Pulsed Power Supply for the U.W. Tokamak Reactor

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FUSION TECHNOLOGY INSTITUTE

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Basic Problem

The University of Wisconsin Tokamak reactor, UWMAK-I, according to present design thinking, will require repetitively pulsed power for the divertor and transformer coils with peak values of up to about 700 MW or more. These pulses are at best undesirable if not prohibitive, even for the largest electric power systems.

Because the pulsed power is used to produce a magnetic field, the load is basically an inductor which might be supplied from a dc source, such as a Graetz bridge converter, Fig. 1, which serves as the interface with the conventional three phase power system. Such Superconductive Inductor Converter (SIC) units have been described elsewhere[1, 2]. Figure 2 shows the distribution of the divertor coils, D1 to D4, and the transformer coils, T1 to T5, around the D shaped toroidal field magnets proposed for the UWMAK-I fusion reactor. The pulsed power requirements for these coils as a function of time is shown in Fig. 3.

Figure 3(a) shows the pulsed current and power requirements for the divertor coils. It is characterized by a charging time interval T_c, a hold interval T_h and a discharge interval of T_d. If there were no losses, all of the energy stored during the time interval T_c should be recovered during the period T_d after the hold period T_h. For this ideal no-loss case, the average power required from the power system would be zero, while the peak power required ($P_p = 1.0$) might be several hundred MW. Figure 3(b) shows the pulsed current and power requirements for the transformer coils. The slow change in transformer current during the burn time is used to maintain the necessary plasma current. Again for a no-loss case the average power required from the utility power system could be zero.

Figure 3(c) shows the pulsed current and power required from a Superconductive Energy Storage Inductor (SESI) to reduce the power system requirements to a constant demand. Figure 4 shows how the divertor, transformer and SESI units with their converters and control systems would be interconnected with the three phase power system.

Fig. 5 shows some of the protective items needed in such an arrangement. In case of power system disturbances requiring the opening of circuit breakers on the ac side, thyristor valves V_{7Y} and $V_{7\Delta}$ would first be made conducting so as to provide a path for the inductor current to bypass the converter. S_4 could be just a disconnecting switch to be closed for long periods of non-operation. S_1 would normally be closed. It would be opened in case of emergency need for dumping energy externally. The magnitude of R would be fixed by insulation limits and discharge times deemed adequate. The need for both S_3 and S_2 might be questioned. However, for completeness both are shown. S_2 is a superconductive switching device.

Restoration of normal operation is readily achieved. Adjustment of the converter delay angles for a very low output voltage permits converter output current to be controlled. Any parallel path such as S_4 (or other) can thereby have its current reduced to zero so that opening of the switch can take place without arcing.

For a numerical example consider that the several divertor coils constitute an inductance having a maximum stored energy of 10 MWhr. The peak power requirement will depend upon the charging time, T_c. Table 1 lists the maximum power requirements and converter costs for a charging time of 100 seconds. Convertor costs are based on \$40/kW of average power during the charge time T_c for a completely engineered and installed system with all controls. Requirements have all been calculated for a burn time of 90 minutes. A larger burn time would require a higher starting current for the transformer coils and would modify the transformer converter costs proportionately but have only a slight effect on the SESI cost. A more important factor in the determination of the SESI cost is the permitted minimum in the ratio I/I_p for the SESI unit during charge and discharge.

The following several reasons indicate the desirability of keeping the current level high in the SESI unit.

a) For a given transformer-converter supply to the SESI unit there is a maximum available voltage which can be applied to the storage magnet. If the current becomes small, then the power switching output is proportionately small; therefore high current levels are desireable.

b) A large change in SESI current would be associated with a large change in cyclic stress in the support structure. This would increase the fatigue of the structural material and also increase mechanical hysteresis losses.

c) The hysteresis losses in the superconducting filaments in the conductors of the SESI can be reduced by reducing the storage current and magnetic field excursions. Therefore high current levels with small changes are desireable.

The obvious disadvantage of maintaining a nearly constant high current in the SESI is the large size of the SESI unit required.

The five cases represented in Table 1 differ primarily in the size of the SESI unit. In the first case no cyclic power is taken from the utility power system and the stored energy in the SESI is allowed to drop only 20% from its rated value during cycling. In the second case the 20% drop is permitted but 200 MW peak power is withdrawn and returned to the utility system. In the third case a 50% energy drop is permitted in the SESI and only losses withdrawn from the utility system. In the fourth case the 50% energy drop is permitted and 200 MW peak power is withdrawn from the utility system. As would be anticipated, a reduction in charge time for the divertor is accompanied by an increase in the peak power and in the converter costs. The maximum stored energy in the divertor and transformer coils remains the same. Case five is the same as case four except for a charge time of 50 instead of 100 seconds.

The proportion of energy stored in the transformer and divertor coils is governed to a great extent by the required transformer current. The primary factor determining the transformer current is the plasma resistivity. The values presently considered appropriate vary widely depending on the plasma phenomena predicted for reactor conditions. Three values have been considered: a) the spitzer resistivity, b) neoclassical behavior (2 to 5 spitzer) and c) anomolous behavior ($\sim$12 spitzer). For a plasma resistivity near 5 spitzer the maximum stored energy in the divertor coils is about the same as that stored in the transformer coils. This is the 10 MWhr shown in Table 1.

All of the divertor and SESI coils may be provided with a closely coupled shield winding which is connected in parallel to the coils, see Fig. 4. The purpose of this normal metal shielding coil is to carry short duration ac currents while shielding the superconducting coils.* The eddy current losses now appear in the shield, possibly at 20K which is an advantage. Since shield losses would be excessive during the long charge and discharge periods of the cycle, the switches S_2 and S_3 in Figure 4 are provided to disconnect the shield during these periods. With appropriate control systems, the 20K shield windings on the divertor magnets could provide field compensation for plasma drift if the period of the drift is in the one to ten second region.

The shielding concept has also been applied to the 5-10 sec. pulsed storage unit designed by the UW-NAL energy storage group.[3, 4, 5]

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*The University of Wisconsin Energy Storage Project team, supported by the Wisconsin Utilities Association and the Wisconsin Alumni Research Foundation, developed the use of an additional external shield winding around a superconducting magnet to reduce cyclic changes in current and magnetic field from the locale of the superconductor windings.

References

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3. M. Kuchnir, et al, Bul. Am. Phys. Coc., Series II, Vol. 19, No. 1 (1974), DJ8, p. 54.
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Table 1

Power Supply Sizes and Costs

Charge Time, T_c (sec)	Operating Conditions	Supply Unit	Maximum Stored Energy (MWhr)	Maximum Power (MW)	Converter Costs 10^6 \$	SESI Cost 10^6\$	Total Cost 10^6\$
100	20% SESI Energy Discharge; Only losses obtained from utility system.	Divertors	10	500	10.0	---	---
		Transformers	10	500	10.0	---	---
		SESI	85	1000	20.0	70	110
100	20% SESI Discharge; 200 MW obtained from Utility system	SESI	60	1000	20.0	50	90
100	50% SESI Discharge; Only losses obtained from Utility system	SESI	35	1000	20.0	32	72
100	50% SESI Discharge; 200 MW Obtained from utility system	SESI	25	1000	20.0	25	65
50	50% SESI Discharge; 200 MW Obtained from utility system	Divertors	10	1000	20	---	---
		Transformers	10	1000	20	---	---
		SESI	30	2000	40	29	109

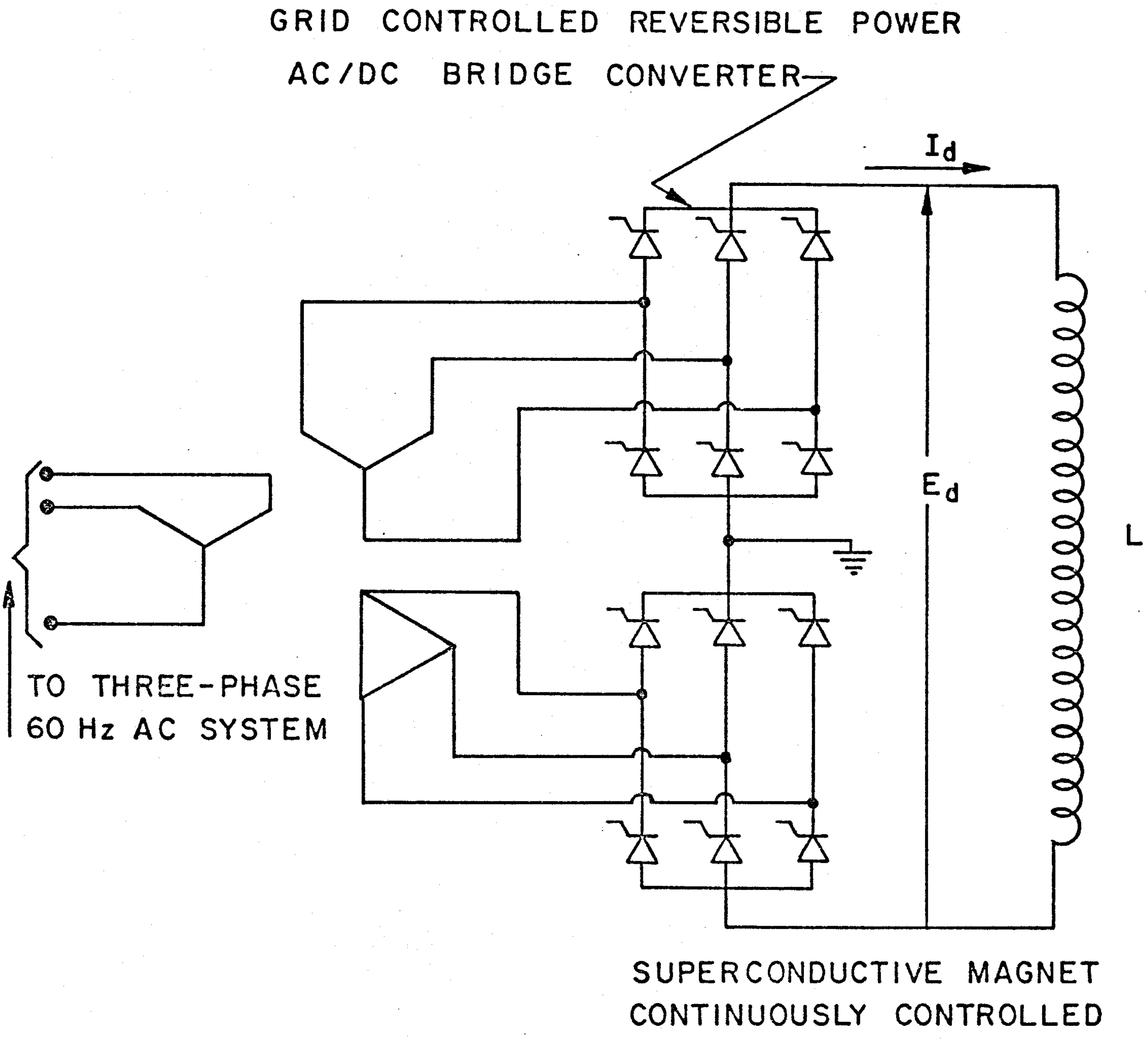
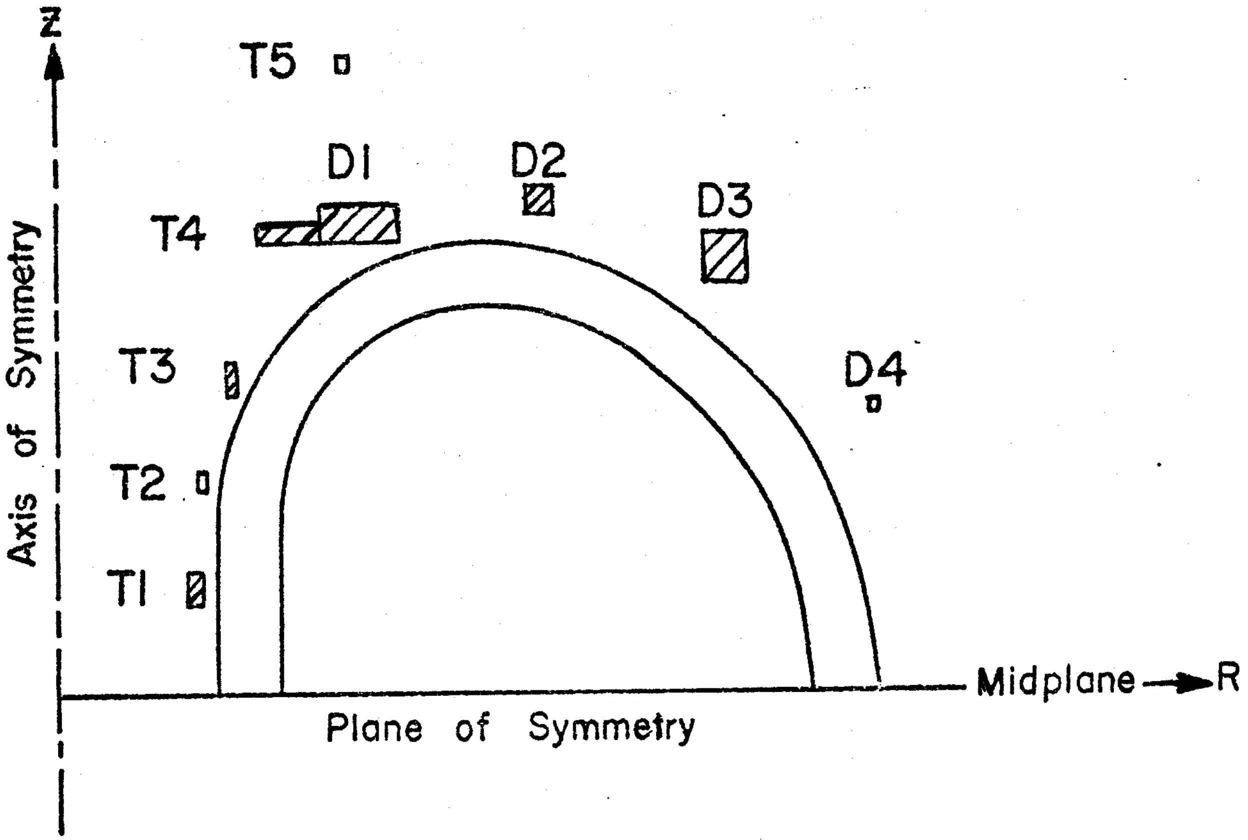


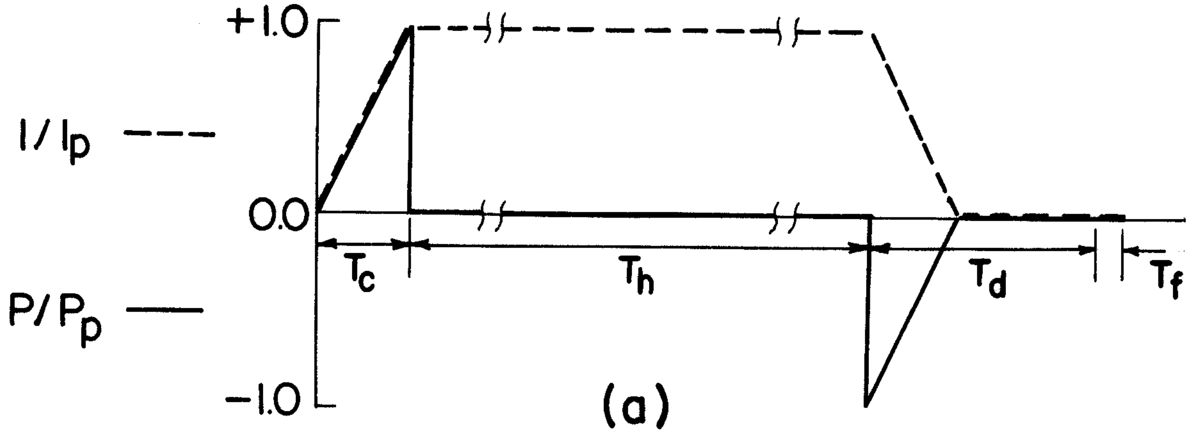
Figure 1. Basic circuit elements for superconductive energy storage inductor unit for power system applications.



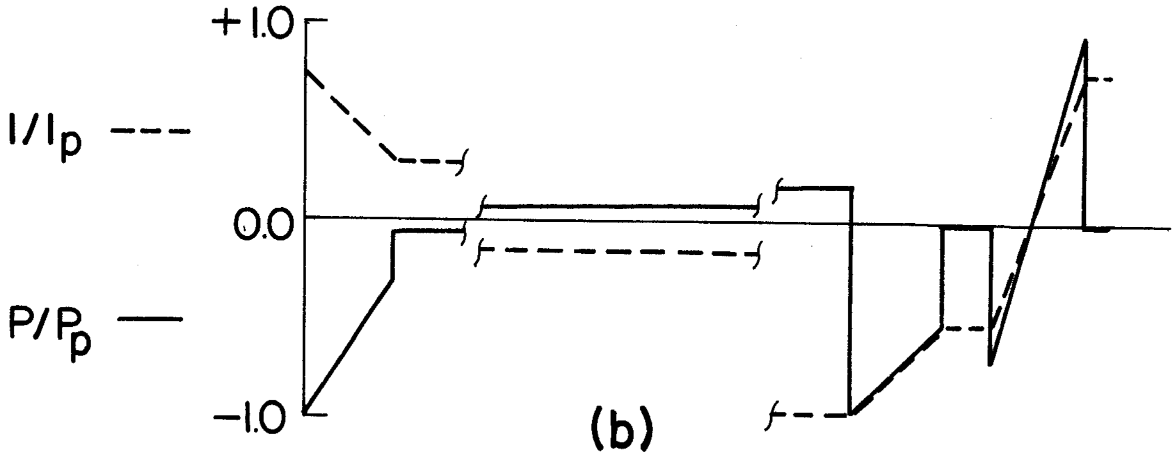
Position of Divertor and Transformer Coils

Figure 2

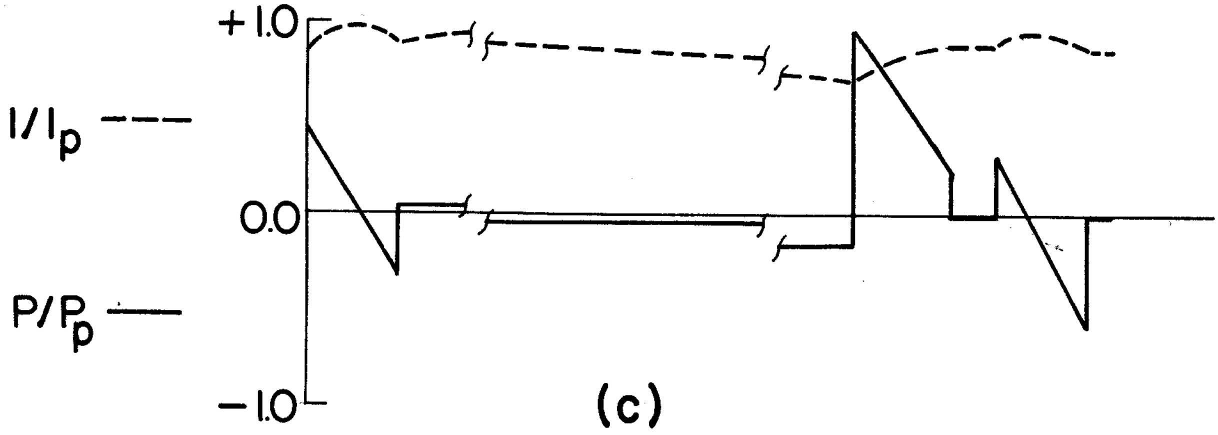
UWMAK-I PULSED POWER REQUIREMENTS



DIVERTER CURRENT & POWER



TRANSFORMER CURRENT & POWER



SESI CURRENT & POWER

Figure 3

FUSION PULSED POWER SUPPLY

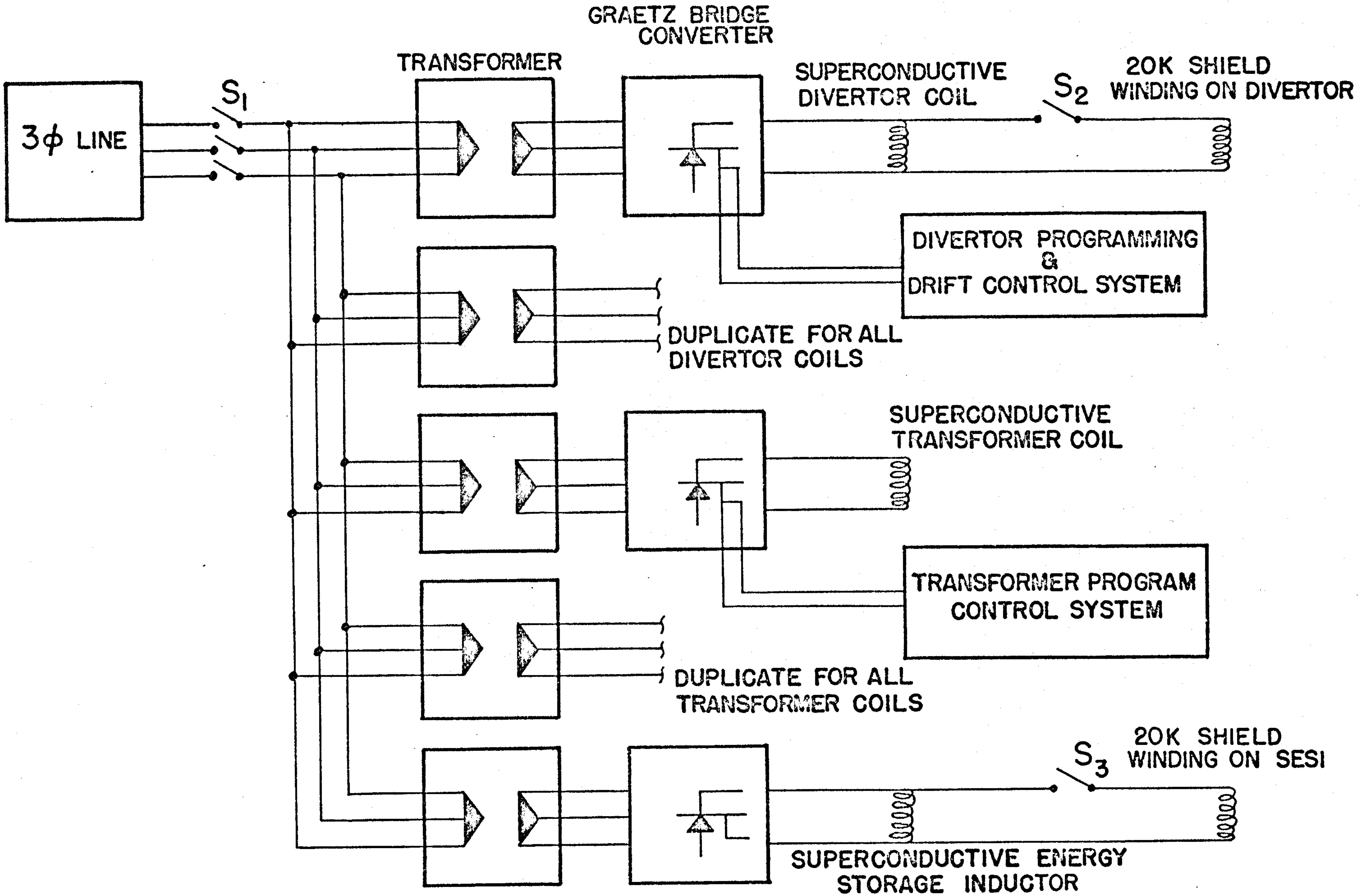


Figure 4

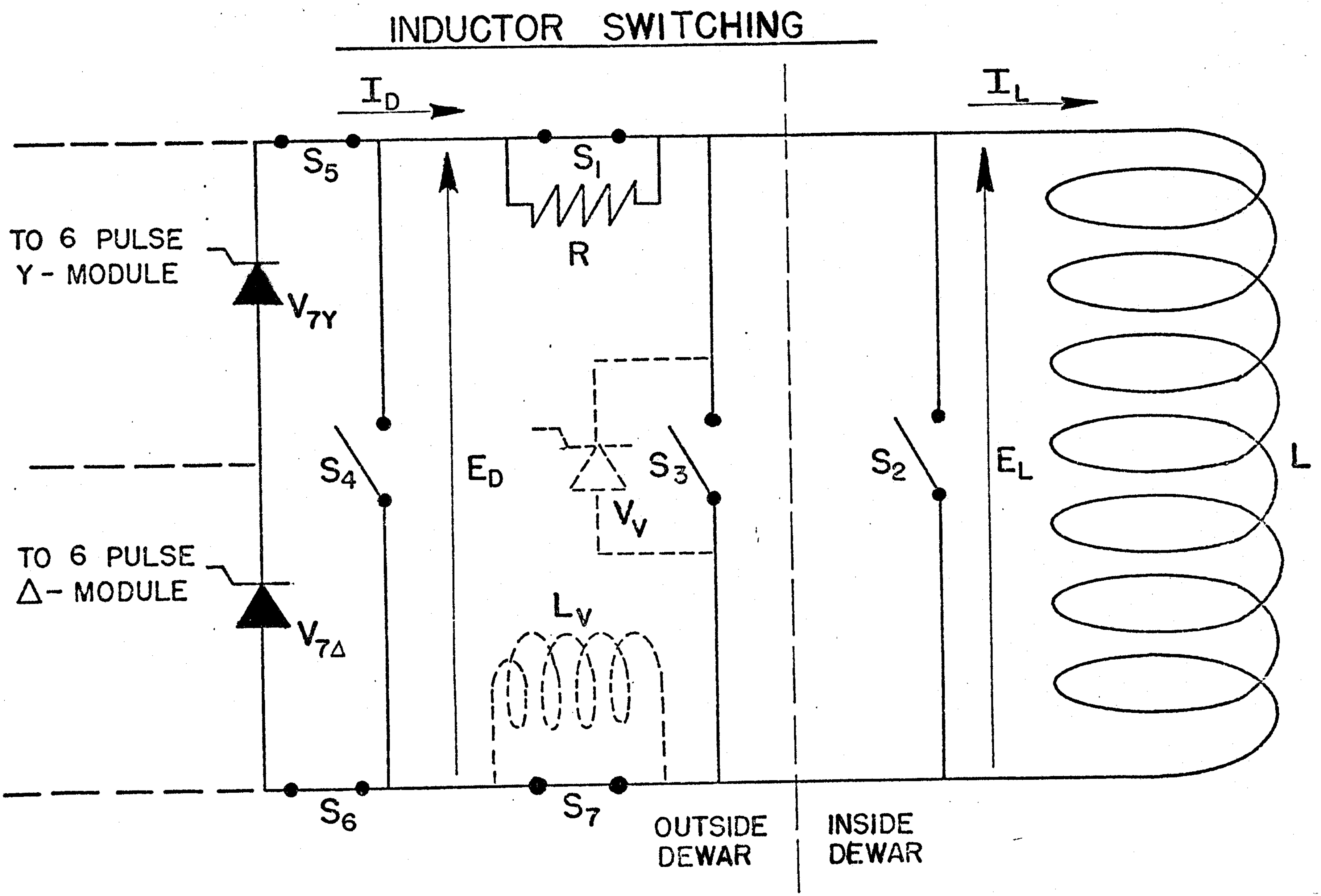

INDUCTOR SWITCHING
I_D
I_L
S_5
S_1
R
TO 6 PULSE Y - MODULE
V_{7Y}
S_4
E_D
S_3
V_V
S_2
E_L
L
TO 6 PULSE Δ- MODULE
$V_{7\Delta}$
L_V
S_6
S_7
OUTSIDE DEWAR
INSIDE DEWAR

Figure 5