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AUTHOR(S): J. D. Rogers, H. J. Boenig, and W. V. Hassenzahl

SUBMITTED TO: Instrument Society of America
Philadelphia, PA

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

Form No. 836
St. No. 2629
1/75

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

SUPERCONDUCTING MAGNETIC ENERGY STORAGE FOR ELECTRIC UTILITIES AND FUSION SYSTEMS*

by

J. D. Rogers, H. J. Boenig,
and W. V. Hassenzahl

Los Alamos Scientific Laboratory of the
University of California, Los Alamos, NM 87545

ABSTRACT

Superconducting inductors provide a compact and efficient means of storing electrical energy without an intermediate conversion process. Energy storage inductors are under development for load leveling and transmission line stabilization in electric utility systems and for driving magnetic confinement and plasma heating coils in fusion energy systems. Fluctuating electric power demands force the electric utility industry to have more installed generating capacity than the average load requires. Energy storage can increase the utilization of base-load fossil and nuclear power plants for electric utilities. The Los Alamos Scientific Laboratory and the University of Wisconsin are developing superconducting magnetic energy storage (SMES) systems, which will store and deliver electrical energy for load leveling, peak shaving, and the stabilization of electric utility networks. In the fusion area, inductive energy transfer and storage is being developed. Both 1-ms fast-discharge theta-pinch systems and 1-to-2-s slow energy transfer tokamak systems have been demonstrated. The major components and the method of operation of a SMES unit are described, and potential applications of different size SMES systems in electric power grids are presented. Results are given of a reference design for a 10-GWh unit for load leveling, of a 30-MJ coil proposed

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* Work done under the auspices of the Department of Energy.

for system stabilization, and of tests with a small-scale, 100-kJ magnetic energy storage system. The results of the fusion energy storage and transfer tests are presented. The common technology base for the various storage systems is discussed.

I. INTRODUCTION

The phenomenon of superconductivity offers the possibility of using inductors as energy storage units. The nondissipative dc-current carry capability and the low ac-current generated losses of a superconductor place the design of high current inductors within reach of useful application. Inductive energy storage has at least an order of magnitude higher energy density than capacitive energy storage and is attractive on an economic basis because of the volume-related cost saving alone. Only in the last 15 years has the superconducting technology been sufficiently advanced to make the applications covered in this paper become practical. Only more recently, during the last three years, has relatively fast energy transfer of a few seconds or less, into and out of a superconducting energy storage coil been demonstrated. The pulsed coil technology described has been under development at the Los Alamos Scientific Laboratory (LASL) since 1968.

Electric utilities experience periodic load variations on a seasonal, weekly, and daily basis. The daily maximum and minimum loads of a power company may differ by more than a factor of two. The resulting poor load factor is an economic burden to the utilities because their installed capacity must be capable of meeting the peak demand and yet much of this capacity is idle during periods of low demand. Today, inexpensive but inefficient units, such as peaking gas turbines, are used to meet the peak loads; and some power companies are providing customer incentives, such as time-of-day metering and load demand control, to level the diurnal load variation.

Energy storage units can be used to meet the peak-power requirements and to absorb the excess energy available during periods of low-power demand. By the year 2000 as much as 5% of the total electric energy production could be supplied by energy storage. [1] To date, only pumped-hydro storage, with units up to 15,000 MWh, has been used very effectively.[2] Other energy storage technologies include chemical storage in the form of batteries and hydrogen, thermal storage, compressed-air storage, and magnetic storage. [3,4,5] Economic considerations eliminate inertial storage in flywheels for utility applications. Presently, most of these storage technologies are technically feasible but are not economically competitive with gas turbines or pumped-hydro storage.

Superconducting magnetic energy storage (SMES) has several attractive features. SMES units will have fewer site restrictions than pumped-hydro and compressed-air storage, which require specific rock structures, abundant water, aquifers, etc. Large SMES units can be constructed in the rock formations near most large load centers, and extensive new transmission systems will not be required. SMES units will have a response characteristic of less than a cycle to power system demand, which can improve power system stability. The fast response has been demonstrated in laboratory experiments. SMES units should have a high efficiency. The energy is stored electromagnetically without an intermediate mechanical or chemical energy state. The power requirements of the refrigeration equipment and the converter losses for a daily cycle amount to about 10% of the stored energy. This 90% efficiency compares favorably with the 70% to 75% efficiency for pumped-hydro, compressed-air, and battery storage.

The cost for a large SMES unit (10 GWh) is estimated to be about 30 $/kWh. This cost is competitive with costs for pumped-hydro, advanced batteries, and compressed air storage plants.

The LASL and the University of Wisconsin (UW) are developing SMES systems for electric utility applications. [6,7] The superconducting magnets for these systems range in size from small units a few meters in diameter and height, which will store as little as 30 MJ (8.3 kWh), up to large installations several hundred meters in diameter and height, which will store as much as 10,000 MWh.

A technology development program for pulsed superconducting energy storage systems for fusion applications has been underway at LASL since 1968. Both high-β, theta-pinch[8] and for low-β tokamak ohmic-heating[9-11] systems will need nondissipative energy storage to achieve overall power balance. Liners, Z-pinches, lasers, and pulsed electron beam machines are examples of fusion devices which require large, fast energy delivery systems.

The toroidal Reference Theta-Pinch Reactor (RTPR) would require about 60 GJ delivered in 30 ms, the linear theta-pinch fusion-fission hybrid reactor needs about 25 GJ in 2 ms,[12] and a liner reactor may require about 10 GJ in 1 ms. The ohmic-heating coils in present U.S. designs of tokamak experimental power reactors have about 1-2 GJ of stored energy, and the storage currents must be reversed in 0.5 to 2 s to induce plasma current.[13-17]

Feasibility experiments of Magnetic Energy Transfer and Storage (METS) systems for 1-ms discharge from 300-kJ to 540-kJ superconducting coils have been successfully demonstrated for delivery of energy to an adiabatic theta-pinch plasma compression coil for fusion.[18] Pulsed energy simulation of both the tokamak plasma ohmic-heating and burn cycles has also been demonstrated with a superconducting energy storage coil and a dc-commutated mechanical capacitor.[19]

II. SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM DESCRIPTION

The SMES coil is immersed in a liquid helium bath, which keeps it superconducting at a temperature below 4.5 K. Both the coil and the helium are contained in a sealed stainless steel vessel, which is in a vacuum. The vacuum exists between the inner vessel and an outer vessel, which must be impermeable to air, and is maintained by vacuum pumps. This dewar limits the heat flux from the ambient temperature surrounding to the liquid helium bath. A closed-cycle refrigeration system cools and liquefies the boiloff helium gas and returns it to the liquid bath. For economic reasons, the inductor will be a short solenoid, a coil with a ratio of height to diameter of about 1/3. A transformer and a converter will connect it to a 3-phase utility bus and will regulate the power flow. During the charge phase of the energy storage cycle, the converter will rectify ac power to dc for charging the coil. Stored energy can be returned to the utility bus for peak-load demands by operating the converter as an inverter. Commercially available thyristors are used as the switching elements in converters. Fig. 1 shows the SMES system components in block diagram.

A full-wave Graetz bridge, as shown in Fig. 2, is the fundamental building block of a line-commutated converter. The charging rate and the power flow between the 3-phase bus and the coil are determined by the amplitude and polarity of the bridge voltage according to the relationships

$$\frac{dI_d}{dt} = \frac{V_d}{L} , \tag{1}$$

and

$$P_d = V_d I_d \tag{2}$$

where I_d is the coil current, V_d is the applied voltage, L is the coil inductance, and P_d is the coil power. The magnetic energy, W_m, in the coil is proportional to the square of the coil current

$$W_m = \frac{1}{2} L I_d^2 . \tag{3}$$

Phase-angle control of the thyristors in the converter determines the dc-output voltage, V_d, which can be varied between its maximum value, $V_{d\ max}$, corresponding to the full rectifier mode, and its minimum value, $V_{d\ min}$, cor-

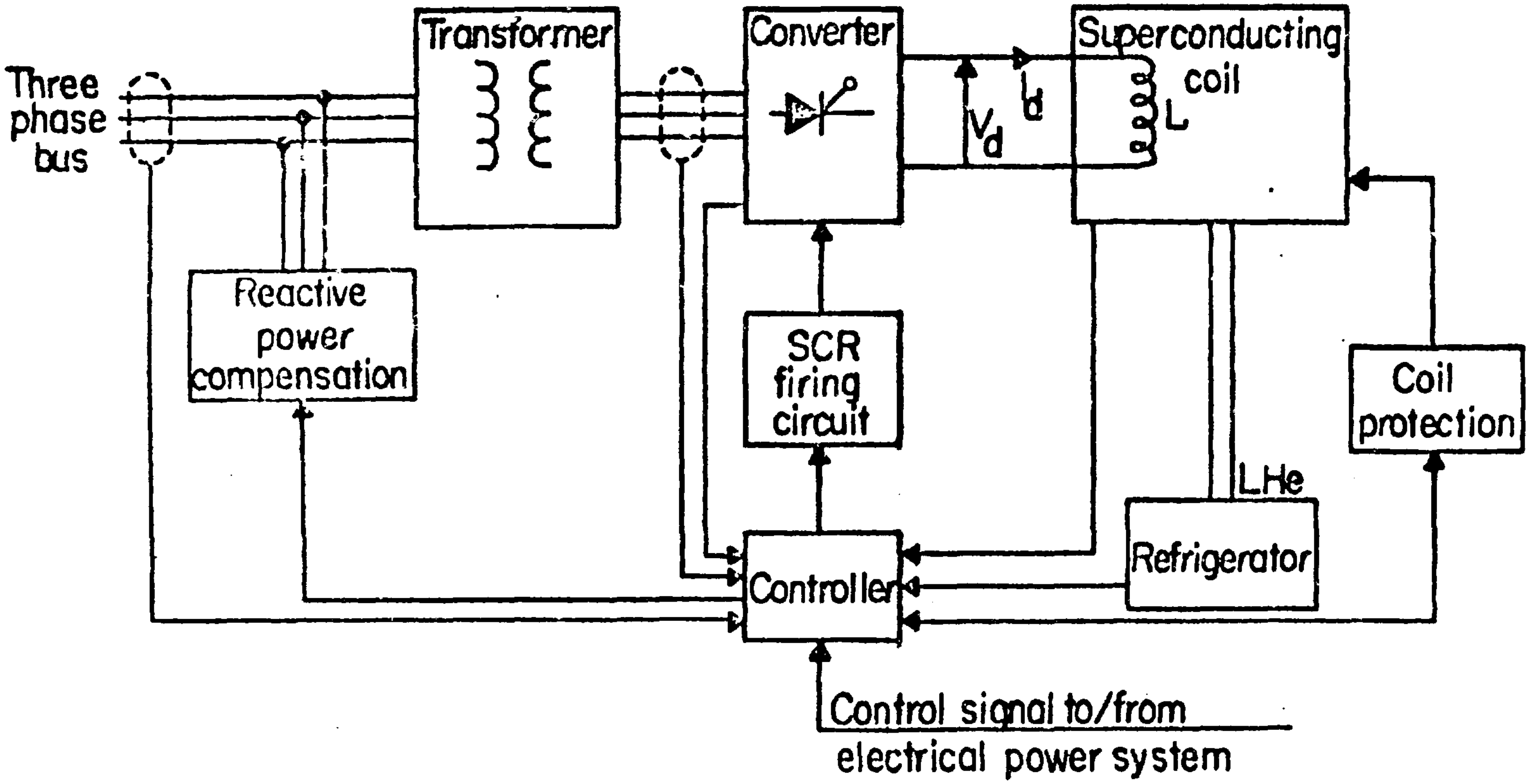

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Fig. 1 Components of a superconducting magnetic energy storage system.

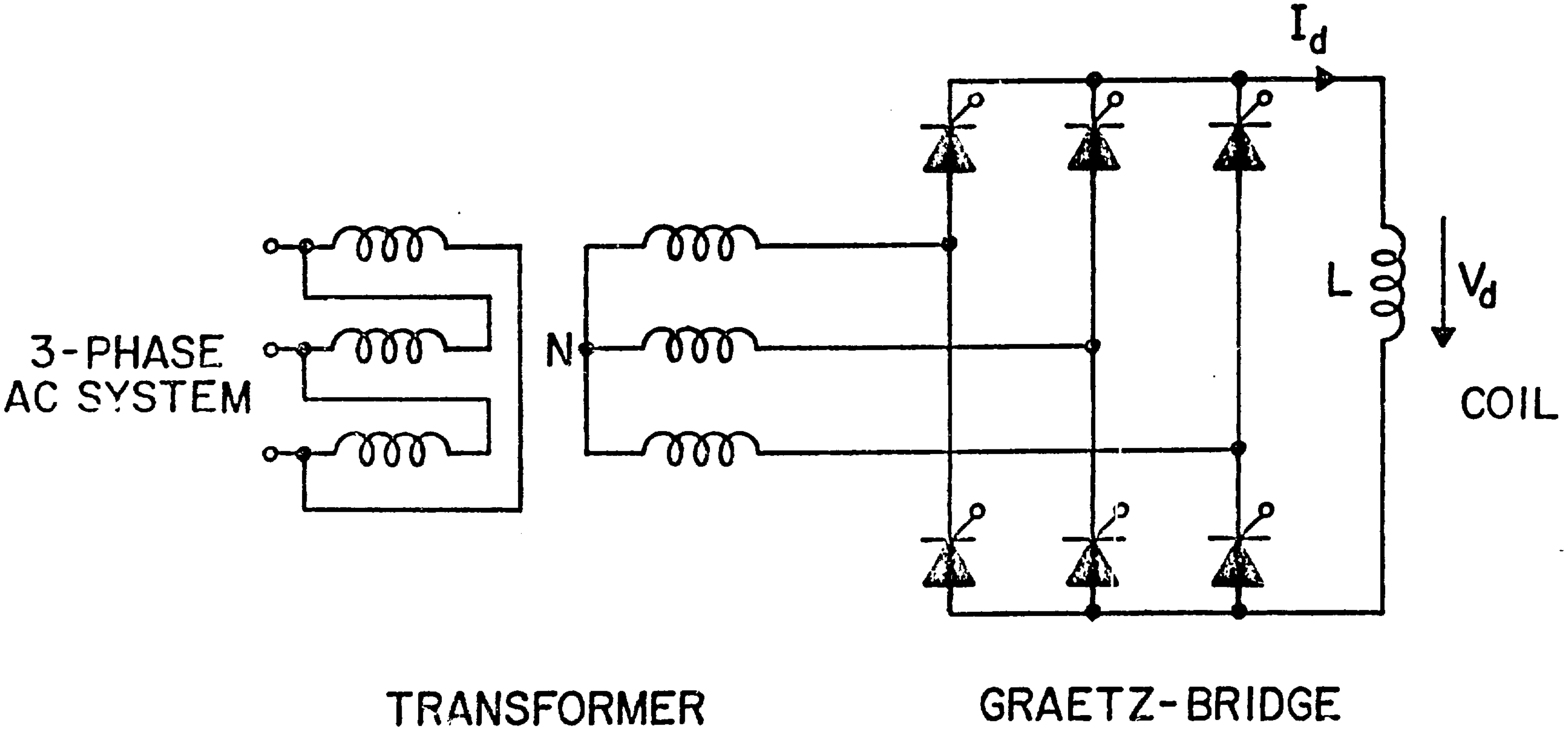

Fig. 2 Schematic of a full-wave, 6-pulse Graetz bridge.

responding to the full inverter mode. Because of the unidirectional current flow in the thyristors, the converter power is reversed when the sign of the bridge voltage is reversed. For positive V_d, the current increases and the coil charges. When the converter voltage is made negative, the coil will discharge and the current will decrease.

A phase-controlled converter requires reactive power from the ac bus during both modes of converter operation. A reactive power compensation network, such as a capacitor bank, a synchronous condenser, or a static, reactive-power-controlling device is needed to provide power factor correction. Large SMES systems for electric utility applications will most likely use 12-pulse converters.

The SMES system has current and voltage operating limits. The short sample current of the superconductor and the mechanical structure of the coil determine the highest operating current, $I_{d\ max}$. Cyclic stress considerations in the coil support structure determine the lowest current, $I_{d\ min}$. The maximum converter voltage or the maximum stand-off voltage in the coil determine the maximum charge-discharge rate. An additional restriction may apply for maximum power level because of system considerations. The operating range with these restrictions is the crosshatched area shown in Fig. 3, which is a per-unit, voltage-current diagram for a SMES unit with an energy extraction of 84% of the maximum stored energy ($I_{d\ max}/I_{d\ min} = 2.5$).

A unique characteristic of a SMES system, compared to storage systems which use electromechanical energy conversion, is its ability to switch almost instantaneously from one operating mode to another. Ideally, the average switching time for the converter from the rectifier mode to inverter mode and back is one fourth of a period of the bus frequency. This time does not depend on the pulse number of the line-commutated converter but does exclude the time delay necessary to establish the proper thyristor gating sequence. In practice, however, the gating control of a 60-Hz converter requires one to three milliseconds

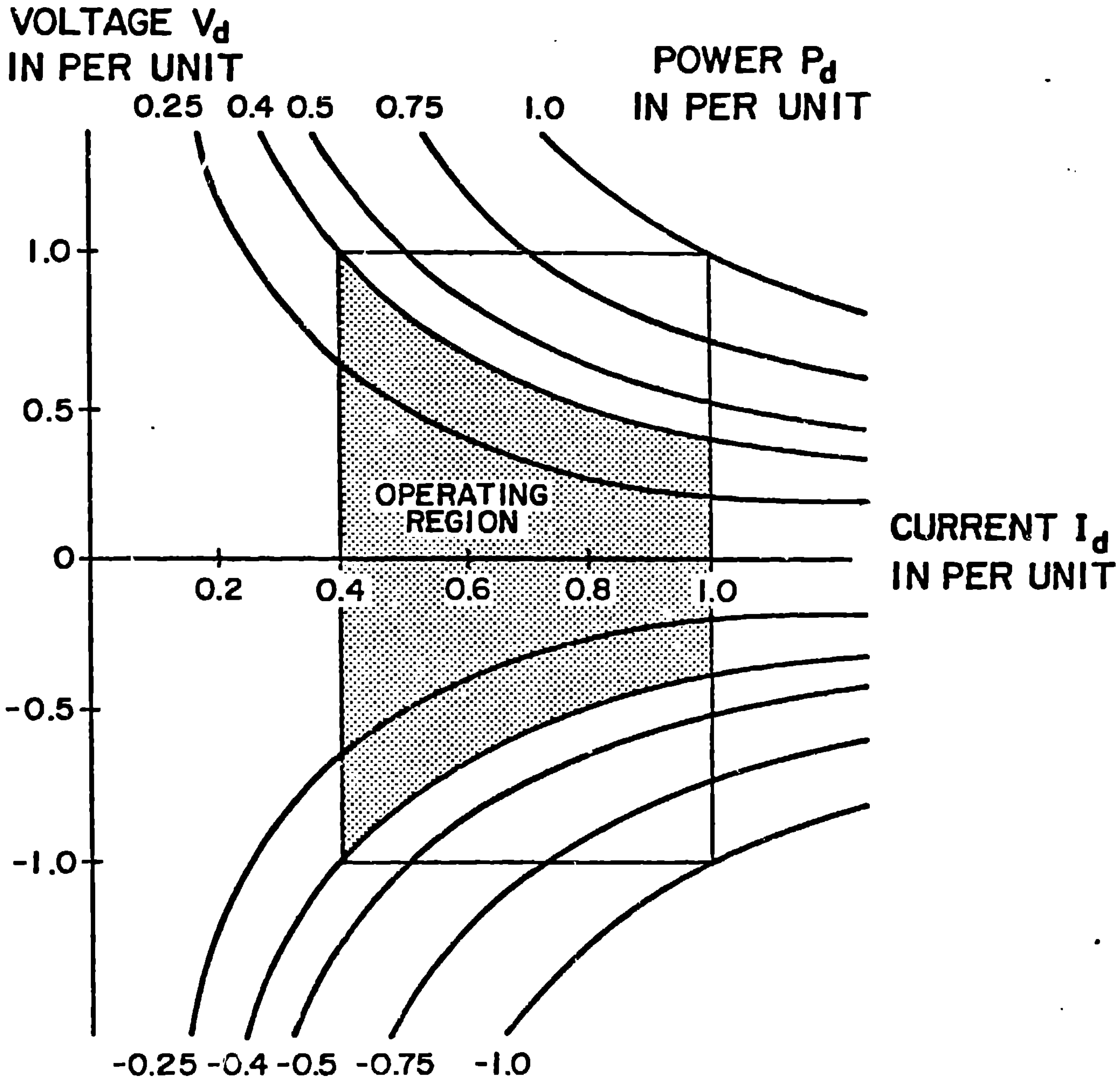

Fig. 3 Operating characteristic of a SMES unit.

to generate the correct gating sequence following a change in demand input. This rapid time response also makes a SMES system attractive for improving the transient stability of a power system besides satisfying peak-shaving and load-leveling requirements.

III. SMES APPLICATIONS IN ELECTRIC UTILITY SYSTEMS

The load experienced by the electric utilities varies periodically on a seasonal, weekly, and daily basis, and randomly during shorter time periods, seconds to tens-of-minutes. The types of energy storage systems for the utilities may be separated according to the duration of the load variation. On a seasonal basis the utilities typically use some form of fuel storage to meet the winter or summer peak load. The daily and weekly load variations are met by pumped-hydro storage, gas turbines, and old, inefficient fossil-fired power plants. At present, the short-term load variations are met by adjusting the power output of one or more power plants on the system. Each of these short-term load variations is discussed below and a SMES unit which might meet their power and energy requirements is described.

A. Load Leveling

The daily load may vary by as much as a factor of three, although factors of 1.3 to 2 are typical. A representative weekly load curve, which is for the Michigan Electric Coordinated Systems is shown in Fig. 4.[20] Generally, power demands are met by a combination of three or more types of power generation, including the base load generation consisting of the more efficient fossil fueled or nuclear power plants; the intermediate load generation (midrange peaking), consisting of older, smaller, less-efficient fossil fueled plants and energy storage units; and the peak-load generation, consisting mainly of gas turbines and energy storage units.

The use of energy storage systems allows coal and nuclear fuels to be sub-

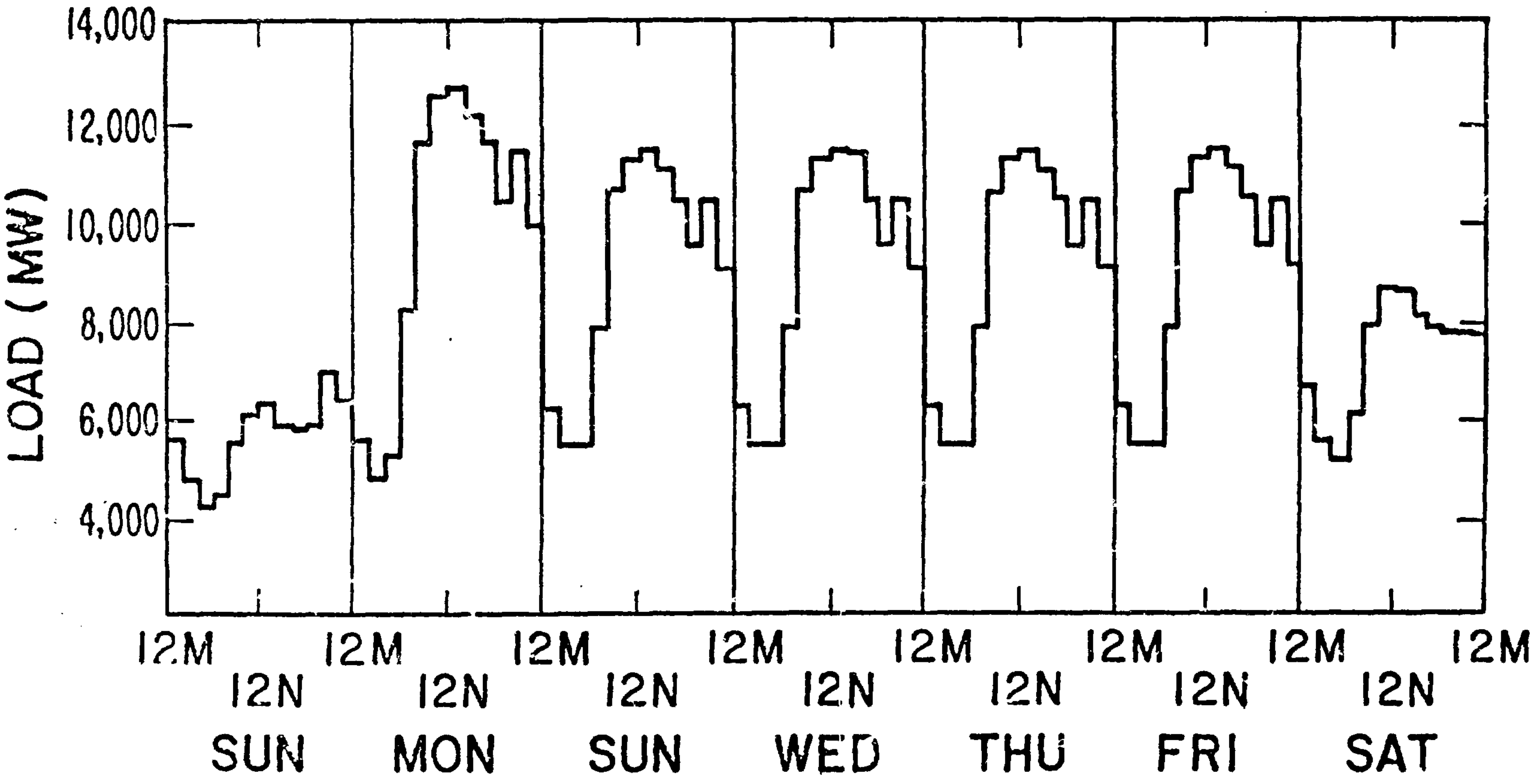

Fig. 4 Typical weekly load distribution for an electric utility.

stituted for oil and natural gas. If 5% of the electric energy used is generated by gas turbines and if energy storage units could replace half of this capacity, then the potential reduction in annual oil consumption would be about 4 x 10^8 bbl's.

A desirable energy storage unit should be efficient, inexpensive, easily sited, have no adverse environmental effects, and have a high energy denisty. Pumped-hydro storage has been used extensively and has been quite effective but is limited for want of desirable sites.

A SMES unit has several advantages for diurnal energy storage. It may be located near the load, which eliminates the need for additional transmission lines. It should have an efficiency of about 90% as compared with the 70% to 75% which is typical of pumped-hydro plants. Because of the fast response of the converter, a SMES unit should improve system stability and provide spinning reserve [21].

A SMES unit with the same capacity as the pumped-storage unit in Ludington, MI, which has a storage capacity of 15,000 MWh and a power capacity of 2076 MW, would be a solenoid about 340-m diam and 114-m high. Whereas Ludington cost \$351 x 10^6 in 1973 (or \$503 x 10^6 in 1978 based on 7% inflation), the estimated cost of an equivalent SMES unit is about \$480 x 10^6. This does not include transmission or other credits. Details of a unit with only slightly lower energy storage capacity are presented in Section IV.

The superconducting coil will be constructed several hundred meters underground in solid rock, which acts as a structural material. The rock contains the magnetic forces on the coil. A shield coil with a radius of about four times that of the main magnet wi[illegible] [illegible] located just below [illegible] magnetic fields in the vicinity of a SMES unit. It is possible to store large amounts of energy in a relatively small volume, because superconductors allow high magnetic fields. For example, the Ludington plant occupies about 10 $(km)^2$. The equivalent SMES unit would require only 1.5 $(km)^2$, including all the land area within a shield coil. Some of this land could be used for agricultural purposes.

B. System Stability and Short-Term Load Variations

The output of power generation plants must be adjusted to balance random and periodic load variations, such as those caused by steel rolling mills, arc furnaces, etc. The generators, which are cycled to meet these loads, experience reduced reliability and life expectancy.

An energy storage unit capable of leveling these short-term power variations would be of great value to a utility. The SMES units for diurnal load leveling might have a converter capacity of 1000 to 2000 MW. As the response time of the converter to a power demand is less than a cycle, it will be possible to meet these short-term power demands by varying the power in the converter by a few percent. This particular function could also be satisfied by a small SMES unit that stored only 100 to 500 MJ but had a converter capable of delivering 20 to 50 MW. Units of this type would have a 3-to-8-m diameter and could be fabricated by industry today.

Occasionally, load variations and the subsequent generation response cause an electrical power system to become unstable. System instabilities can be avoided by limiting the load variation, by changing the electrical characteristics of transmission lines, by reducing the time response of the generation plants, and/or by providing system damping.

One specific location where an energy storage device might improve the stability of a power system is on the intertie between the Pacific Northwest and southern California. Two ac lines and one dc line transmit power along this corridor. Under certain conditions an instability arises on the ac line.[22] This instability has been overcome by installing a feedback system that controls the converter power at the northern terminal of the dc line, thereby damping the power oscillation on the ac line. This solution is not completely satisfactory as the power flow on the ac line depends on the dc line working properly. If the dc line fails, the power flow on the ac line should increase to take up the load, rather than decrease because of reduced stability.

A small SMES unit, storing 30 MJ and having a 10-MW converter, could damp the oscillations which occur at a frequency of about 0.35 Hz. The LASL and the Bonneville Power Administration (BPA) are collaborating to determine if this type of storage device would be an effective and economical component for the BPA power system. Table I shows the major design parameters for the stabilizing unit. Much of the technology base for the 30-MJ coil has been established as a part of the fusion program pulsed inductive energy storage work.

C. Spinning Reserve

The electric power utilities are required to have a minimum spinning reserve capacity which amounts to about 10% of the load or 1.1 times the largest generation unit on line. This is equivalent to having an entire power plant continuously on line but not delivering power. The cost for this reserve is a burden to the utilities. It may be possible to substitute additional converter capacity on a large SMES unit for the spinning reserve. This can be accomplished by choosing the design voltage, current, and power capacity of a SMES unit always to have reserve capacity during normal scheduled operation. During the periods of low-power demand, 4 to 6 h at night, the storage unit can be charged at the maximum rate with the converter operating at full capacity. Spinning reserve on the system is achieved during this period through the ability of the converter to change from charge to partial charge or discharge in less than one cycle. During the times of day when the unit is neither charging nor discharging, the SMES unit will be a substitute for spinning reserve. During the longer periods of high-power demand, 8 to 12 h during the day, the energy storage capacity of the unit will normally be a fraction of the maximum converter capacity. The excess discharge capacity of the system may then take the place of the spinning reserve for the utility system.

TABLE I

DESIGN PARAMETERS FOR A 30-MJ SMES STABILIZING SYSTEM

Maximum power capacity	10	MW
Operating frequency	0.35	Hz
Energy exchange	9.1	MJ
Maximum stored energy	30	MJ
Magnet current at full charge	4.9	kA
Maximum field at full charge	2.8	T
Maximum magnet terminal voltage	2.2	kV
Magnet operating temperature	4.5	K
Magnet lifetime	$>10^7$	cycles
Heat load at 4.5 K	<150	W
Inductance	2.5	H
Mean coil radius	1.5	m
Coil height	1.2	m
Winding thickness	0.42	m

IV. A 10-GWh SMES SYSTEM DESIGN

The LASL is developing a reference design for a 10-GWh SMES unit for diurnal load leveling. One of the major purposes of a reference design is to provide a starting point for detailed engineering designs. Some of the parameters and the cost of this unit are given in Tables II and III.

A. Energy Storage Coil and Support Structure

The coil is a thin-walled, 300-m-diam, 100-m-high solenoid as shown in Fig. 5. The size and shape are the result of a cost optimization and the dimensions are determined by the maximum field. Other geometries such as toroids

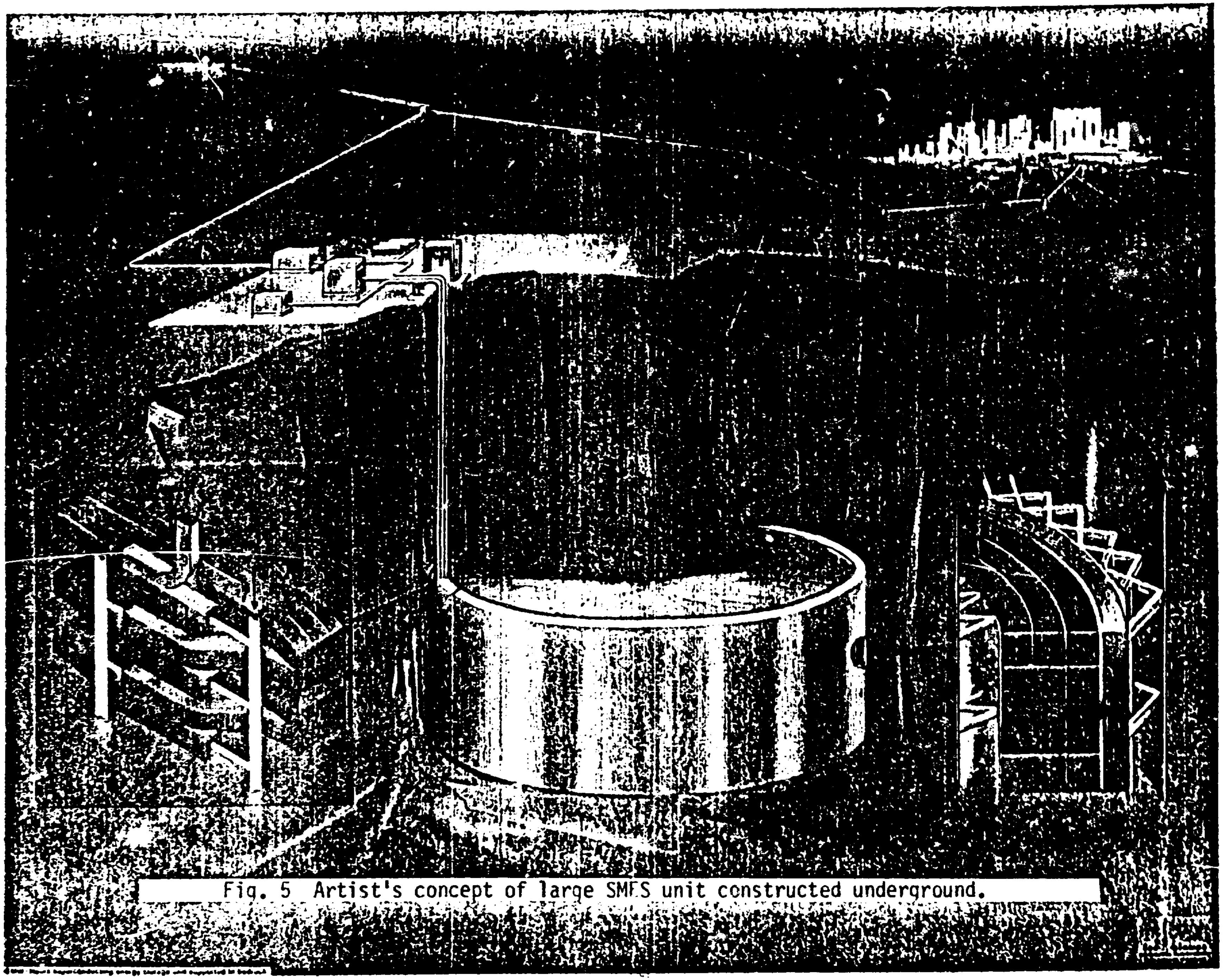

Fig. 5 Artist's concept of large SMES unit constructed underground.

have been considered, but they require such large quantities of superconductor that they are not economically attractive.

The magnetic forces must be contained by rock to reduce the cost of the system. If stainless steel bands, such as those used in large bubble chamber magnets, were used in a SMES coil, their cost alone would far exceed the cost of other types of storage systems. A set of struts and rods, as shown in Fig. 6, is required to transmit the forces from the magnet at 1.8 K to the rock at about 300 K.

The arrangement in Fig. 6 allows both the axial-compressive forces and the radial-expansive forces to be transmitted to the rock. The stresses and deflections associated with the thermally induced contraction of the magnet during cooldown and the magnetic (Lorentz) forces on the conductor are taken up by rippling as shown at the top of the figure. The axial loads are allowed to accumulate until they reach the allowable stress in the conductor, about 138 MPa (20000 psi), then they are transmitted through struts to the rock. This is easily accomplished if the parts of the magnet closer to the midplane are stepped inward to have a slightly smaller radius.

The coil will be placed at a level below the surface of the earth where the compressive stresses in the rock are larger than the tensile stresses produced by the magnet. Thus the rock will always remain in compression, but the magnitude of the compressive stress will decrease and increase as the magnet is charged and discharged.

B. Conductor

Superconductor for a SMES coil must be reliable (this includes but is not limited to stability considerations), must cost as little as possible, must be capable of being fabricated with existing techniques or extensions of those techniques, and must be flexible enough to be wound into a magnet in a 3-m-wide tunnel.

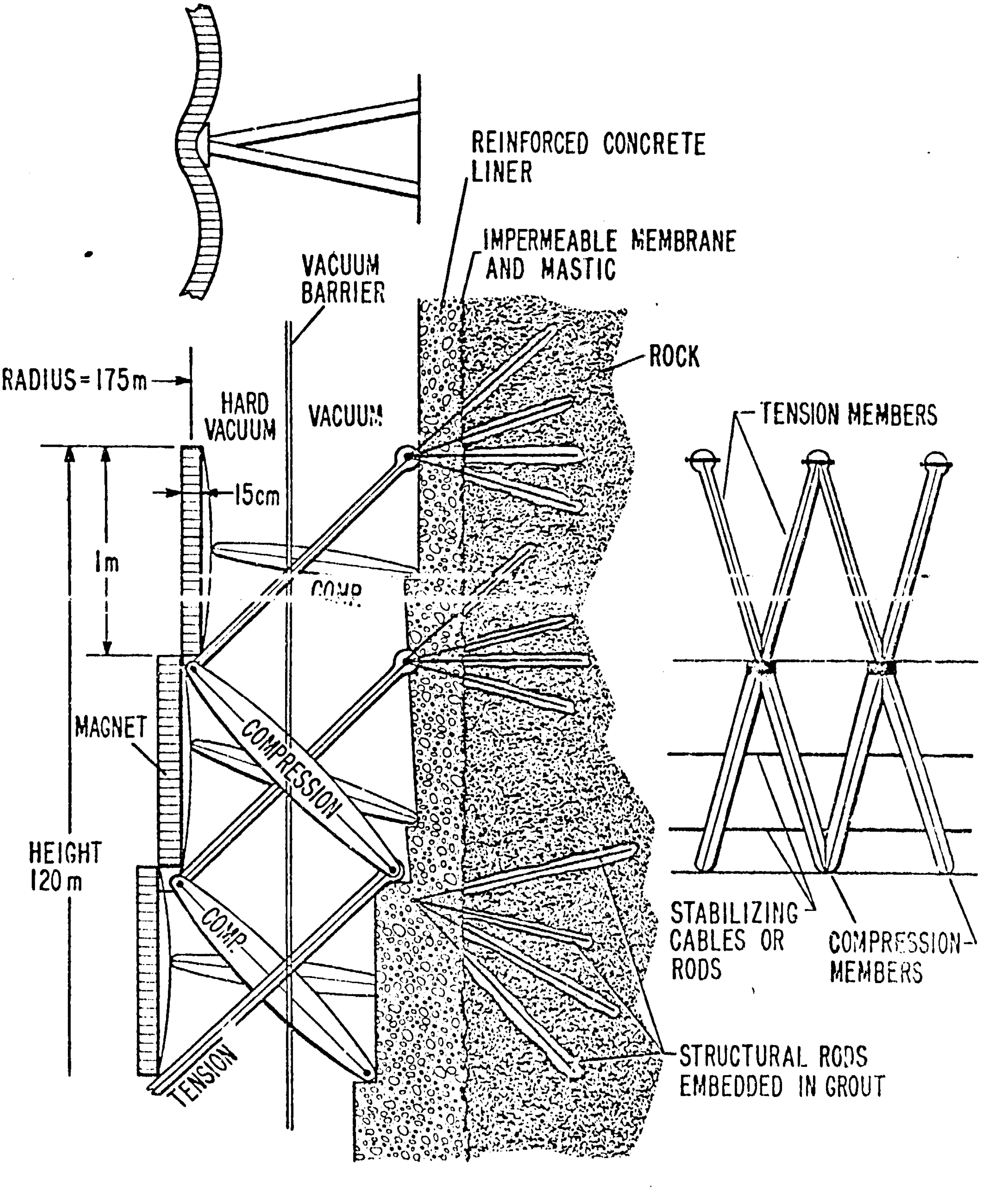

Fig. 6 Magnet and support structure cross section of a 10-GWh SMES unit.

TABLE II

SMES 10-GWh REFERENCE DESIGN ENERGY STORAGE COIL SPECIFICATIONS

Energy stored at full charge	4.6×10^{13} J (12.8 GWh)
Energy stored at end of discharge	1.1×10^{13} J (0.31 GWh)
Current at full charge	50 kA
Current at end of discharge	24.4 kA
Maximum power output or input	2500 MW
Terminal voltage to provide P_{max} at end of discharge	103 kV
Inductance	37 kH
Maximum field at conductor at full charge	4.5 T
Operating temperature	1.85 K
Mean coil radius	150 m
Coil height	100 m
Coil radial thickness	260 mm
Number of turns	9937
Number of radial turns	5
Winding pattern	Double Pancake
Conductor length	9.39×10^{6} m
Conductor mass	9.57×10^{6} kg

TABLE III

COST OF A 10-GWh ENERGY EXCHANGE SMES UNIT
BASED ON 1.3 X 10^4 MWh MAXIMUM STORED ENERGY,
89% EFFICIENCY FOR A 24 h CYCLE (GIVING A NET OUTPUT OF 9500 MWh),
1.8 K OPERATION, AND 10^{-10} Ω-m RESISTIVITY ALUMINUM AT 5T

(millions of dollars)

Material costs	91.9
Fabrication costs	66.1
Assembly costs	74.2
Rock excavation 1.9×10^5 m^3 @ \$50/m^3	9.5
Helium	9.0
Refrigerator	20.5
Construction cost	271.2
Engineering at 12%	32.5
Total	303.7
Storage cost $\frac{\$303.7 \times 10^6}{9.5 \times 10^6 \text{ kWh}}$	\$32/kWh

The criteria of minimum cost affects the overall magnet design and operation. Operation at 1.8 K rather than at 4 to 6 K and the use of NbTi rather than Nb_3Sn reduce the total system cost considerably. The use of high purity aluminum instead of copper as the current stabilizer reduces the cost and the size of the conductor.

To fabricate the conductor with existing techniques, a design has been chosen in which the NbTi is extruded in copper and the aluminum is added in subsequent fabrication steps. To meet the flexibility criterion, a conductor design was selected in which several insulated subconductors are in parallel electrically and are cabled to reduce hysteretic losses. One of the several possible conductor configurations that meet these criteria is shown in Fig. 7.

C. Converter

Line-commutated, solid-state converters are being used extensively in high-voltage, dc-power transmission. In comparison, converters for large SMES systems will have medium to high voltage and current ratings. A SMES system with 10-GWh energy extraction and a 4-h charging time will require a charging power of 2500 MW. Because of the purely inductive load and the requirement that the maximum power be available at all operating currents, the maximum voltage and maximum current do not occur at the same time. Thus, the converter has to be designed for a power greater than the maximum power flow ever expected through the converter. For the 10-GWh unit the voltage rating is 103 kV and the current rating is 50 kA.

Phase-controlled converters generate harmonics and absorb reactive power. Advanced converter circuits are used to minimize these unwanted effects. The harmonic content of the ac-line current is reduced by using 12-pulse or 24-pulse instead of 6-pulse converter modules. Tuned filter networks can remove the remaining harmonics. The reactive power requirement for phase-delay angles around 90° is especially critical when the power factor is close to zero. The reactive

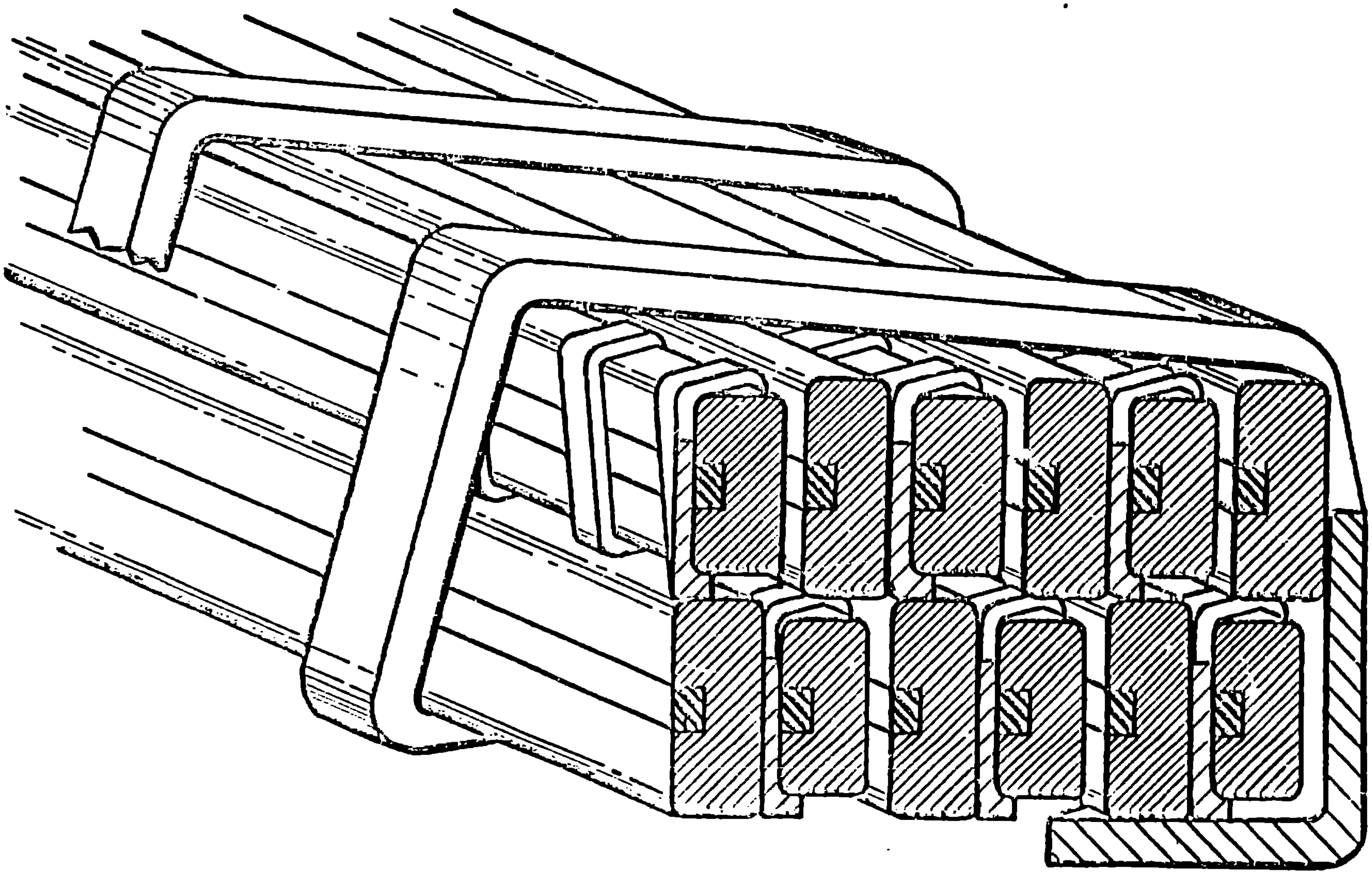

Fig. 7 Possible advanced conductor design using modular conductor as components.

power requirement can be reduced by subdividing the converter into several series connected modules. During operation, the phase-delay angles of all but one module are kept at 0°. That one module has a phase-delay angle that depends on the voltage requirement. All those converter modules at 0° require only a small amount of reactive power caused by commutation. By neglecting the commutating reactances, a converter subdived into n modules would require n times less reactive power than a single converter.

Figure 8 shows one possible circuit configuration of a converter for a 10-GWh SMES system. To reduce the reactive power requirement, the converter is designed as a series connection of four 12-pulse modules each with its own power transformer. Each module is designed for 25.8 kV at maximum current, 50 kA, and consists of two 6-pulse bridges connected in parallel by an interphase reactor which balances the current flow in the two bridges. At maximum coil current, each 6-pulse bridge will provide 25 kA dc. Each 12-pulse module can be bypassed by a mechanical switch when the module voltage is zero and then the module can be disconnected from the 3-phase bus. This improves the overall converter efficiency by removing the forward voltage drop of at lease four series-connected thyristors.

The installed converter power rating and the converter cost can be decreased by designing those modules which are switched out of the circuit first (i.e. at a low current) for the current at which they are switched off, rather than for the maximum current. Theoretically, if there were an infinite number of converter modules, the converter could be designed for a rating $P_{max} (1 + \ln (I_{max}/I_{min}))$ instead of $P_{max} I_{max}/I_{min}$. Because four converter modules having ratings of about 25 kV will be used, the theoretical limit may be approached in a 100-kV converter. This module switching scheme will result in savings for SMES systems with a large discharge depth.

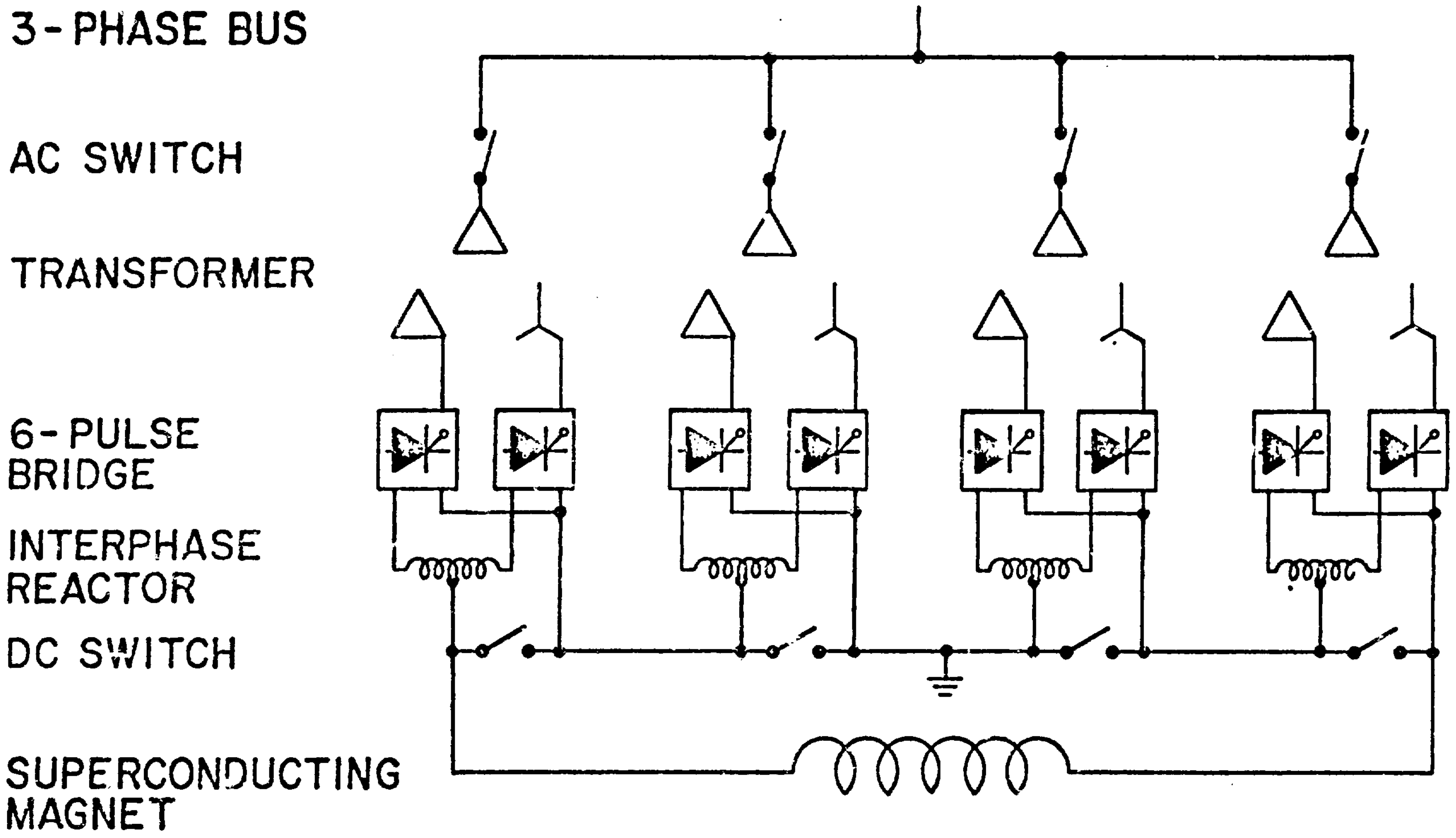

Fig. 8 Four series connected 12-pulse converter modules forming a converter,

V. SMALL-SCALE SMES SYSTEM TEST

Although large SMES units, storing up to 10-GWh, are not expected to be built before the year 2000, their performance and electrical behavior can be predicted by computer studies or small-scale tests. A small-scale system, which included all the components described in Section II except the refrigerator, was tested to evaluate the electrical characteristics of a SMES unit.[23]

The system shown in Fig. 9 contained a 70-H superconducting coil built by stacking eight 3000-turn coils in series. The quench current above which the 70-H coil lost its superconducting property was 45 A. A 12-pulse, solid-state converter and a power transformer with a 6-phase secondary winding interfaced the magnet to the 3-phase laboratory bus. The maximum converter output voltage used in the experiment was 150 V.

The control system for the model SMES unit was designed with all the features necessary for the automatic operation of a large SMES unit on the utility bus. The total system consisted of the converter, bridge 1 and 2 in Fig. 9; the feedback controller: and one digital controller for each bridge. The closed-loop system was a power control loop. The "power reference" is the demand signal that, depending upon the field of application, can come from a power system dispatcher, a preprogrammed source, or from a change of the line frequency. The power of the superconducting coil is adjusted to equal this power demand.

The feedback controller consisted mainly of a division circuit and a power controller. It determined how the digital controllers must change the phase-delay angle to adjust the output voltage of each bridge to meet the new power demand. The power controller was used for fine regulation, while the computed voltage demand signal provided coarse regulation.

Controllers for the lower and upper current limits were included to prevent operation of the SMES unit outside the current limits. For symmetrical

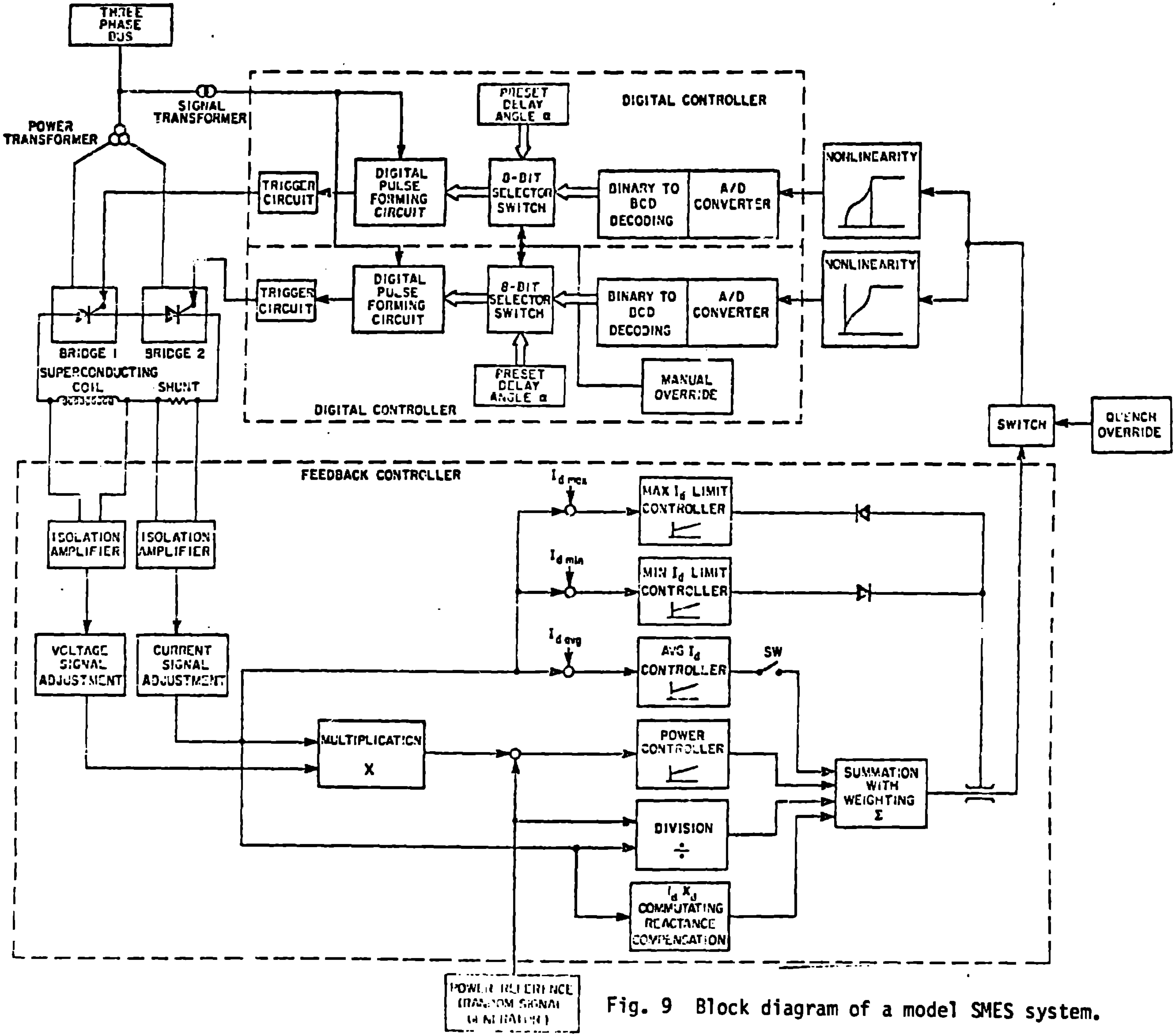

Fig. 9 Block diagram of a model SMES system.

power references with an average power of zero, an average-current controller should be included. This controller kept the average magnet current constant and counteracted any dc-offset voltages in the control circuitry, thereby preventing the drift of the current to one of the limits.

Each digital controller was a pulse forming network that generates thyristor gate pulses. The gate pulses were delayed in phase relative to the zero crossing of the line voltage by an angle varying from 0° to nearly 180°, as determined by the control system. The control circuitry compensated for the nonlinear relationship between the bridge output voltage and the phase-delay angle and provided, consecutive voltage control to reduce the reactive power requirement of the converter.

The total system was tested with different power demands. The transition time for rectifier-inverter and for inverter-rectifier switching was measured to be 5 to 6 ms. Figure 10 shows the coil current, coil voltage, and coil power for random power demand. Because of the fast time response of the converter, the coil power followed the power demand closely. The response to sinusoidal power demands was measured at frequencies up to 30-Hz. The fixed time delay of five to six milliseconds in the converter resulted in more phase shift between the power demand and the actual coil power for higher frequency power demands. No control system instabilities were observed during the experiments with a superconducting magnet, even with 30-Hz sinusoidal power demands.

VI. INDUCTIVE ENERGY STORAGE FOR FUSION

A. Theta-Pinch Magnetic Energy Transfer and Storage (METS)

The METS inductive energy storage system was developed to deliver 488 MJ in 0.7 ms to a 40-m radius toroidal theta-pinch system, called the Scyllac Fusion Test Reactor (SFTR), [24] for adiabatic compression of a fusion plasma.

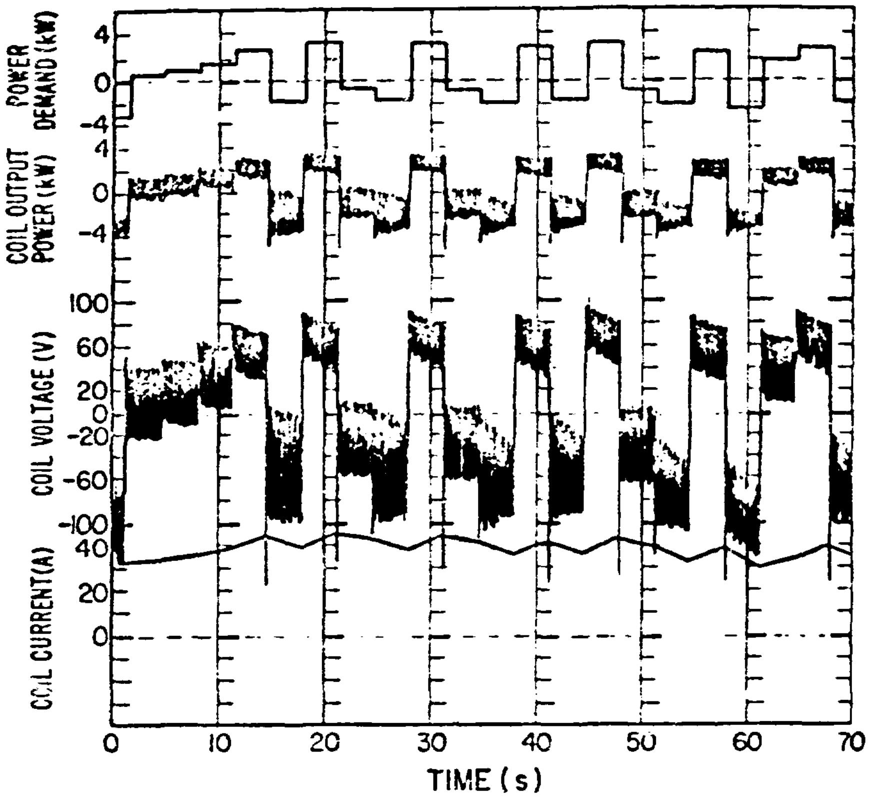

Fig. 10 Coil voltage, current, and power response to a random power demand signal (L=33H).

A design optimization study [25] for the METS system [26] led to modular energy storage coils of approximately 400-kJ size. These were to be charged in series and discharged in parallel for a nearly 100% efficient energy transfer.

The theta-pinch, METS system is characterized by the resonant circuit of Fig. 11. Coil charging is accomplished with a shunt switch external to the dewar. Discharge is initiated by opening the shunt followed by opening of the HVDC interrupter, B. The interrupter is counterpulsed to extinguish the arc by a current from the transfer capacitor, C_t, which has been back charged. Current then transfers to the compression coil with a peak voltage across the circuit developing at one-half the transfer period. The energy is then trapped in the compression coil by closing the ignitron crowbar, IG_{CB}, for the fusion burn cycle to be completed during the 250-ms L/R decay time of the loop.

The combined modular circuits of Fig. 11 are shown in Fig. 12 which is representative of four such modules out of 1280 required, 10 coils in each of 128 dewars, to provide the 488 MJ. The superconducting energy storage coils, connected in series, are, after being charged, disconnected from the power supply by the opening of the external circuit breaker shown at the top of the figure. This forces the current into the parallel loop vacuum interrupters, B_2. The no-load cryogenic disconnects between coils are then opened to isolate each module. The B_2 switches are then opened mechanically and counterpulsed to extinguish the arc to effect their electrical opening. The resonant L-C-L circuits are thus established and the energy transfers to the compression coils where it is trapped for a 250-ms e-folding, L/R decay by closure of the crowbar switches B_4 and B_5.

The parameters for the METS coils made by LASL and Westinghouse are listed in Table IV. The coil made by LASL used a monolithic, copper matrix, NbTi superconductor manufactured by Magnetics Corporation of America (MCA). The conductor had 2640 filaments and measured 0.508 cm by 1.016 cm. The matrix ratio

PROTOTYPE METS CIRCUIT

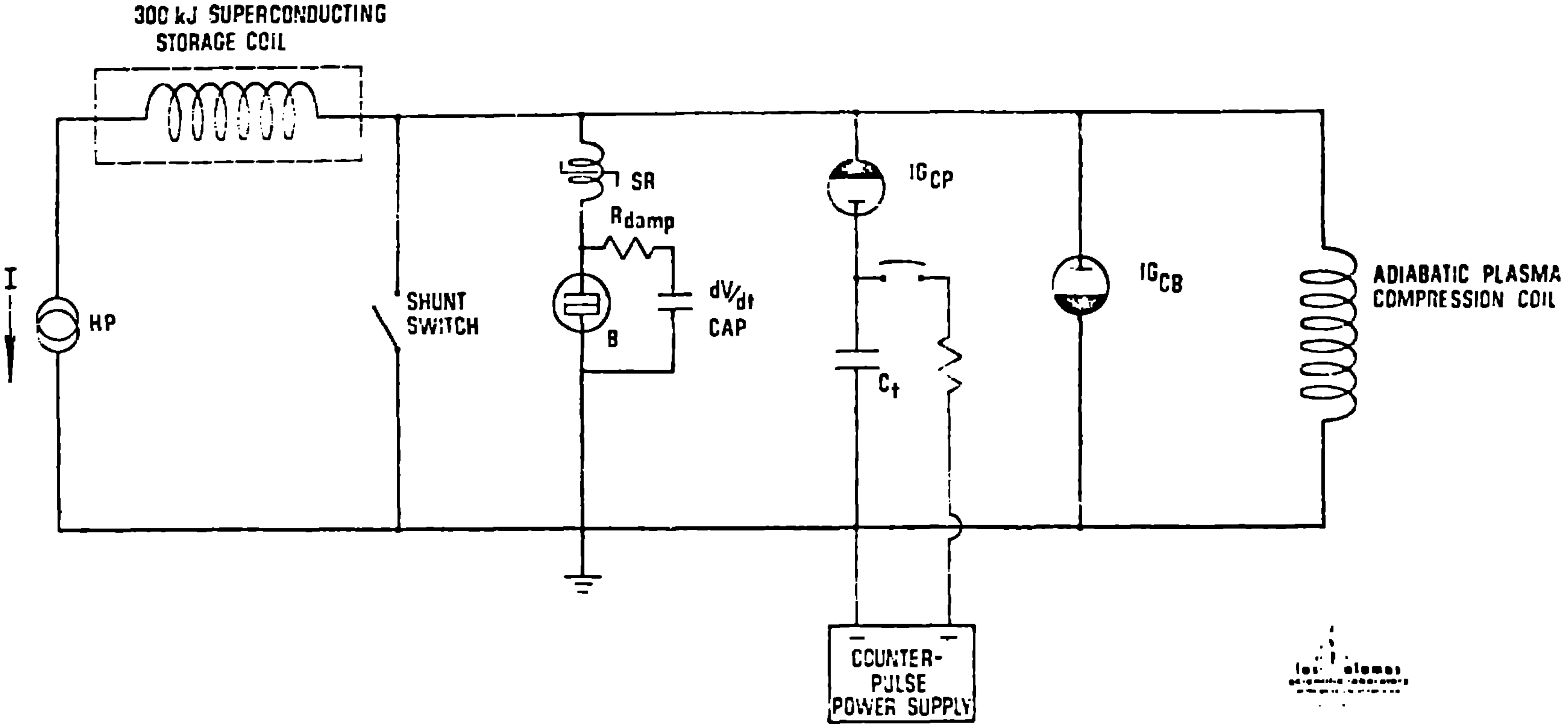

Fig. 11 Prototype SFTR-METS circuit.

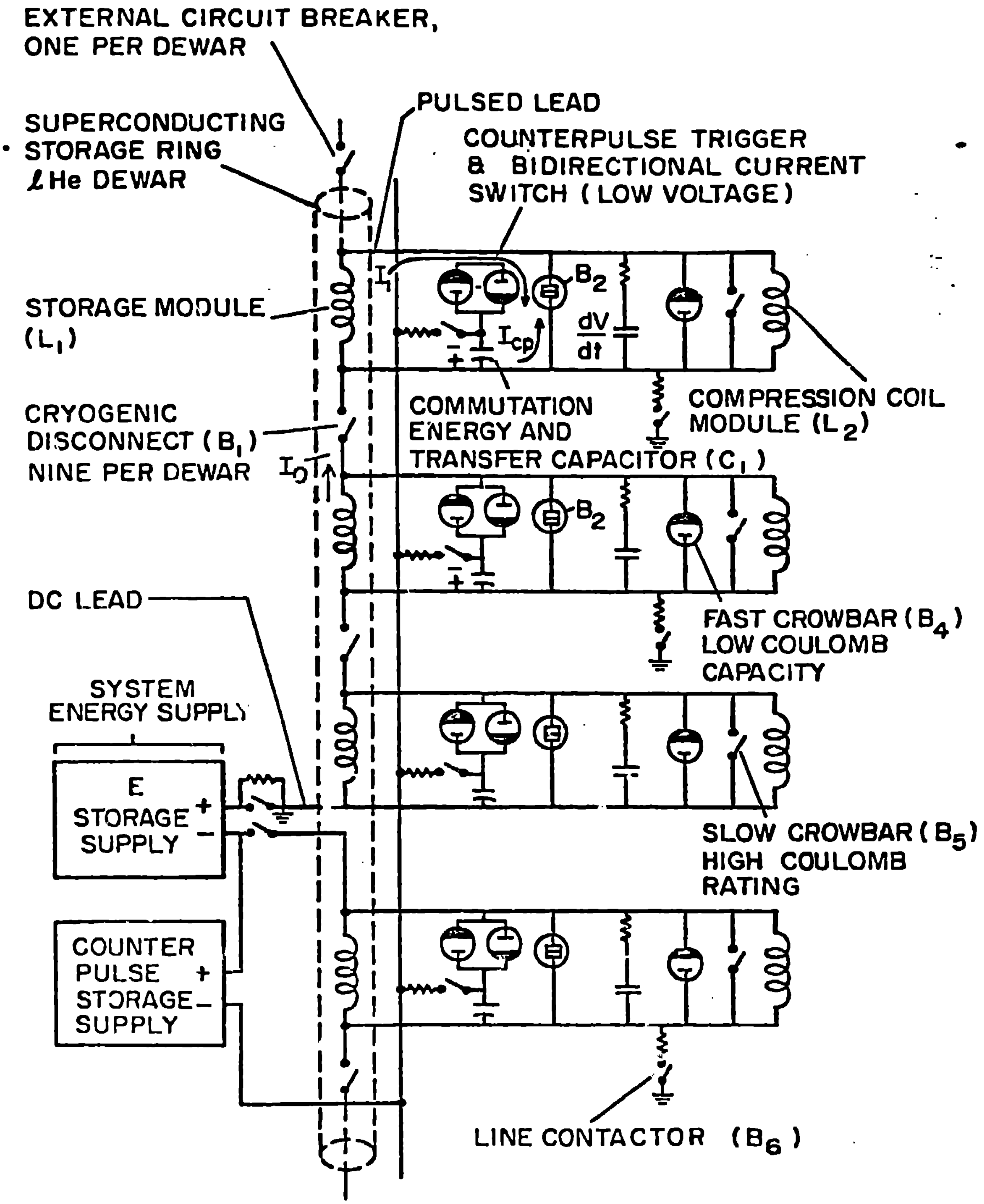

Fig. 12 SFTR-METS circuit.

TABLE IV

PARAMETERS OF 300-kJ ENERGY STORAGE COILS

	LASL	Westinghouse
Inductance, mH	4.87	6.05
Resistance at 20°C, Ω	0.0896	0.165
Stored energy at 10 kA, kJ	244	302
Length, cm	73.0	79.1
Mean radius, cm	28.7	25.5
Winding thickness, cm	0.508	4.74
Number of turns	122.5	159.5
Number of layers	1	4
Central field at 10 kA, T	1.82	2.13
Conductor support method	self-supporting	toothed coil form
Matrix ratio, Cu:NbTi	6:1	2.5:1
Wire diameter, mm	-	0.813
Filament diameter, μm	32.3	18
Number of filaments per wire	2640	529
Wire twist pitch, cm^{-1}	0.13	1.42
Number of active wires in cable	1	72
Type of transposition	none	Roebel transposition
Cable width, cm	1.016	1.68
Cable thickness, cm	0.508	0.84

was six, and the twist pitch was one per 7.7 cm. The central region of conductor was void of NbTi filaments. The alloy was 45% Ti by weight. The conductor, depending upon its orientation, tested at 9 to 12 kA limiting short sample current [27], i.e., 9 to 12 kA before losing its superconducting properties. The coil is a single layer, edge wound solenoid, 56.3-cm i.d. by 73.0-cm long and has 122.5 turns. The conductor is fiber glass tape wrapped, wound under tension onto a G10 epoxy-fiber glass cylindrical form, and epoxy potted onto the form.

The coil tested successfully to 12.5 kA and 386 kJ of energy stored. It was pulse tested at 10 kA and 35 kV and with transfer times as short as 1 ms in an L-C-L circuit as shown in Fig. 11.

The 300-kJ coil, designed and fabricated by Westinghouse Electric Corp.,[28] was made with a 72-active-strand Cu matrix, NbTi superconducting cable. The conductor was manufactured by MCA and the cable by Westinghouse. The Cu to NbTi matrix ratio for the 0.81-mm o.d. wire is 2.5 with 529 NbTi filaments. The 10-kA cable has twelve sub-bundles of six active strands wrapped around a seventh strand. The sub-bundles are wrapped around a Kapton* insulated stainless steel strap. The wire specification required 280 A[$2(10)^5$ A/cm^2] short sample critical current at 2.5 T and 10^{-13} ohm-cm and tested at +21% to -6% of this value. The wire has a twist pitch of 1.42 cm and is Westinghouse Omega insulated.

The limiting transport current was measured by the method reported by Miranda and Rogers.[27] The results are given in the graph of Fig. 13. The scatter in data is inherent in the test method used and is not a characteristic of the cable.

The coil is a four-layer solenoid with the cable wrapped under tension in close fitting helical grooves onto cylindrical concentric epoxy-fiber glass forms. Each winding layer is overwrapped with fiber glass, B-stage epoxy-fiber glass, and Kapton. Forty kilovolts standoff is provided by the ends of the coil forms

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*duPont trademark.

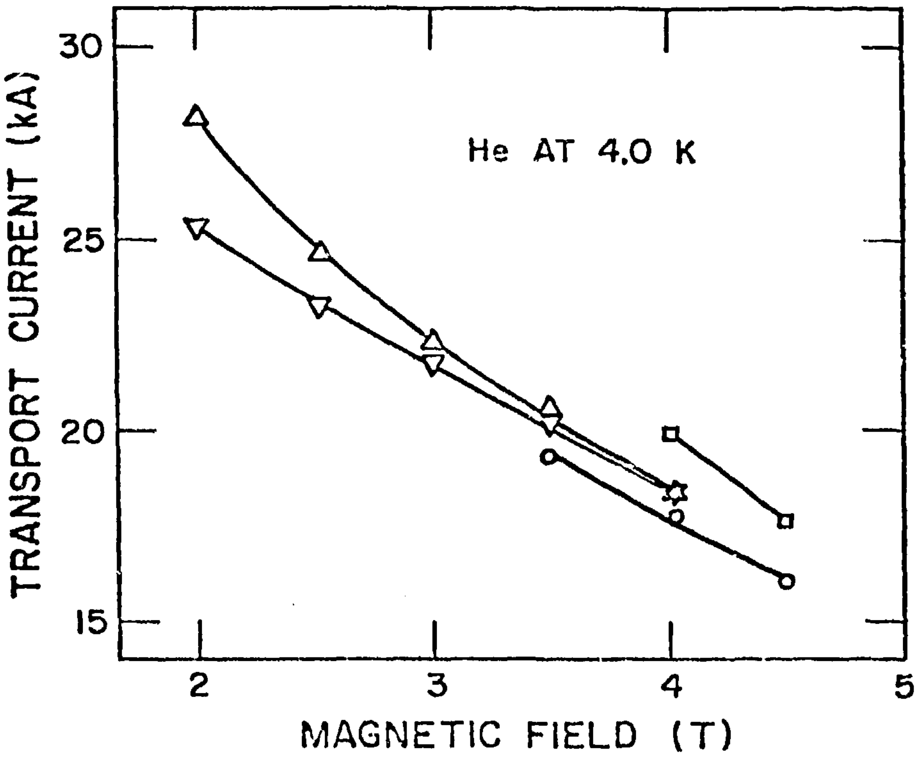

Fig. 13 Limiting transport current of the entire 84 strand 300-kJ Westinghouse conductor. Only 72 strands were active in the coil.

and overwrap extended beyond the conductor windings. The winding is highly ventilated with vertical slots in each coil form. Good contact with the ℓHe bath is achieved. The coil, as the fourth winding layer is being completed, is shown in Fig. 14.

The coil was operated with pulsed energy transfer at the 300-kJ level for 50 cycles. This was the nominal design level of 10 kA and 2.23-T central field on the winding. The energy transfer period was 2.4 ms. The coil was then charged to 13.4 kA and 2.99 T for a stored energy of 0.54 MJ. This energy was pulsed from the coil with transfer voltages near 40 kV. A fast transfer at reduced energy with a 1-ms time safely reached 58 kV.

B. <u>Tokamak Ohmic-Heating and Burn Cycle Simulation</u>

The Westinghouse-METS coil was also used to demonstrate the use of superconducting magnetic energy storage in a simulated tokamak ohmic-heating and burn cycle.[19] This performance, although much more demanding than that required for the 30-MJ SMES unit intended for the BPA system, establishes the feasibility for use of such units for transmission line stabilization.

Figure 15 gives the circuit used for bipolar operation of the coil in conjunction with a commutated dc generator acting as a mechanical capacitor. Figure 16 shows the oscilloscope trace of the experimental current. The storage coil was first charged to -12 kA with a continuous duty dc-homopolar and then oscillated through zero current to near +5 kA by connecting it in parallel with the dc generator. The damped half sinusoidal energy transfer corresponds to the energy change expected to be consumed in plasma heating in a tokamak. After this bipolar operation, the rectifier bank (power supply) was connected across the coil to charge it to +12 kA. This corresponds to the burn phase of the tokamak cycle. The entire cycle can then be repeated; however, the trace of Fig. 16 was concluded by ringing the energy out in the dissipative resistance of the coil, dc-generator parallel loop.

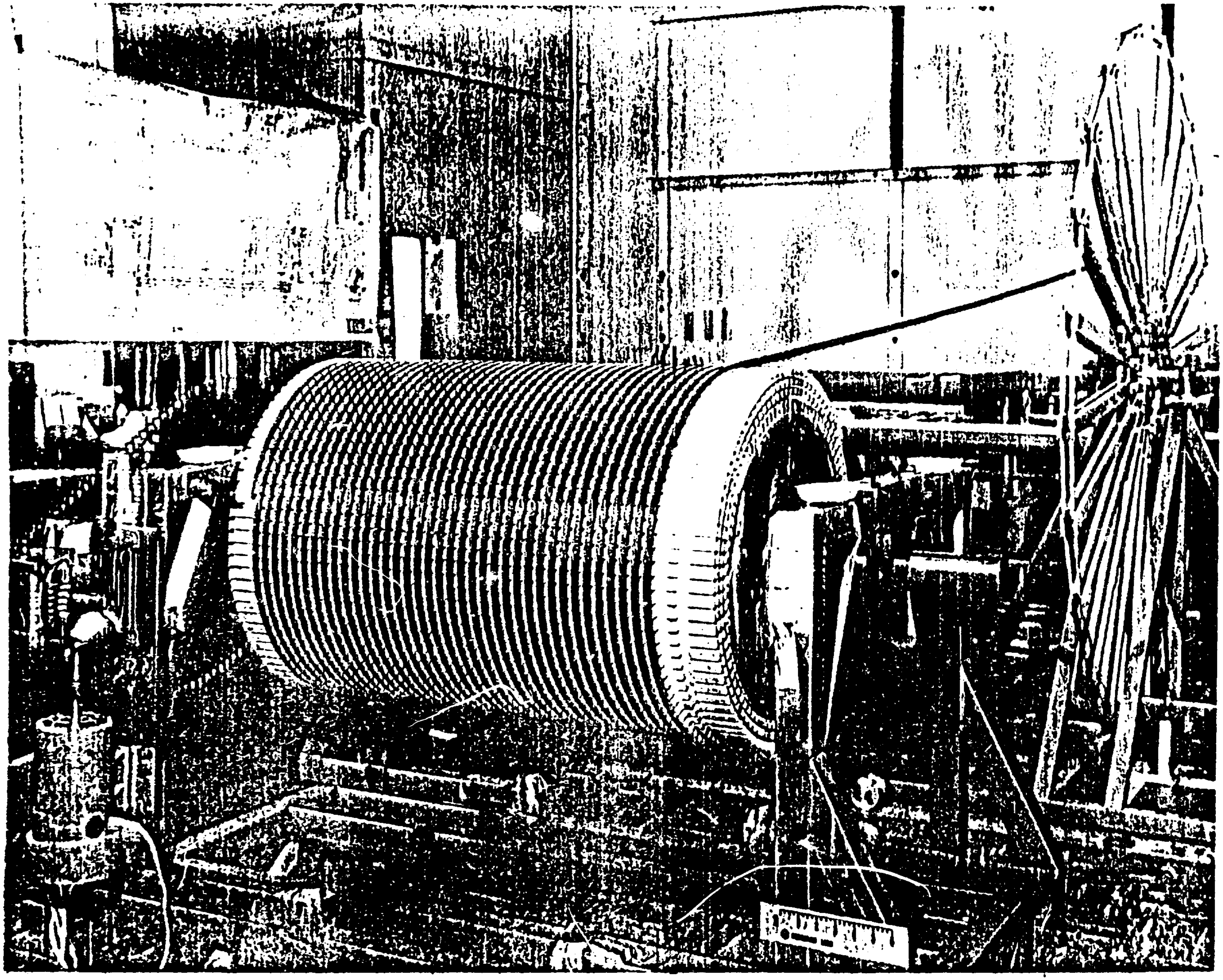

Fig. 14 300-kJ Westinghouse coil during fabrication.

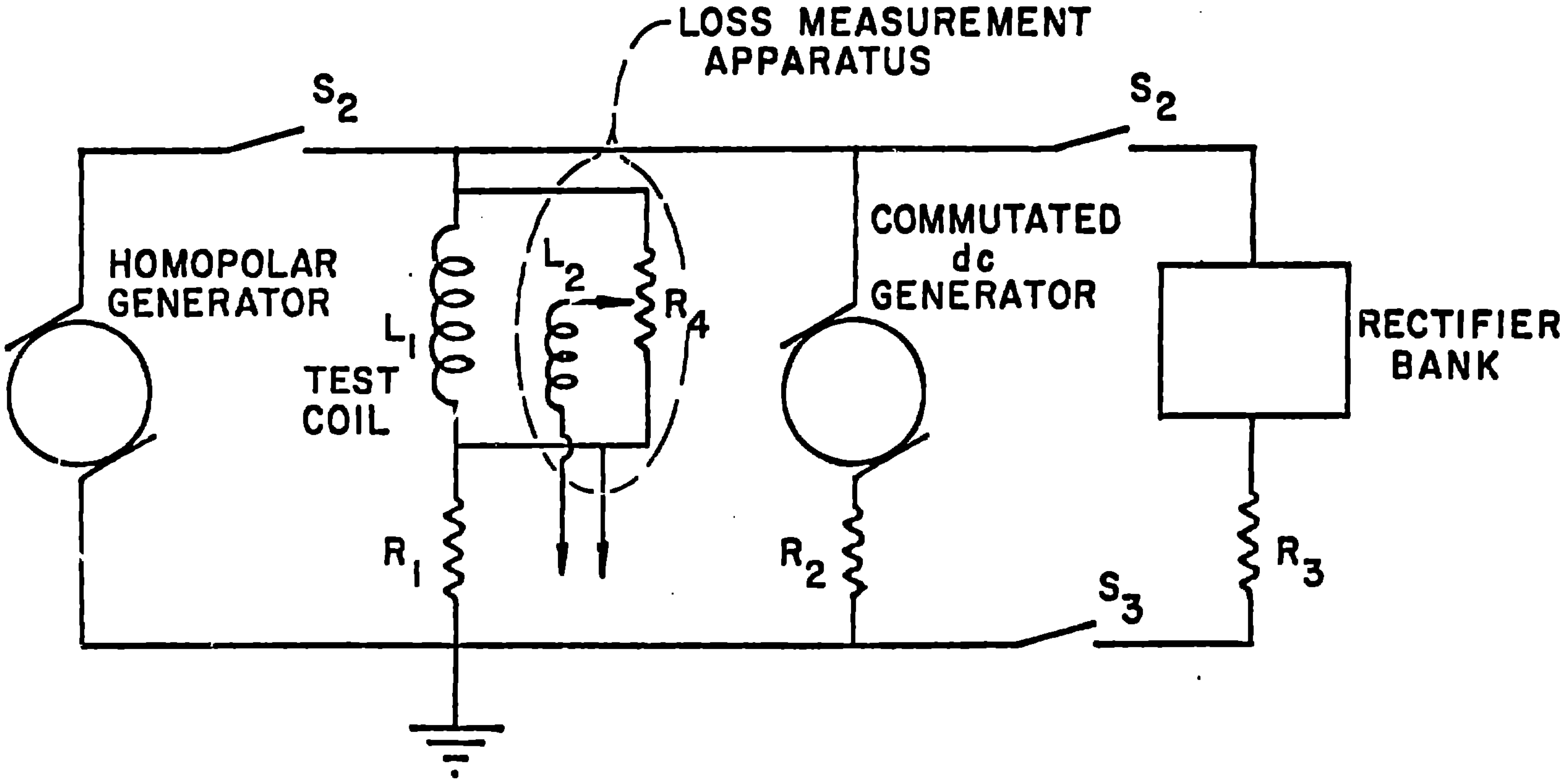

Fig. 15 Circuit for operation of the Westinghouse-METS coil in a tokamak ohmic-heating cycle.

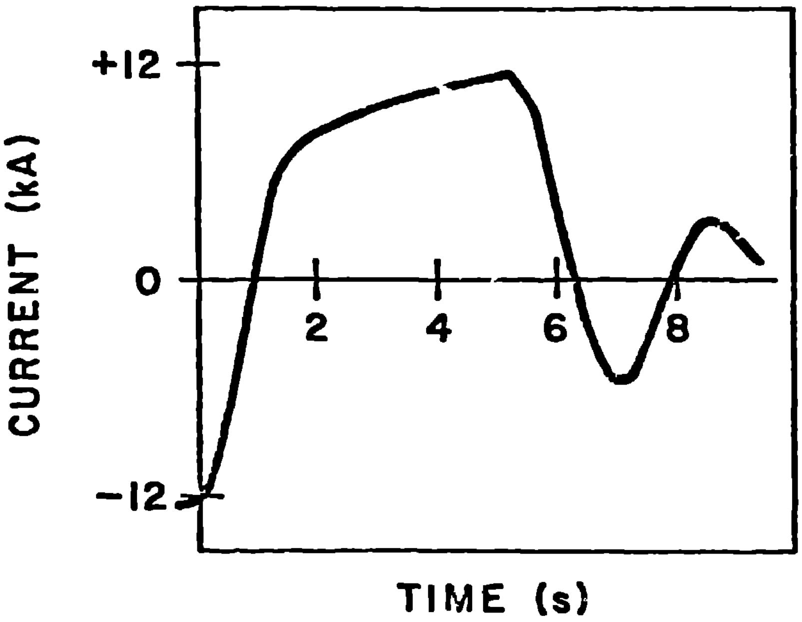

Fig. 16 Oscilloscope trace of current versus time of the experimental tokamak ohmic-heating cycle.

VII. CONCLUSIONS

Superconducting magnetic energy storage units should prove to be effective components of electric power systems. These devices can be used for load leveling and peak shaving, can satisfy spinning reserve requirements, and can improve system stability. The fast time response of the control system will allow a fairly small SMES unit to damp oscillations on power systems. Significant technology advances with magnetic energy transfer and storage for fusion applications have demonstrated the feasibility of superconducting, inductive energy storage coils as useful electrical circuit elements. Much of the METS coil design detail of the superconducting cable and the structure is directly adaptable to the SMES stabilizing unit.

ACKNOWLEDGEMENT

The authors wish to thank R. I. Schermer, W. S. Ranken, W. D. Smith, R. D. Turner, P. Thullen, J. D. G. Lindsay, and D. M. Weldon for their work contributing to this paper.

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