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Summary

A system is described which provides pulsed power for Tokamak fusion reactor diverter and transformer coils. It consists of an ac/dc Graetz bridge and a dc superconductive energy storage magnet with a dc/ac/dc double conversion bridge to transmit the pulsed energy to the reactor coils. This scheme reduces not only the real power pulse requirement but also the reactive power pulses (voltage dips) on the utility power system. Detailed superconducting magnet design is included. The storage magnets are cryogenically stabilized short solenoids in the 1-15 MWh range. Because of the low repetition rate this pulsed power supply does not give rise to excessive energy losses. The cost of the power conditioning interface and the storage magnets for both UWMAK-I and UWMAK-II designs are given.

Introduction

The power demand of the poloidal field coils is presented in Fig. 1 for a University of Wisconsin designed Tokamak fusion reactor.[1] Typically, repetitive power pulses with peaks of up to about 1000 MW are required. Such a pulsed power load is highly undesirable from an electric power system point of view, even if it is not prohibitive. An alternate power source which absorbs the pulsed demand would be useful.

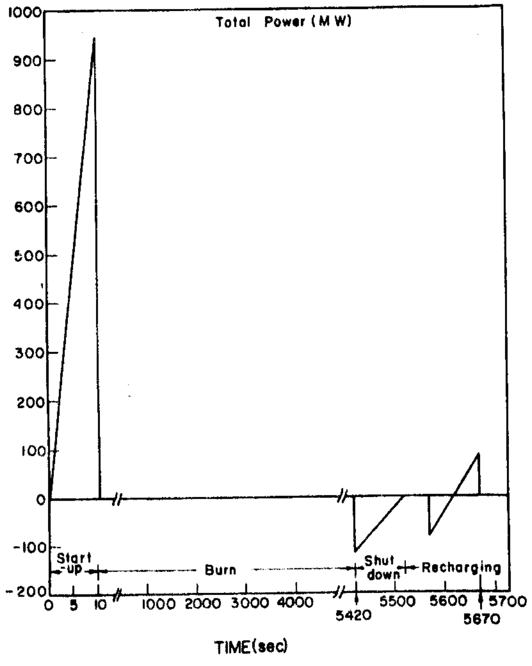

Fig. 1. Power demand curve of the poloidal field coils.

The University of Wisconsin Energy Storage Group has studied the feasibility of superconductive energy storage for power systems.[2] An inductor-converter unit serves as the interface system which cushions the electric power system from high peak power pulses. Such an interface scheme can be readily used in the present occasion. It has also been proposed that a dc/ac/dc double conversion circuit[3] would permit transfer of energy with minimum loss from one inductor to another.

In this paper, following a short description of the power supply arrangements, we will describe the design of superconductive energy storage inductors for the two University of Wisconsin designed Tokamak fusion reactors, UWMAK-I[4] and UWMAK-II.[1] The efficiency of such an energy storage and transfer scheme, and the cost estimation of the entire power supply system will also be discussed.

Power Supply Arrangements

The basic arrangement of supplying pulsed power to the poloidal field coils is via two parallel converters #1 and #2 shown in Fig. 2(a). Converter #1 is an ac/dc grid-controlled Graetz bridge[5] which provides an ideal interface between the inductive load and a large three-phase ac utility system. This converter supplies a linearly increasing power up to a maximum value P_1^{max} (Fig. 2(c)). Thereafter, additional power P_2 is provided from storage through converter #2. A large electric utility system might be able to supply P_1^{max} up to 500 MW without exceeding the allowable electrical system frequency deviation and attendant voltage fluctuations. With $P_1^{max} = 500$ MW the power requirements from storage through converter #2 are listed in Table I.

Table I
Power Demands From Energy Storage Units

	UWMAK-I	UWMAK-II
Peak power	480 MW	430 MW
Discharge time	49 sec	4.6 sec
Pulse repetition interval	96.5 min	95.5 min
Energy storage capacity planned	15 MWh	1.0 MWh
Percentage of energy cycled	22%	27%

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*Now with Oak Ridge National Laboratories

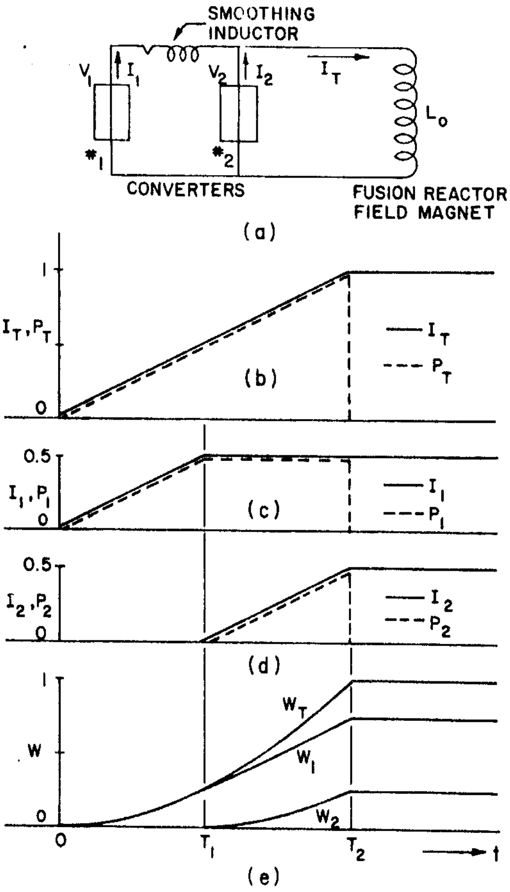

Fig. 2. Representative fusion reactor pulsed load characteristics.

The power P_2 from converter #2 is supplied from a superconductive energy storage inductor, L_s, shown in Fig. 3. The converters 2' and 2 together with the capacitor bank form a dc/ac/dc double conversion sub-unit.[3] DC power is drawn out of the storage unit, converted to ac at a selected frequency and rectified back to dc supplied to the load. This scheme is necessary to avoid the excessive losses incurred in simply connecting one inductor to another. The power flow is reversible. The energy stored in the inductive loads can be returned to the storage unit during the discharge cycle. The power source converter, Fig. 3, which is connected to a three-phase power system merely supplies the loss in the circuit system. Thus this circuit arrangement serves to minimize both the pulsed power and corresponding reactive volt-ampere requirements from the three-phase power system. The double conversion sub-unit is described more fully in reference 3.

The energy storage units are sized to cycle only about 25 percent of the stored energy in order to reduce hysteretic losses and in order to maintain magnet structural forces at all times.

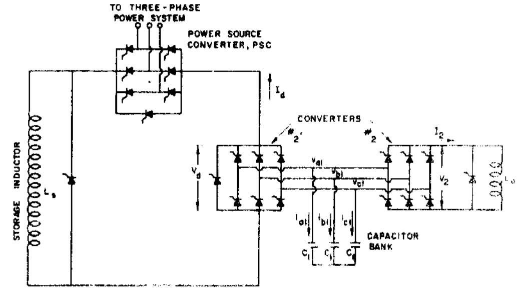

Fig. 3. Circuit diagram of superconducting energy storage inductor unit L_s and the dc/ac/dc double conversion sub-unit.

Magnet Design

An optimization study by Moses[7] shows that the best configuration for an energy storage magnet is a short solenoid. The length to diameter ratio is chosen to be 0.3 for both storage units. By limiting the maximum axial magnetic field to 5.0 T the radii of the solenoids become 14.6 m for the 15 MWh unit and 5.95 m for the 1 MWh unit. The magnets are designed to allow a maximum voltage of 10 kV. Thus the minimum full current required is about 50 kA, which in turn determines the inductance and the ampere-turns of the magnets.

The conductor consists of NbTi filaments embedded in a copper matrix which is soldered to a copper backing strip. It is wound with interleaved stainless-steel strips for reinforcement. A cross section of the conductor is shown in Fig. 4. Pool boiling helium at 4.2 K is used to cool the conductor. The cryogenic stability criterion is used to size the conductor with edge and face cooling flux taken to be 0.3 W/cm^2 and 0.15 W/cm^2, respectively. Rather than anticipate the development of high current conductors, we propose that four ∿ 13 kA conductors be wound in parallel. Full current in the copper requires only about 90 percent of the surface cooling available, a reliability allowance. When the stabilizer carries the total current the maximum temperature in the superconducting composite is about 4.72 K. The superconductor is sized to carry the total current at T = 5.0 K and B = 5.0 T with a critical current density of 8×10^4 A/cm^2. It is found that filament sizes as large as 0.038 cm (.015 in.) in diameter are small enough for smooth current sharing[8] between the superconductor and copper. The copper to NbTi ratio of the conductor is 38 to 1.

The stainless-steel reinforcing strips are sized to limit the tensile stress on the copper close to its yield stress of 82.7×10^6 N/m^2 (12,000 psi). For the UWMAK-I storage unit the average tangential stress

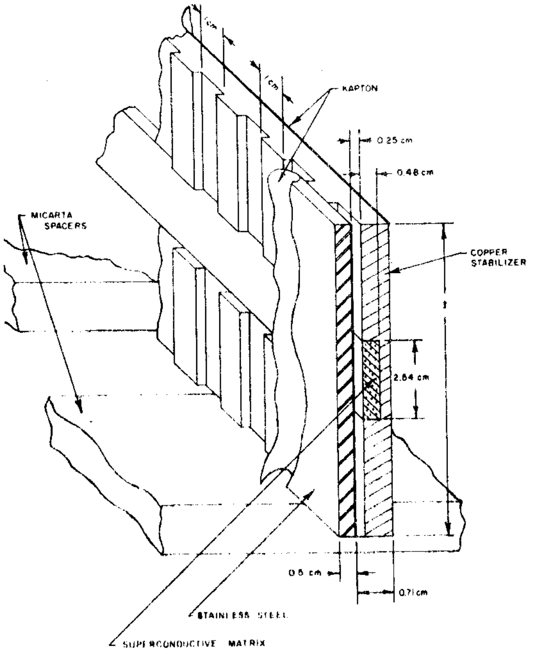

Fig. 4. Conductor cross section.
ℓ = 8.89 cm for UWMAK-I.
ℓ = 8.26 cm for UWMAK-II.

at the midplane[9] varies from 152 x 10^6 N/m^2 (22,100 psi) at the inside diameter to 142 x 10^6 N/m^2 (20,600 psi) at the outside diameter. The corresponding stresses on copper are 97 x 10^6 N/m^2 (14,100 psi) and 90.6 x 10^6 N/m^2 (13,100 psi), respectively. For the UWMAK-II storage unit the tangential stress at the midplane varies from 106 x 10^6 N/m^2 (15,400 psi) at the inside diameter to 96.0 x 10^6 N/m^2 (13,900 psi) at the outside diameter. The corresponding stresses on copper are 85.2 x 10^6 N/m^2 (12,300 psi) and 76.8 x 10^6 N/m^2 (11,100 psi), respectively.

The overall assembly of the magnets is rather similar to the NAL bubble chamber magnet.[8] Insulation between the conductors and the reinforcing strips is provided by 0.05 cm thick Kapton sheets. The stack of pancakes are separated by micarta slats 0.635 cm thick and 5.1 cm wide which cover 50 percent of the surfaces. The four parallel conductors are transposed in reversing order from one pancake to the other in order to minimize inductance differences and the resulting uneven current distributions. The specific physical parameters of the energy storage magnets for both UWMAK-I and UWMAK-II are listed in Table II.

Table II

Characteristics of the Superconductive Energy Storage Magnets

	UWMAK-I	UWMAK-II
Solenoid winding inside diameter	28.45 m	11.45 m
Solenoid winding outside diameter	29.95 m	12.35 m
Coil length	8.60 m	3.50 m
Number of pancakes	90	39
Number of turns per pancake (4 conductors per turn)	11	11
Conductor current	13.3 kA	12.5 kA
Total ampere-turns	52.7x10^6At	21.5x10^6At
Inductance	38 H	2.9 H
Conductor dimension (height x width)	8.89x0.714 cm	8.26x0.714 cm
Number of superconducting filaments per conductor (0.038 cm in dia.)	147	138
Copper to NbTi ratio	38:1	38:1
Reinforcing stainless-steel strip dimension	8.91x0.953 cm	8.28x0.238 cm
Conductor current density	2095 A/cm^2	2119 A/cm^2
Overall current density	817 A/cm^2	1365 A/cm^2
Maximum axial magnetic field	5.0 T	5.0 T
Magnetic field on the axis	2.19 T	2.18 T
Conductor length per pancake (four in parallel)	1010 m	411 m
Magnet weight	5.37x10^6 kg	0.512x10^6 kg

Energy Loss Calculation

There are two different kinds of energy losses in a superconductive energy storage inductor: the more routine continuous losses due to thermal radiation, mechanical supports and current leads; and the pulsed ac losses arising from rapid current charging and discharging.

With 10 cm of aluminized mylar superinsulation between inner and outer dewar the thermal radiation heat input to the 4.2 K liquid helium is estimated to be 5 μW/cm^2. Multiplying by the total surface area of the inner dewar one arrives at the thermal radiation power loss for both magnets as listed in Table III. The mechanical support is designed to support the total magnet weight with a compressive stress of

138×10^6 N/m^2 (20,000 psi). The average thermal conduction over the 10 cm strut is taken to be 1.7 W-cm/cm^2. The total thermal conduction loss through the mechanical supports are also listed in Table III. A properly designed current lead should have a heat loss of 5 mW/A or less.[10] The total loss through the four pairs of 13 kA leads amounts to 520 W, which is one of the largest unavoidable losses.

Table III

Heat Losses
Average Per Cycle

	UWMAK-I	UWMAK-II
Thermal radiation	86.7 W	15.1 W
Mechanical support conduction	648 W	61.7 W
Leads	532 W	500 W
Average ac losses	136 W	117 W
Miscellaneous (10% of the above)	140 W	69.4 W
Total heat losses at 4.2 K	1.54 kW	764 W

The pulsed ac losses involve three different mechanisms. The eddy current loss in copper arises from the diffusion of the pulsed magnetic field. For the UWMAK-II storage unit, this amounts to 61.9 kW during the 4.6 sec current discharge period. The superconducting filament coupling loss arises from shielding currents flowing through the normal metal matrix.[11] For filaments twisted with a 30 cm pitch this power loss is 58.4 kW. The superconductor magnetic hysteresis loss adds another 12.8 kW. Thus the total ac power loss during the 4.6 sec. current discharge period is 133 kW, which is generated locally inside the conductor. However, considering the liquid helium surface cooling power of 1.02 W/cm, this heat generation will increase the conductor temperature by only about 0.01 K. Therefore during operation, including energy discharge, the conductor temperature will not rise above 5.0 K. Self recovery of superconductivity is ensured in the event of a conductor momentarily going normal.

Because of the long repetition periods (∿ 96 min.) of these fusion power reactors the average ac power losses are relatively small, see Table III. If the repetition rate were higher, then more complicated magnets with flux shields[12] or with less stable ac composite conductors might be needed. For the UWMAK-II storage magnet the total energy loss per cycle at 4.2 K is about 4.38 MJ. This requires 1313 MJ of refrigeration energy.

Cost Estimation

The superconductive energy storage solenoids are estimated[13] to cost $\$44.3 \times 10^6$ for the 15 MWh unit, and $\$4.80 \times 10^6$ for the 1 MWh unit. The reinforcing stainless steel support amounts to 30 percent of the total cost of the 15 MWh unit, but only 12 percent of the total cost of the 1 MWh unit. This is consistent with the expectation that mechanical structure plays a more vital role in larger energy storage magnets. The UWMAK-I storage unit requires a refrigerator rated at 1.54 kW at 4.2 K, while UWMAK-II requires 764 W at 4.2 K (see Table IV). A unit cost of \$720/W is used to calculate the refrigerator cost. The refrigeration system costs listed in Table IV include also the liquid helium inventory and storage dewar costs.

Table IV

Cost List

	UWMAK-I	UWMAK-II
Superconductive energy storage unit	$\$44.3\text{x}10^6$	$\$4.80\text{x}10^6$
Refrigeration system	$\$1.37\text{x}10^6$	$\$0.65\text{x}10^6$
dc/ac/dc double conversion bridge	$\$12.0\text{x}10^6$	$\$10.75\text{x}10^6$
ac/dc Graetz bridge	$\$15.0\text{x}10^6$	$\$15.0\text{x}10^6$
Total power supply system	$\$72.7\text{x}10^6$	$\$31.2\text{x}10^6$

The dc/ac/dc double conversion bridges, Fig. 3, are rated at 480 MW and 430 MW (see Table I), respectively. It is believed, because of the short pulse nature, that unit costs as low as \$25/kW are possible. As discussed previously, the power source converter is called upon to supply a very low average power loss continuously. Its power rating will be very low, and its cost negligible. The ac/dc Graetz bridge converter (#1 in Fig. 2) rated at 500 MW, however, costs about $\$15 \times 10^6$. Therefore, the total power supply system capital cost for the poloidal field coils is estimated to be $\$72.7 \times 10^6$ for UWMAK-I and $\$31.2 \times 10^6$ for UWMAK-II. It has been shown earlier[6] that obtaining pulsed power from the line to the allowable limit with the smallest storage unit possible is always most economic. For example, in UWMAK-II, if the superconductive energy storage unit were to supply the total pulse power required (Fig. 1), then the storage unit capacity would be 5.2 MWh at a cost of around $\$18 \times 10^6$. The dc/ac/dc double conversion bridge would have to be rated at 930 MW and cost $\$23 \times 10^6$. Thus the total power supply system cost would be about $\$42 \times 10^6$, 35 percent higher than the present arrangement.

Conclusion

The combination of a superconducting energy storage magnet and a double conversion dc/ac/dc bridge circuit can be used to provide pulsed power to Tokamak poloidal field coils. The circuit is particularly well suited for the expected pulsed times in the 1-100 second range. The major disadvantage is the cost of the storage magnet. The 1000 MW-10 s example above would require $\$30 \times 10^6$ for an ac/dc Graetz bridge to pulse 1000 MW directly from a three phase utility company line while

$\$42 \times 10^6$ is required to provide all of the pulsed energy from storage. The major advantage is that use of the energy storage system can completely remove both the real power pulse requirement and the reactive power pulses (voltage dips) on the electric utility system. For economy the maximum tolerable power pulse should be obtained directly from the line with the remaining power pulse to be obtained from storage via the double conversion bridge.

The major cost items are the bridge elements which must be purchased according to the maximum power requirement at about $40/kW or possibly, somewhat less for very short pulsed use. Comparisons with other storage and transfer schemes can be made with the above cost estimates for energy storage-double conversion systems.

Acknowledgement

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