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SUPERCONDUCTING MAGNETIC ENERGY STORAGE

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ABSTRACT

The U.S. electric utility industry transmits power to customers at a rate equivalent to only 60% of generating capacity because, on an annual basis, the demand for power is not constant. Load leveling and peak shaving units of various types are being used to increase the utilization of the base load nuclear and fossil power plants. The Los Alamos Scientific Laboratory (LASL) is developing superconducting magnetic energy storage (SMES) systems which will store and deliver electrical energy for the purpose of load leveling, peak shaving, and the stabilization of electric utility networks. This technology may prove to be an effective means of storing energy for the electric utilities because a) it has a high efficiency ($\sim$ 90%), b) it may improve system stability through the fast response of the converter, and c) there should be fewer siting restrictions than for other load leveling systems. A general SMES system and a reference design for a 10-GWh unit for load leveling are described; and the results of some recent converter tests are presented.

I. INTRODUCTION

Electric utilities in the U.S. experience periodic load variations on a seasonal, weekly, and daily basis. In many cases the daily maximum and minimum load of a power company will vary 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 and 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 even the load distribution.

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. It has been estimated that by 1990 energy storage units with a power capacity as high as 12% of the installed generation can be used for peaking purposes.

Of all the possible energy storage methods proposed, only pumped-hydro storage[1] with units up to 15 000 MWh has been used very effectively. Other energy storage technologies being developed for use in the electric utility industry include chemical storage in the form of batteries and hydrogen, thermal storage, compressed air storage, and magnetic storage. Economic considerations eliminate inertial storage in flywheels for utility applications. Most of these storage technologies are at the stage of development where they are technically feasible but are not economically competitive with gas turbines. Engineering development will be required to bring each of these technologies into a competitive position.

Superconducting magnetic energy storage (SMES) has several attractive features:

1. SMES units will have few site restrictions. Pumped-hydro and compressed air storage require specific rock structures, abundant water, aquifers, etc. Large SMES units can be constructed in the rock formations near most large load centers. Thus extensive new transmission systems will not be required.

2. SMES units will have a fast response to power system demand. The transition from storing energy to delivering energy and vice versa occurs in less than a cycle. This fast response of a SMES unit can improve power system stability.

3. SMES units should have a high efficiency. The power requirement for 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 80% efficiency for pumped hydro, compressed air, and battery storage.

4. It has been estimated[2,3] that the cost for a large SMES unit (10^4 MWh) will be about 30 $/kWh. This cost is competitive with costs for pumped hydro, advanced batteries, and compressed air storage plants.

The Los Alamos Scientific Laboratory (LASL)[4] and the University of Wisconsin[5] are developing superconducting magnetic energy storage systems for electric utility applications. These systems range in size from small units a few meters in diameter and height which will store 30 to 50 MJ (8.3 to 13.8 kWh) up to large installations several hundred meters in diameter and height which will store as much as 10,000 MWh.

This paper briefly discusses the major components of a superconducting magnetic energy storage system and the potential areas of application. Details of a reference design for a 10^4-MWh unit and electrical tests with a 100-kJ model SMES system are presented.

II. SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM DESCRIPTION

The several components of a SMES system are shown in Fig. 1. The superconducting magnet is immersed in a liquid helium bath, which keeps it superconducting at a temperature below 4.5 K. A closed-cycle refrigeration system cools and liquefies the boiloff helium gas and returns it to the liquid bath. The magnet which, for economic reasons, will be a short solenoid, with a ratio of height to diameter of 1/3, is connected to a 3-phase utility bus by means of a transformer and a converter. The line-commutated converter regulates the power flow between the SMES unit and the utility bus. During the charge phase

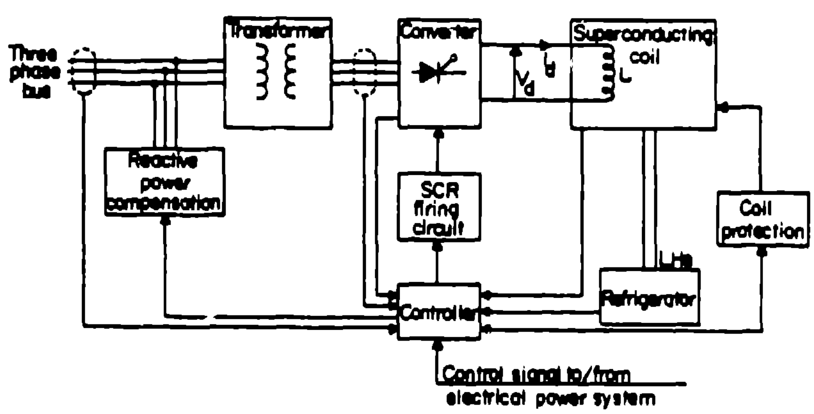

Fig. 1. Major components of a superconducting magnetic energy storage system.

of the energy storage cycle, the converter is operated as a rectifier to convert ac to dc power for charging the magnet. The 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 but modern mercury vapor valves could be used in large SMES converters should the valves prove to be more economical than the solid-state units.

Phase angle control of the thyristors in the converter determines the dc output voltage, V_d, which can be varied between its maximum value, $V_{d\ max}$, in the full rectifier mode and its minimum value, $-V_{d\ max}$, in the inverter mode. Because of the unidirectional current flow in the thyristors, the converter power can be reversed simply by reversing the sign of the bridge voltage. For positive V_d the magnet current increases and the magnet charges. When the converter voltage is made negative the magnet will discharge as the current decreases.

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 use 12-pulse or even higher pulse number converters. Converters with a high pulse number have inherent advantages with respect to the reactive power requirement and harmonic content of the line currents. These improvements will justify the increased cost for the transformer, the converter, and the more complex control system.

A unique characteristic of a SMES system, compared to storage systems which use electromechanical energy conversion, is its ability to almost instantaneously switch from one operating mode to another. Ideally, the average switching time for the converter from the rectifier mode into the inverter mode and vise-versa is one fourth of a period of the bus frequency. This time does not depend upon the pulse number of the line-commutated converter, but assumes no time delay is necessary to establish the proper thyristor gating sequence. In practice, however, the gating control of a 60-Hz converter requires one to three milliseconds to generate the correct gating sequence following a change in demand input.

This rapid time response should make a SMES system attractive for improving the transient stability of a power system, in addition to satisfying peak-shaving and load leveling requirements.

III. APPLICATIONS

The load experienced by the electric utilities varies periodically on a seasonal, weekly, and daily basis, and randomly during shorter 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 cycling the power output of one or more power plants on the system. Each of these load variations is discussed below and an SMES unit which might meet the power and energy requirements of a utility is described.

A. Load Leveling

The load variations experienced by a utility on a daily basis may be as great as a factor of three, although a factor of 1.3 to 2 is typical. A representative weekly load curve is shown in Fig. 2.

The power companies are required to meet all power demands. Generally this is accomplished by a combination of three or more types of power generation.

1. The base load generation, which supplies about 70% of the energy requirements of a system and has about 40 to 50% of the peak capacity, is furnished by the more efficient fossil fueled or nuclear power plants. These units operate most efficiently at rated power output and most reliably when not subject to power variations.

2. The intermediate load generation (midrange peaking) which supplies about 25% of the total energy and has about 40% of the system power capacity, consists of older, smaller, less-efficient fossil fueled plants and energy storage units.

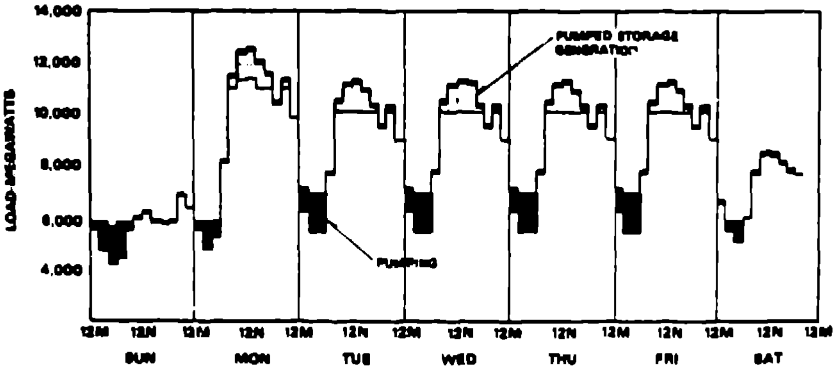

Fig. 2. Weekly load curve for a utility having pumped-hydro storage.

3. The peak load generation delivers only 5 to 7% of the systems energy but has 15 to 20% of the power capacity. This generation capacity consists of low cost generators, mainly gas turbines and energy storage units. Although the initial cost is low for the peaking turbines, the fuel oil used is very expensive. These units operate at low thermal efficiencies and require considerable maintenance.

A load duration curve is shown in Fig. 3. This curve shows the hours of operation during a year of the various types of generations.

The utilities are considering ways of decreasing the diurnal load variations rather than increasing the power capacity. The load factor can be improved by power demand control or time-of-day metering in which the charge to the customer for peak power is greater than for off-peak power.

Even though load factors may be increased by various incentives to the customer, the growing electric power requirements and the replacement of old existing units which could be cycled by new, large power plants will increase the utilities need for intermediate and peak generation.

Energy storage plants can be used for load leveling on an electric system. An energy storage unit does double duty by accepting energy from a base load power plant during periods of low demand usually at night and then delivering energy to the electric system during periods of high demand, usually

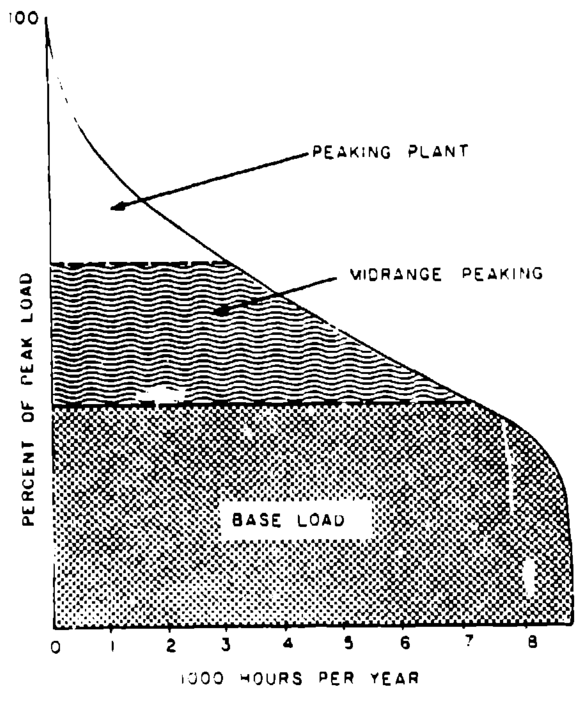

Fig. 3. Load duration curve for a utility showing the annual hours of operation at various power levels.

during the day. A desirable energy storage unit should be efficient, inexpensive, easily sited, have no adverse environmental effects, and have a high energy density.

Pumped hydro has been used extensively and has been proven quite effective. Unfortunately there are few desirable sites left for pumped-hydro installations. Several other energy storage devices have been proposed for diurnal storage of electrical energy. These include: SMES, compressed air, batteries, flywheels, and thermal (steam or hot oil). Economic considerations eliminate flywheels from this application. Most of these technologies are at the stage of development where they are technically feasible but are not economically competitive with gas turbines. Engineering development is required to bring each of these technologies into a competitive position.

The operation of the Ludington[1] pumped-hydro storage is shown in Fig. 2. This plant is the largest in the world, having a storage capacity of 15 000 MWh and a power capacity of about 1800 MW. It is located on a bluff overlooking Lake Michigan and is several hundred miles from Detroit, MI the major load. A SMES unit would have several advantages for this application.

1. It could be located near the loads eliminating the need for additional transmission lines.

2. It would have an efficiency of about 90% instead of the 70% typical of pumped-hydro plants.

3. Because of the fast response of the SMES converters, it could improve system stability and provide spinning reserve.

A SMES unit which would have the same capacity as Ludington would be a solenoid about 340-m dia. and 114-m high. Whereas Ludington cost $\$351 \times 10^6$ in 1973 (or $\$470 \times 10^6$ in 1977 based on a 7% inflation), the current estimated cost of the SMES unit is about $\$480 \times 10^6$. This does not include transmission or other credits. Details of a slightly smaller unit are presented in section IV.

B. System Stability and Short Term Load Variations

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

One specific application of an energy storage device for the electric utilities in the U.S. 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. This instability has been overcome by installing a feedback system to buck power oscillation on the ac line by controlling the power flow through the converter at the northern terminal of the dc 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, 30-MJ storage capacity with a 10-MW converter could damp the oscillations which occur at a frequency of about 0.3 Hz. The Los Alamos Scientific Laboratory and the Bonneville Power Administration are collaborating to determine if this type of storage device would be an effective and economical component of this power system.

Even in the operating conditions where there are no instabilities the continuous load variations, as shown in Fig. 4, must be met by continuously varying the power generation. These load variations may be random or periodic. Periodic load variations are caused by steel rolling mills, arc furnaces, drag shovels, etc. Power peaks of up to 50 MW may be generated.

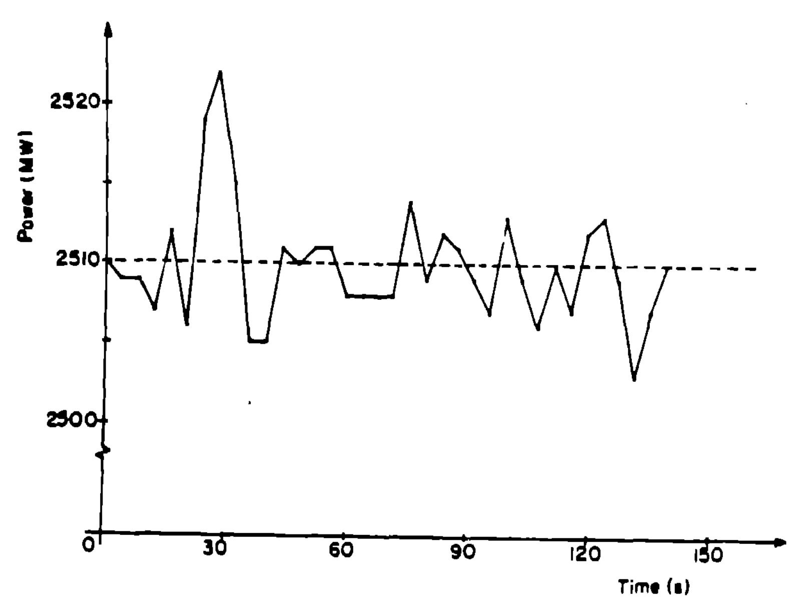

Fig. 4. Short-term power variation on an electric utility.

The cycling of generators to meet the load reduces their reliability and life expectancy.

An energy storage unit which can absorb these short-term power variations can be of great value to a utility. The large 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 which stored only 100 to 500 MJ but which had a converter capable of delivering up to 20 to 50 MW. Units of this type would have a diameter of 3 to 8 m and could be fabricated by industry today.

C. Spinning Reserve

The electric power utilities are required to have a minimum "spinning reserve" capacity which amounts to about 10% of the present load or 1.1 times the largest generation unit on line. This is equivalent to having an entire power plant continuously on line and spinning but not delivering power. The cost for the spinning 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 unit(s). This can be accomplished by choosing the voltage and current of the SMES unit, and the power capacity of the converter such that there will always be reserve capacity. During the short 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 storage unit will be limited to discharge rates of only about 50% of the maximum converter capacity. The excess discharge capacity of the system will take the place of part or perhaps all of the spinning reserve for the utility system.

IV. A 10 000-MWh SMES SYSTEM

The Los Alamos Scientific Laboratory has recently completed the reference design for a 10 000-MWh SMES unit for diurnal load leveling. This design will be described in detail in a separate report.[3] One of the major purposes of developing a reference design was to provide a starting point for detailed engineering designs. Some of the parameters and the cost of this unit are given in Tables I and II respectively.

TABLE I

SMES - REFERENCE DESIGN MAGNET SPECIFICATIONS

	10 GWh
Energy stored at full charge	4.6×10^{13} J
Energy stored at end of discharge	1.1×10^{13} J
Current at full charge	50 000 A
Maximum power output or input	2500 MW
Terminal voltage to provide P_{max} at end of discharge	103 000 V
Inductance	37 000 H
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

A. Magnet Design and Support Structure

The magnet is a thin-walled, 300-m diameter, 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 which could change as more is learned about the performance of various superconductors.

Other geometries such as toroids 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 in order to reduce the overall cost of the magnet system. If stainless steel bands, such as those used in large bubble chamber magnets, were used in a SMES magnet, their cost alone would far exceed the cost of other types of storage systems.

A set of struts and rods (or some other structure) is required to transmit the forces from the magnet at 1.8 K to the rock at about 300 K.

TABLE II

SMES UNIT COSTS

10^4-MWh Energy Exchange; 1.3 x 10^4-MWh Gross Storage Capacity. 89% Efficiency for 24-h Cycle: 1.8 K, 30 Strand Al Stabilized, $\rho = 1 \times 10^{-10}$ Ω-m at 5 T.

Material Costs			91.9
Fabrication Costs			66..
Assembly Costs			74.2
Rock Excavation 1.9 x 10^5 m^3 @ \$50/m^3	9.4		
Helium	9.0		
Refrigerator	20.6		
		Balance of Plant	39.0
		Total Cost	271.2
		Engineering at 12%	32.5
		Total	303.7 x 10^6

Net Output = 10 000 MWh x $(1 - .02 - \frac{.09}{3})$ = 9500 MWh

Storage Cost $\frac{303.7 \times 10^6}{9.5 \times 10^6 \text{ kWh}}$ = \$32/kWh.

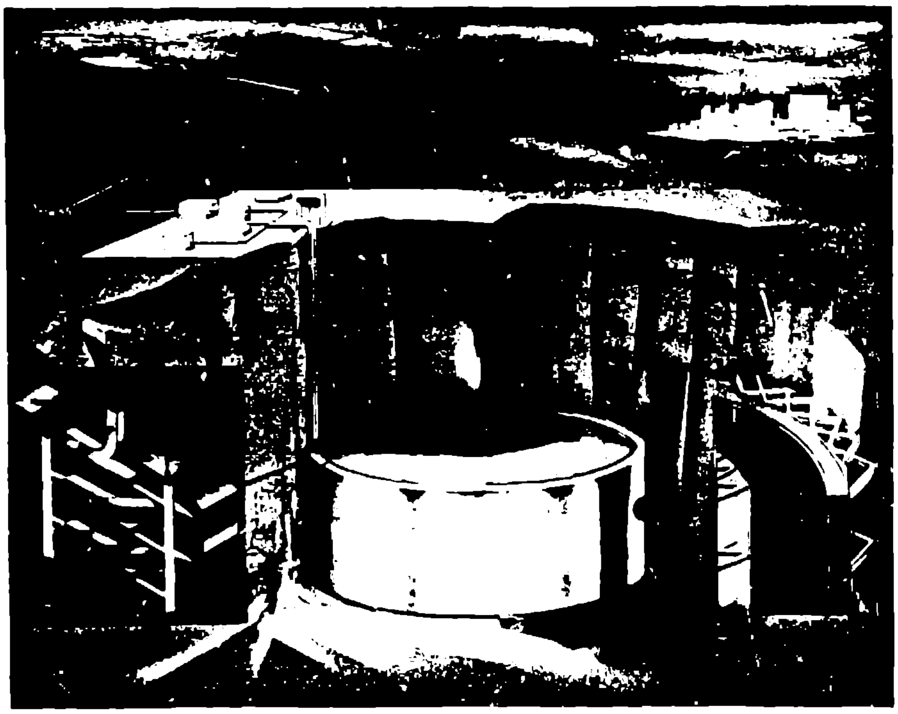

Fig. 5. Artist's concept of a large SMES unit constructed underground.

The arrangement shown 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 contraction of the magnet during cooldown are taken up by rippling as shown at the top of the figure. The axial loads may be removed when they reach the allowable stress in the conductor, about 138 MPa (20 000 psi) if the parts of the magnet closer to the midplane are stepped inward to have a slightly smaller radius. This may be seen by the placement of contact point of compression and tension members with the magnet.

The magnet 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.

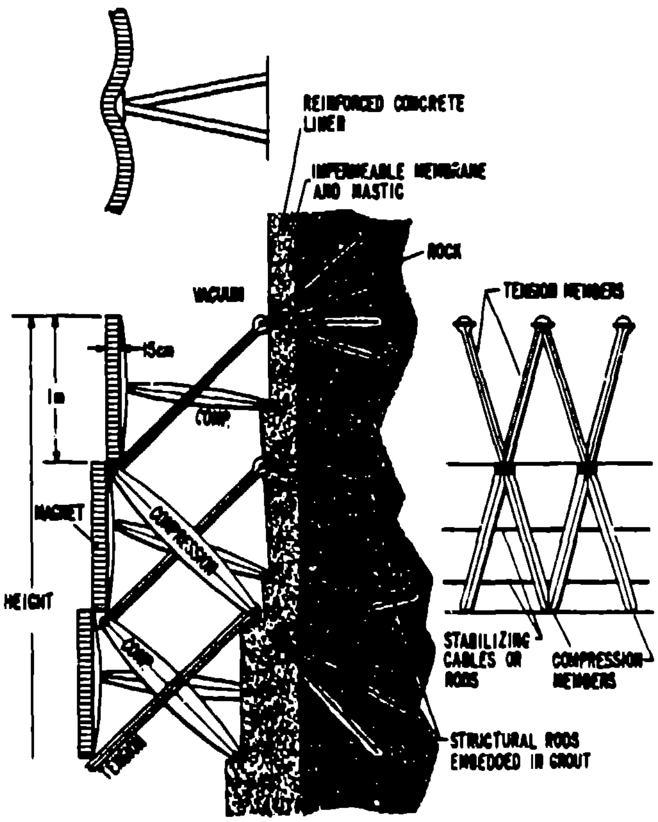

Fig. 6. Cross section of 10^4-MWh SMES unit showing the magnet and support structure.

B. Conductor

During the past few years superconductors have improved with the better understanding of the reasons for losses and instabilities. Several criteria were used in the selection of a conductor for the reference design.

1. It must be reliable (this includes but is not limited to stability considerations).
2. Its cost must be as low as possible.
3. It must be fabricable with existing techniques, or extensions of those techniques.
4. It must be flexible enough to be wound into a magnet in a 3-m wide tunnel.

The criteria of minimum cost affects the overall magnet design and operation in addition to affecting the type of conductors. Operation at 1.8 K rather than at 4 to 6 K and the use of NbTi rather than Nb_3Sn considerably reduces the total system cost. The use of relatively 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 conductors are in parallel and are cabled to reduce hysteretic losses. One of several possible conductor configurations which meet these criteria is shown in Fig. 7.

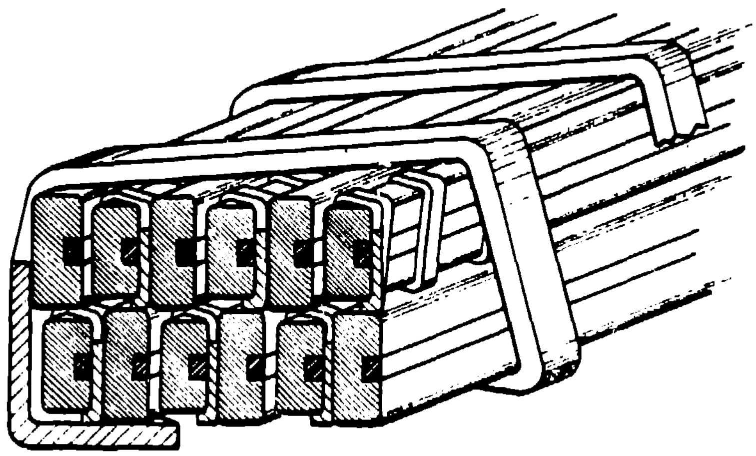

Fig. 7. Possible advanced conductor design using modular conductor as components.

V. SMES ELECTRICAL SYSTEM AND TESTS

A. Converter

The converter is the electrical interface between the superconducting magnet and the utility bus. Figure 8 shows a full wave (Graetz) bridge, the fundamental building block for advanced line-commutated converters. 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 relationship

$$\frac{dI_d}{dt} = \frac{V_d}{L} \quad (1)$$

and

$$P_d = V_d I_d . \quad (2)$$

Combining these equations the power is given by

$$P_d = L \frac{dI_d}{dt} I_d . \quad (3)$$

The magnetic energy W_m in the coil is proportional to the square of the coil current

$$W_m = \frac{1}{2} L I_d^2 . \quad (4)$$

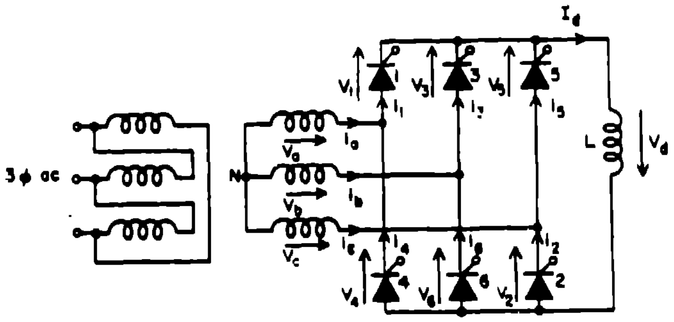

Fig. 8. Schematic of a full-wave, 6-pulse Graetz bridge.

The SMES system has current and voltage operating limits. The short sample current of the superconductor and the magnet stability determine the highest operating current of the coil $I_{d\,max}$. Stress considerations in the rock structure determine the lowest coil current $I_{d\,min}$. The maximum converter voltage or the maximum standoff voltage in the coil determines the maximum charge/discharge rate. The utility company may impose an additional restriction that a maximum power level cannot be exceeded because of system considerations. The operating range of a SMES unit with these restrictions is the crosshatched area shown in Fig. 9, which is a per-unit, voltage-current diagram for a SMES unit with an energy extraction of 84% of the maximum stored energy ($I_{d\,max}/I_{d\,min} = 2.5$).

Line-commutated, solid-state converters are being used extensively in high-voltage dc-power transmission, in reversible dc-motor drives, and for power supplies for large magnet systems used in particle accelerators and plasma fusion machines. The operation of converters for SMES units has many characteristics in common with the above mentioned applications, however, there are also considerable differences. Converters for large SMES systems will have medium to high voltage and current ratings. A 10-MWh SMES unit with a 6-min charge/discharge time and an energy extraction of 75% requires a 210-MW converter at 7 kV and 30 kA. A system with 10^4-MWh energy extraction and a 4-h

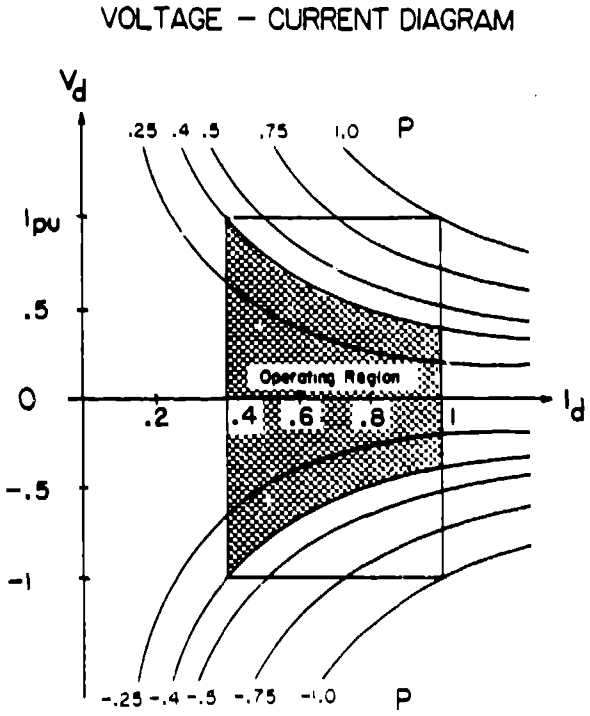

Fig. 9. Operating characteristics of an SMES unit.

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 10^4-MWh unit the voltage rating is 103 kV and a current rating of 50 kA.

Phase-controlled converters generate harmonics and absorb reactive power. Advanced converter circuits have to be used to minimize these unwanted effects. The harmonic content of the ac line current is reduced by using 12-pulse or even 24-pulse converter modules. Tuned filter networks can remove most of the remaining harmonics. The reactive power requirement is especially critical because the converter operates at any phase delay angle between 0 and nearly 180°. At $\alpha = 90°$ the power factor is 0 for a Graetz bridge. The reactive power requirement can be reduced considerably by subdividing the total SMES system converter into several series connected modules. The phase delay angles of all but one module are kept at 0°, and the one module has a variable phase delay angle depending upon the voltage requirement. All those converter modules which operate at 0° do not require phase control reactive power but do require a small amount of reactive power caused by commutation. Neglecting the commutating reactances a converter subdivided into n modules requires n times less reactive power than a single converter.

Figure 10 shows one possible circuit configuration of a 200-MW converter for a 10-MWh SMES system. The maximum converter voltage is 6.9 kV and the maximum current is 30 kA. 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 1725 V at maximum current,

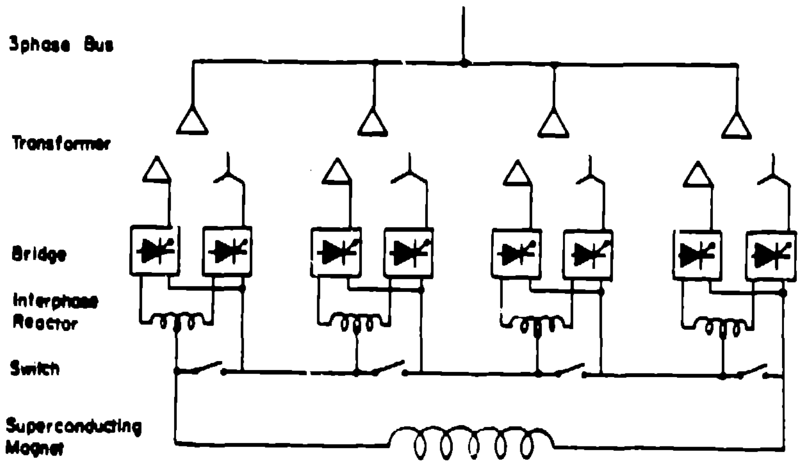

Fig. 10. Four series connected 12-pulse converter modules forming a 200-MW converter.

30 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 secondary winding of each transformer will provide 15-kA dc. Depending on the required system reliability a bridge for 1725 V and 15 kA can be designed by using in each leg of the bridge three or four 76-mm, water-cooled thyristors in parallel and two or three in series. Each 12-pulse module can be bypassed by a mechanical switch when the module voltage is 0 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 least four series connected thyristors.

By switching modules in and out, the installed converter power and therefore the converter cost can be decreased by designing those modules which are taken out of the circuit first, for just the current at which they are switched off rather than the maximum current. Theoretically the converter has to be designed only for a rating $P_o[1 + \ln(I_{max}/I_{min})]$ instead of $P_o(I_{max}/I_{min})$ where P_o is the maximum power. This results in considerable savings especially for SMES systems with a large discharge depth.

B. Converter and Control System Tests

A complete model SMES system has been set up in the laboratory. The system contains a superconducting magnet built up by stacking eight 3000-turn coils in series. The maximum inductance of the magnet is 70 H, however, individual coil terminals are available to provide lower inductance values. The quench current of the 70-H coil is 45 A. A 12-pulse solid-state converter and a power transformer with a 6-phase secondary winding interface the magnet to the 3-phase laboratory bus. Figure 11 shows the power circuit and the automatic control system. Maximum converter output voltage is 150 V.

The automatic control system for the model SMES unit is designed with all the features which are necessary for automatic operation of a large storage magnet on the utility bus. Power demand is the reference signal into the control system. This input signal which for a large SMES unit will come from the power system dispatcher has been simulated in the model by a random signal generator with positive and negative output signals of variable amplitude. Thus it models the unpredictable demand input to a storage unit associated with random load variation in the power system.

The feedback controller consists of a division circuit and a power control loop with an overriding current control loop. It gives information to each digital controller on how to change the phase delay angle in each bridge to adjust the bridge output voltage in order to meet the new power demand. In

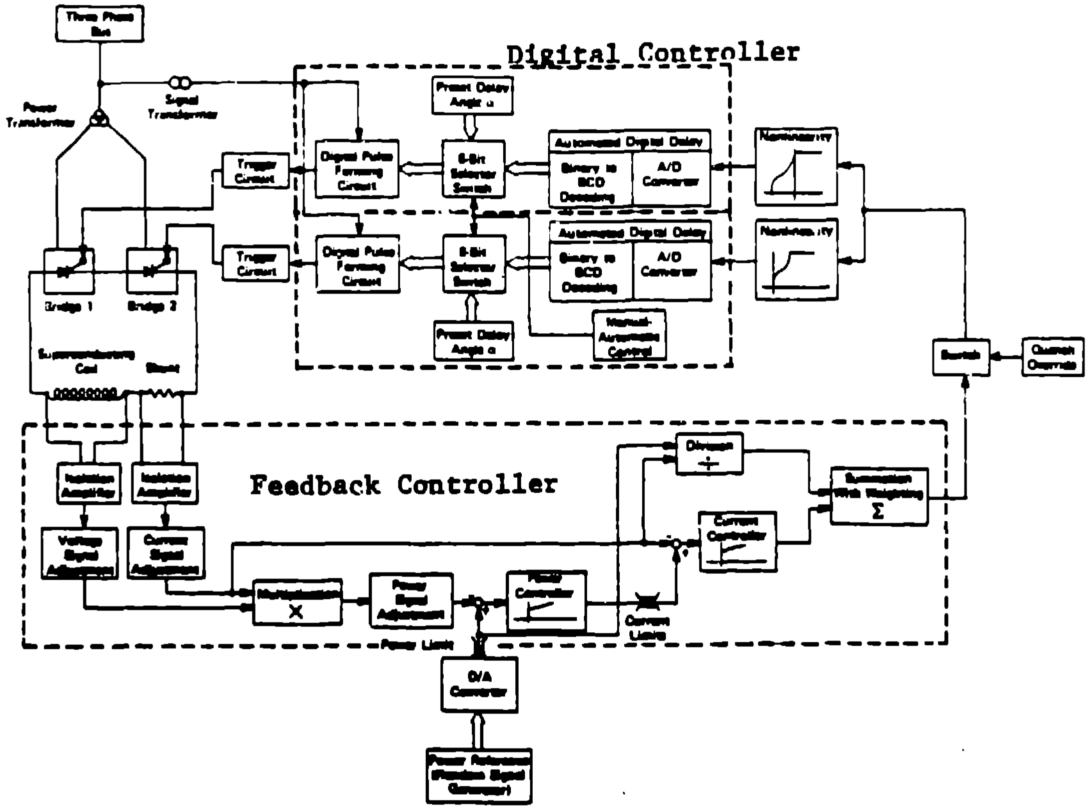

Fig. 11. Block diagram for a 12-pulse converter and control circuit for a SMES system.

the division circuit the power demand signal is divided by the coil current signal. Thus without any time delay the corrected bridge output voltage is computed and the delay angle setting is determined for each bridge in each digital controller. The power and current control loops are being used for vernier regulation while the computed voltage demand signal does the coarse regulation. Current limiting controllers for the lower and upper current limits are included in the feedback controller to prevent operation of a SMES unit outside the current limits.

Each 6-pulse bridge has its own digital controller. The heart of the digital controller is the digital pulse forming circuit which generates 6 pulses. These pulses, amplified in the trigger circuit, are the gate pulses for the 6-thyristors of one bridge. The gate pulses are delayed in phase to the line voltage by an angle which is determined by the control system. For each 6-pulse bridge the dc-output voltage V_d varies with the delay angle α according to a cosine function (commutating reactances neglected)

$$V_d = V_{do} \cos \alpha \ , \qquad (5)$$

with V_{do} defined as the voltage for α equal to zero. Nonlinearities are introduced in the control system to compensate for the nonlinear relationship between V_d and α.

Because of the experimental nature of the model system, the control system has been designed so that the converter can operate in either the manual mode or in the automatic mode. In the manual mode the phase delay angle is manually set in the digital controller, in the automatic mode the feedback controller determines the delay angle setting. In both modes of operation the converter can operate either with symmetrical or asymmetrical firing. In the later case the delay angle of the two 6-pulse bridges are independently varied according to a preprogrammed setting to minimize the reactive power requirement of the converter.

The converter has been tested with both symmetrical and asymmetrical triggering modes.[6] When the two 6-pulse bridges operate in the asymmetrical triggering mode, the line current has high 5th and 7th harmonics, which are delay angle dependent. In a large SMES system 12-pulse bridges will operate in the asymmetrical triggering mode so that the 11th and 13th are the lowest line current harmonics whose amplitudes will be independent of the delay angle.

The 12-pulse converter was tested in the automatic control mode to determine the switching times for charge to discharge (rectifier to inverter) switching and vice versa. Switching times of 5 to 6 ms were achieved. Figure 12a shows the transition from charging to discharging and Fig. 12b shows the transition from discharging to charging.

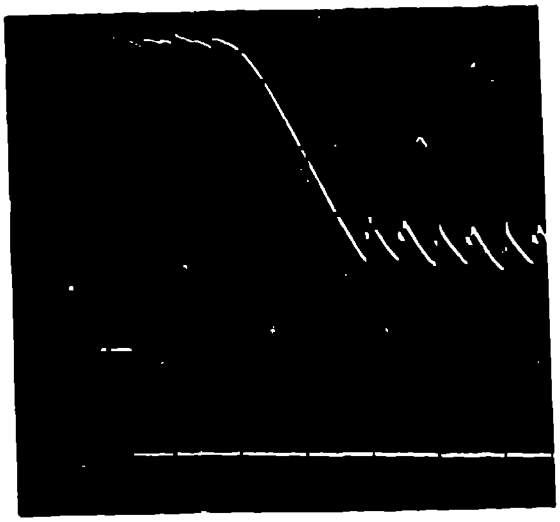

Fig. 12a. The 6 ms transition from charge to discharge of a converter on a SMES unit.

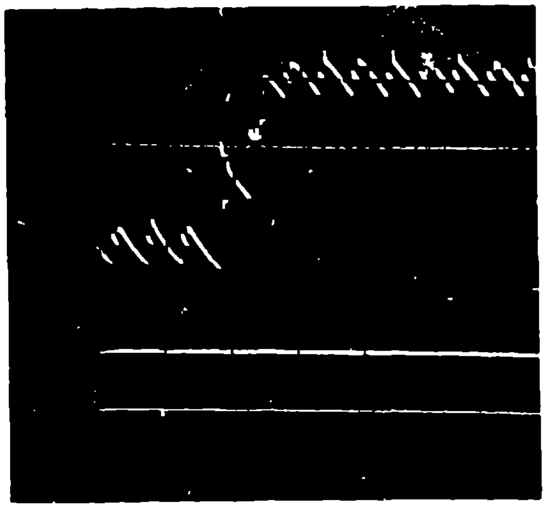

Fig. 12b. The 5 ms transition from discharge to charge.

The lower trace is the power demand, switching from one polarity to the other, while the upper trace is the converter power. Periodic power demand oscillations with frequencies up to 3 Hz have been applied to the control system. The converter power follows the power demand very closely.

VI. CONCLUSIONS AND SUMMARY

Superconducting magnetic energy storage units may 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 effectively damp electromechanical oscillations on power systems.

Additional engineering development will be required to achieve practical large SMES units for load leveling, but the small units for stability purposes could be fabricated by industrial manufacturers with existing technology.

VII. REFERENCES

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