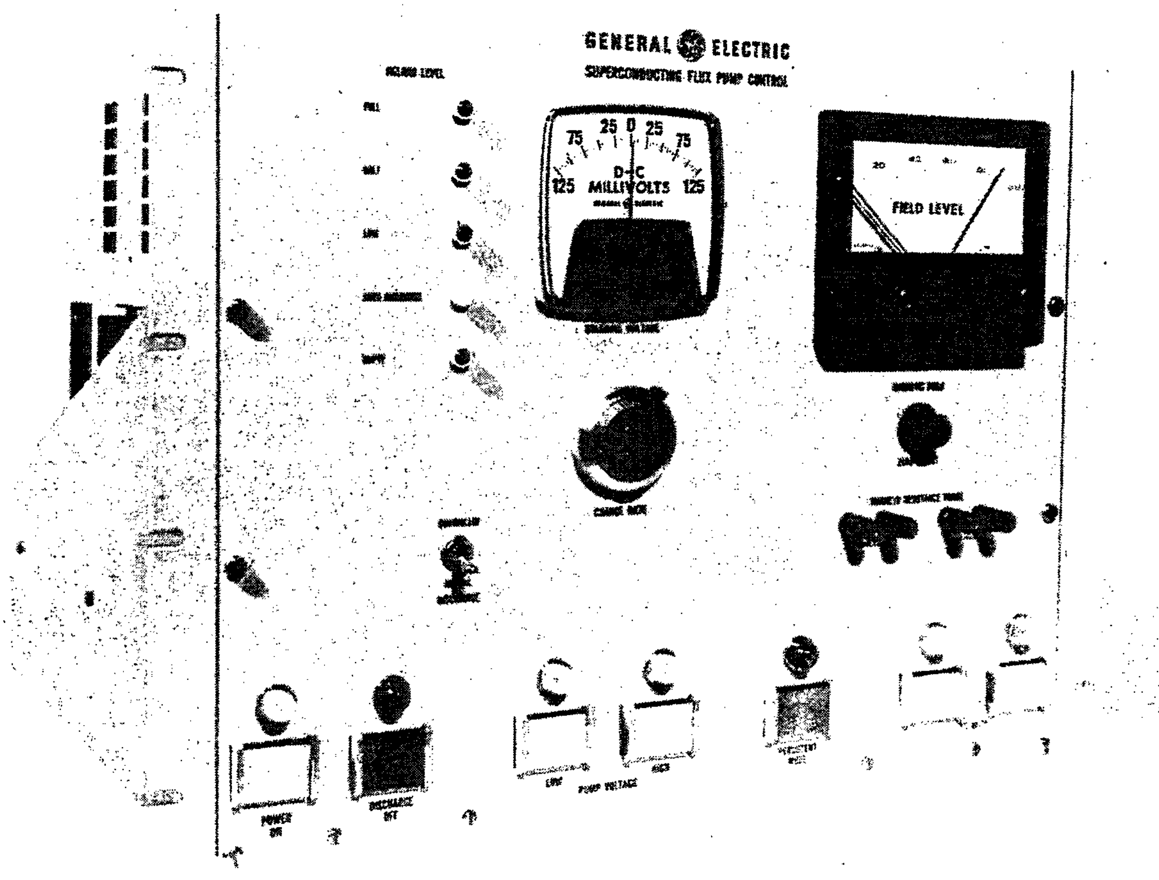

Fig. 9. Flux pump room temperature control unit.