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Superconducting Energy Storage Development for Electric Utility Systems

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SUPERCONDUCTING ENERGY STORAGE DEVELOPMENT FOR ELECTRIC UTILITY SYSTEMS*

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Abstract

High load factors are desirabe goals for all electric utilities to reduce the total power generation cost. Superconducting Magnetic Energy Storage (SMES) technology has progressed to where it shows promise as an alternate energy storage method to pumped hydrostorage to improve electric utility load factors. Experiments at the Los Alamos Scientific Laboratory indicate that a SMES system responds quickly (i.e. in milliseconds) to power system demand and has a high energy storage efficiency. The next generation superconductors suitable for larger SMES units are discussed, component and system test results are presented and some energy storage experiments of a 100-kJ coil and twelve-pulse converter interfaced with an ac power system are described.

1. INTRODUCTION

Superconductivity technology has advanced to a state where it may be able to contribute to the energy needs of our society. The absence of electrical resistance may allow superconductive devices to be smaller, lighter, and more efficient than conventional units. Applied research programs are being supported for superconducting machinery, bulk power transmission and magnetic energy storage. Superconducting magnetic energy storage (SMES) shows technical and economic promise as an efficient method of storing off-peak electric power for reuse during periods of peak power demand.

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Since 1973, the year of the oil embargo, the rapidly increasing costs of fuel oil and natural gas has caused many utilities to reevaluate their operating stragegy and to seek ways to utilize more base load generating capacity. Storage of off-peak energy is a method of obtaining efficient base load operation. Energy storage has long been a desirable goal of the utility industry because of the economic incentives and operating flexibility. Today almost all large bulk energy storage is by pumped hydrostorage. Those utilities which have such storage available. realize significant daily load factor improvement over those which use intermediate and peaking generation units to supply the peak load demand.

However, the scarcity of suitable hydro sites and recent environmental objections have prompted many utility groups to consider other energy storage schemes which might be promising. Further, the need for fossil fuel conservation has fostered both economic and political incentives for pursuing new technologies and bringing them into use. A compressed air energy storage plant is being constructed in West Germany. A fuel cell demonstration and a battery test facility will be constructed in the U.S. through EPRI and ERDA support. These installations will provide operating data needed to evaluate economic and technical characteristics.

The SMES system is based on the relatively recent developments of practical superconductors. Studies of the application of SMES are in progress at the University of Wisconsin and Los Alamos Scientific Laboratory for load factor improvement by peak-shaving and load-leveling. The Wisconsin[1] effort has concentrated on the design study of a 10,000 MWh SMES unit. At Los Alamos[2] small model experiments have been performed, superconductor evaluation experiments have been completed, and a 100 MJ (28 kWh) experimental facility has been designed.

This paper briefly discusses the major components of a superconducting magnetic energy storage system. The electrical parameters are derived for constant power operation of a SMES system during magnet charging and discharging. A circuit to economically and nondestructively evaluate high current superconductors is described and test results for three different experimental superconductors are presented. The second half of the paper deals with the design of an automated model SMES system which operates in a closed-loop power control mode. Test results of a twelve-pulse converter loaded with a superconducting solenoid are given.

2. DESCRIPTION OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Large superconducting magnets, similar in many ways to those being used in physics research, lend themselves to energy storage applications for the electric utility industry. The components of a SMES system are shown in Fig. 1. The magnet is immersed in a liquid helium bath, which keeps the magnet in its superconducting state at a temperature below 4.5 K. A superconducting solenoid is connected to the three phase utility bus by means of a transformer and a converter. A closed-cycle refrigeration system cools and liquefies the boil-off helium gas and returns it to the liquid bath.

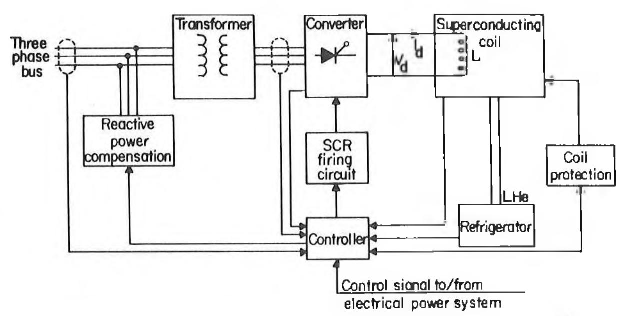


Fig. 1. Major components of a superconducting magnetic energy storage system.

The line-commutated converter regulates the power flow between the SMES unit and the utility bus. During the charge phase of the energy storage cycle, the converter is operated as a rectifier to convert the excess ac power to dc for charging the magnet. The stored magnetic energy can be returned to the utility bus for peak load demands by operating the converter as an inverter. Solid-state converters have been used in our laboratory experiments 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_{max}, in the full rectifier mode, and its minimum value, $-V_{max}$, in the inverter mode. For positive V_d, the magnet current increases and charges the magnet. The charging rate and the power flow from the three phase line into the coil are determined by the amplitude of V_d according to the relationship $dI_d/dt = V_d/L$. When the converter voltage is made negative, a charged magnet will discharge, which causes the magnet current to 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 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 twelve-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. The improvement of performance 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, and assumes no time delay is necessary for establishing the proper thyristor gating sequence. However, the gating control of an actual 60 Hz converter requires one to three milliseconds to generate the correct gating sequence following a change in demand input. The sum of ideal switching time and gating delay time results in a transition time from rectifier-to-inverter mode which is still less than half a cycle. The transition time from the inverter mode into the rectifier mode is identical to the commutation time, and independent of the pulse number of the converter. The total transition time, including a time delay for establishing the new gating sequence in an automated SMES system, is less than one fourth of a cycle for inverter to rectifier switching.

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.(3)

Other attractive features of a SMES system are its high energy density, easy sitability, and its overall high efficiency. For large units, an efficiency of 90 to 95% has been estimated.(4, 5) This is very favorable compared with an efficiency of 72%, as has been reported for the largest pumped hydro storage plant in the U.S. at Ludington, Michigan.(6)

3. SUPERCONDUCTOR EVALUATION TESTS

Research is being directed toward developing high-current and low-cost superconductors which would be practical for large magnetic energy storage units. Commercially available high-performance superconductors have current densities in the range of 2000 A/mm^2.(7) These superconductors are a composite structure of superconductor and normal metal (copper or aluminum) for stabilization. The high-current carrying capability of these conductors makes possible the construction of magnets which can store large amounts of energy ($W_m = 1/2\ LI^2$). Although superconducting magnets capable of storing up to 800 MJ (224 kWh)have been built for applications in nuclear physics, these magnets would not be economical for utility applications.

In recent months, we have tested promising superconductors to evaluate and select a high-current conductor for large storage magnets. The "short sample" (about .25 m in length) method was used for the initial tests. This consists of increasing the current through the test specimen in the presence of a constant magnetic field until the material undergoes a superconducting-to-normal transition or quench. The critical quench current decreases with higher values of the applied magnetic field. Similarly, the self field of a coil ultimately limits its maximum current. Well-designed magnets quench at 90 to 100% of the short sample current.

TABLE I

CONDUCTORS UNDER STUDY

	MONOLITH (AIRCO)	CABLE (MCA)	BRAID (BNL)
CuNi:Cu:NbTi	6:4:1	1:3:1	0.33:1.25:1
Conductor Size (mm)	5.0 x 5.0	1.5 x 6.0	0.71 x 18.2
No. of Strands	———	13	99*
Strand Diam (mm)	———	0.89	0.30
Filaments per Strand	———	2700	517
No. of Filaments	22,800	35,000	50,150
Filament Diam (μm)	12.3	6.2	10
Strand Twist Pitch (mm)	———	7	8.3
Conductor Twist Pitch (mm)	50	55	114 (Transposition)
Filler	———	Sta-Brite (coating)	93% In - 7% Pb
I_c(4T, 4.2°K) $\rho = 10^{-12}\ \Omega$-cm	3300	3100	2700 A
Remarks	———	———	*50 Strands of Superconductor, 49 Strands of #28 Cu

So far, three different conductors for SMES applications and several insulating materials have been investigated. Table I describes the electric and mechanical characteristics of the different conductors. Short test coils, as shown in Fig. 2. have been stacked together to form a magnet which generates a magnetic field of about 4 T (40 kG) at a current of 3000 A. The 4 T field is roughly the same as will be present in the first large-scale SMES system. In this regard, the tests of the small magnets is a valid test for future magnets.

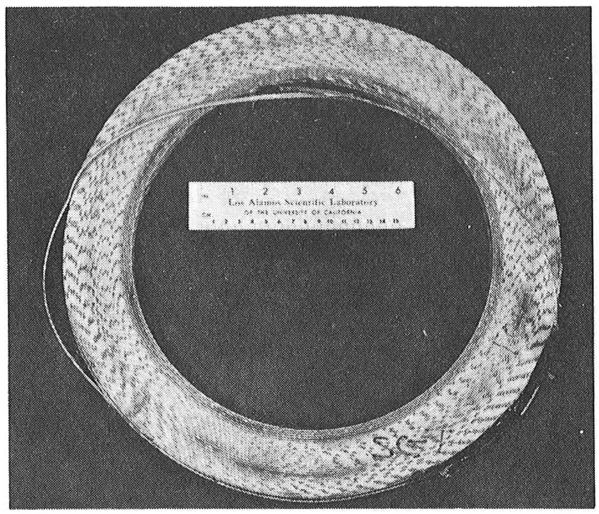
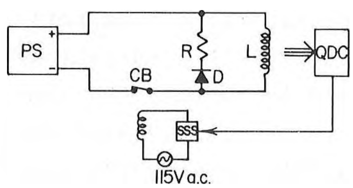


Fig. 2. Pancake coil wound with superconducting cable.

Figure 3 shows the experimental set-up for conductor tests. The circuit is designed to protect the magnet and to minimize the helium boil-off when a quench occurs by dissipating a large fraction of the stored magnetic energy in an external resistor. The circuit breaker CB is closed while charging the magnet and the current increases with rising power supply voltage. The diode D blocks the current path through the discharge resistor R. Quench detection circuits QDC with time constants of about 10 ms sense the beginning of a magnet quench and open a solid-state switch SSS, which causes the breaker to open the main circuit within 15 ms. The coil current is forced through the external discharge resistor R and 80 to 90% of the stored



CB Circuit Breaker
D Diode
L Coil
PS Power Supply
QDC Quench Detection Circuit
R Discharge Resistor
SSS Solid State Switch

Fig. 3. Circuit used for magnet tests to compare the performance of several candidate conductors.

magnetic energy is dissipated outside the liquid helium bath. The first coil to quench is identified on an external display circuit by a light-emitting diode.

The effectiveness of the circuit depends on the speed with which the quench is detected and the opening time of the circuit breaker. The energy deposited in the magnet and the liquid helium bath increases as these delay times increase. An electronic circuit was designed to measure the heat dissipated in the discharge resistor. The resistor current and voltage are amplified and multiplied together to provide the instantaneous power. Integration of this power with respect to time give the energy dissipated in the resistor. Typically, 80 to 90% of the stored magnetic energy is discharged in the resistor. These quench protection circuits are the forerunners of the circuits which will be used to insure safe operation of large SMES units on utility systems.

During the conductor evaluation tests, a 5000 A, 2 V battery power supply energized the magnet at a rate of 10 A/sec to a current of 2000 A. Above that value, the current increase was regulated to 1 A/sec until the magnet quenched. Each of the three magnets tested showed the expected "training" behavior, i.e. the quench current increased with the number of quenches until it reached a saturation value. Conductor #1, a 0.5 mm square monolith, performed poorly. The first quench was about 50% of the short sample current and the magnet reached only 70% of the short sample rating after training. The cable and braid performed very well. The quenches for both conductors began at about 75% of the short sample performance, and in six quenches, the magnets trained to a saturation value of over 95% of the short sample current.

Design work is in progress to develop conductors which have a current-carrying capability of 30 to 50 kA. Such conductors will consist of several cables or braids stacked in parallel with appropriate stabilization material and cooling passages between the individual superconductors.

4. OPERATING CHARACTERISTICS OF A SMES SYSTEM

The electrical parameters of a SMES system can be easily derived under idealized assumptions that the power transformer has no losses and leakage reactances and the converter thyristors are ideal switching devices. The output voltage, V_d, of a twelve-pulse converter is the sum of the two six-pulse bridge voltages. Each bridge voltage follows the cosine of its phase delay angle

$$V_d = V_{d10} \cos \alpha_1 + V_{d20} \cos \alpha_2, \quad (1)$$

with V_{d10} defined as the voltage of bridge i for $\alpha = 0$. The phase delay angles α_1 and α_2 are identified for symmetrical twelve-pulse bridge operation, and α_1

differs from α_2 for asymmetrical bridge operation.

The rate of current change in an inductor is proportional to the applied voltage

$$\frac{dI_d}{dt} = \frac{V_d}{L} \qquad (2)$$

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

$$W_m = \frac{1}{2} LI_d^2. \qquad (3)$$

To calculate operating characteristics of the SMES unit, it is useful to consider the case of constant power P charge or discharge. The power is given by

$$P = L \frac{dI_d}{dt} I_d. \qquad (4)$$

For constant power operation, the converter voltage must follow a $t^{-1/2}$ relationship, which in turn causes the magnet current and field to vary as $t^{1/2}$, and the magnetic energy to vary linearly with time.

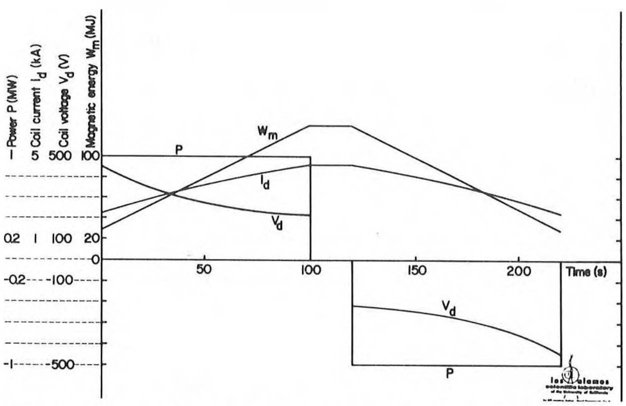


Fig. 4. Electrical parameters of a SMES system.

Figure 4 shows the important electrical parameters for a proposed 100 MJ (28 kWh) magnet. Operation of this system consists of cycling between 130 MJ and 30 MJ for a nominal 75% utilization of the storage capacity. The superconducting coil is designed for an inductance of 12.3 H and the system will have a maximum power limit of $\pm$ 1.0 MW. The lower and upper energy limits and the power rating determine the minimum charge and discharge time, 100 s. These operating limits are governed by several parameters. The upper energy limit is determined by the current carrying capability of the superconductor. The lower energy limit is somewhat arbitrary, but is set by the maximum inverter voltage and the maximum power rating. The maximum voltage and current for the 130 MJ system are $\pm$ 452 V and 4600 A respectively. Figure 4 shows both a complete charge and discharge cycle. A "coasting" or constant current mode of 20 seconds has been arbitrarily chosen between charging and discharging modes. During this time, the converter voltage is reduced to zero, and the system is neither charged nor discharged.

5. CONVERTERS FOR A SMALL SMES SYSTEM

Several electrical engineering problems are foreseen. They must be solved before operating large storage magnets economically and reliably on an electric utility bus can be realized.

(1) Studies must be carried out to determine the converter which minimizes the reactive power requirement and generates line currents with a low harmonic content.

(2) The control system must be designed to optimize the converter linkage of the SMES unit to the three phase bus to achieve the best technical performance for the application.

(3) Further tests must be conducted to show that the converter can effectively respond to the load perturbations in a few milliseconds.

(4) A fault analysis is required, which would include investigating the effect of fault conditions in all the SMES system components, including the transformer, converter, magnet, and refrigerator, and determining the consequence of a component fault on the electrical bus.

(5) Instrumentation and protection system circuitry must be developed to provide system protection during fault conditions.

A complete model SMES system has been set up in the laboratory. The superconducting magnet consists of eight, 3000-turn, coils stacked together as a solenoid. The maximum inductance of the magnet is 70 H; however, individual coil terminals are also available to provide lower inductance units. The quench current of the 70 H coil is 45 A. A twelve-pulse, solid-state converter interfaces the magnet to the three phase 208 V laboratory bus. The system can be operated in either a manual, open-loop or an automatic closed-loop control mode. The converter used in the experiment is a line-commutated, three phase bridge with series smoothing reactors and RC damper circuits for each SCR.

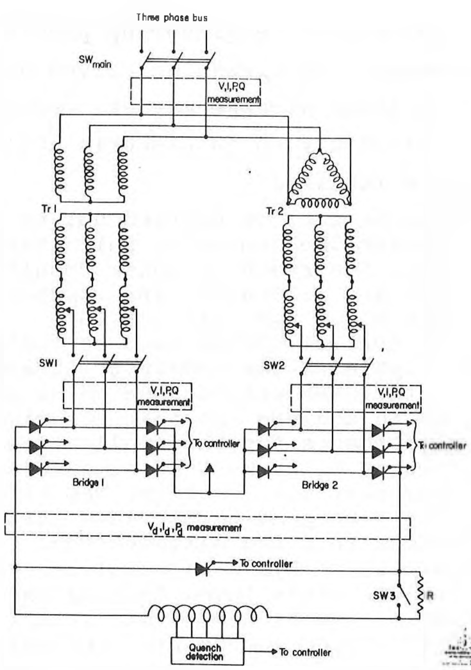


Fig. 5. Power circuit of a model SMES system experiment.

Figure 5 shows the power circuit of the model system. Two identical power transformers, one in a star-star connection, the other in a delta-star connection, form two three-phase systems to provide a 30-degree voltage phase shift between bridges. The two variacs are necessary in this setup to equalize the voltages for both three-phase systems. The transformer turns ratio limits the converter voltage V_d to ± 150 V. The converter current, I_d, is rated at 200 A. The two six-pulse bridges are connected in series. Voltage, current, and real and reactive power are measured at the ac bus and again at the three-phase input to each bridge. In addition, the dc power is measured at the converter dc bus.

During normal charge and discharge operation, switch SW 3, of Fig. 5 is normally closed and by-passes the external resistor R. When the quench protection circuit senses a quench state, the converter firing command signals are terminated, switch SW 3 is opened and the bypass thyristor is then activated. This provides a discharge circuit which decouples the converter and discharges most of the stored energy in the external resistor R.

A twelve-pulse converter (i.e., a multi-bridge system) can be controlled in symmetrically or asymmetrically triggered modes. Symmetrical operation is delaying all firing signals equally for all converter bridges. During asymmetrical operation one bridge has a fixed firing delay angle and the delay of the second bridge is variable. The reactive power requirement of the ac system is less for the asymmetrical operation but more harmonic filtering is required.

6. CONTROL SYSTEM FOR A SMES UNIT

The automatic control system used in recent SMES experiments for the more complex asymmetrical converter control is shown in block diagram form in Fig. 6. Except for the interaction between the power system dispatcher and the SMES controller, 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. In an on-line storage unit, the power system dispatcher remotely controls the charging and discharging rate of the storage plant. The dispatchers input demand provides the reference control signal to the SMES unit. This input has been simulated in the model SMES system by means of a random signal generator, thus reflecting the unpredictable demand input of a storage unit caused by random load variations. The random signal generator provides positive and negative power demands to the converter. From these input demands, the converter controls the power transfer between the storage unit and the utility system. The design of the random signal generator is in TTL logic, and the digital output is converted by a D/A circuit into an analog signal to conform with the analog control system. The amplitude of this signal remains constant during a preset time period at an arbitrary value between + 10 and - 10 V.

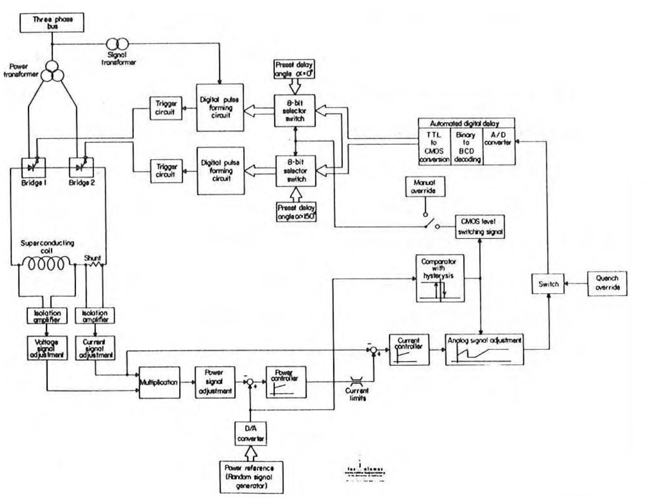


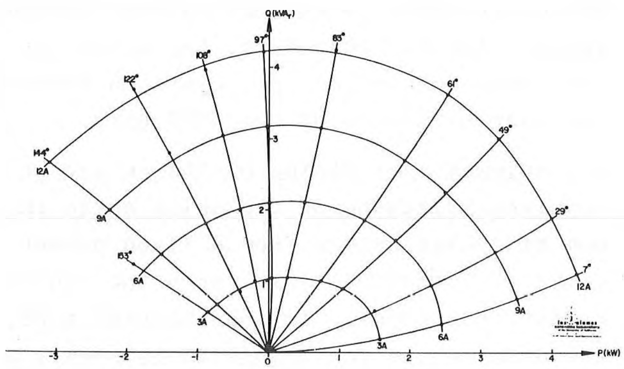
Fig. 6. Twelve-pulse converter control for a superconducting magnetic energy storage system.

As can be seen in Fig. 6, the automatic control system consists of dual feedback loops, a fast current control loop, and a slower power control loop. The power reference input as supplied from the random signal generator is compared with the measured SMES system power ($V_d \cdot I_d$) to obtain an error signal, which the converter must reduce to zero. The inner control loop is necessary to achieve accurate and fast current response controllability. The power controller output signal is the reference input signal for the current controller. In an actual system, the magnet current is varied between its maximum and minimum value according to the maximum and minimum energy limits. Therefore, the output of the power controller only operates between the current limits of the SMES unit.

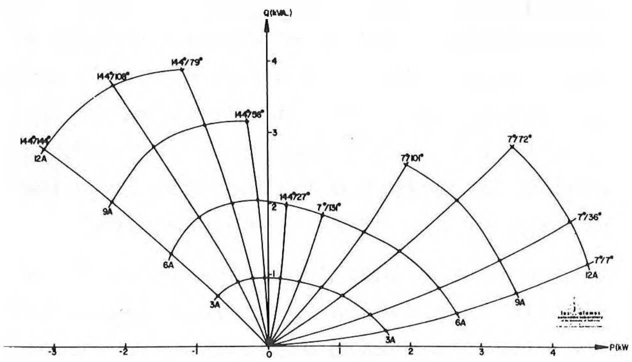
The asymmetrical firing of the converter requires switching of the delay angle in one six-pulse bridge from a fixed preset value to a variable value when the converter switches modes. In the charging mode, the delay angle for bridge #1 is preset at $\alpha_1 = 0$ and the delay angle for bridge #2 varies between $\alpha_2 = 0$ to $\alpha_2 = 150$ degrees (commutation limit) according to the power requirement. During discharge, bridge #2 has a preset delay angle of $\alpha_2 = 150$ degrees and bridge #1 varies its delay angle from $\alpha_1 = 0$ to $\alpha_1 = 150$ degrees. The switching action is activated by the zero crossing voltage of the power reference signal.

Timing of the individual thyristor firing signals is provided by digital pulse forming circuits. Each digital pulse forming circuit divides a half period of a 60 Hz sine wave into 100 steps and generates pulses for the six thyristors in the bridge. These six pulses are delayed in phase by an amount determined by the current controller. The automated digital delay circuit of Fig. 6 converts the output of the analog signal adjustment circuit to the appropriate CMOS signals for input to the digital pulse forming circuit. Each of the twelve output signals of the two digital pulse forming circuits are amplified in the trigger circuits and then applied as gate pulses to the twelve thyristors of the converter.

The twelve-pulse converter was first tested with a resistive load to provide checkout and initial converter data before operation with a pure inductive load. A superconducting coil whose inductance was 2.5 H was used for the SMES experiment with the twelve-pulse converter.



a) Symmetrically controlled converter ($\alpha_1 = \alpha_2$).



b) Asymmetrically controlled converter ($\alpha_1 \neq \alpha_2$).

Fig. 7. Power loci diagram for a 12 pulse converter operating with a superconducting solenoid coil.

Both symmetrical and asymmetrical converter triggering were investigated. Figure 7 shows the power loci diagrams which were obtained for both triggering modes obtained from recent SMES experiments. Real and reactive power were measured electronically for different delay angles α_1 and α_2 and recorded on an x-y recorder. Points of constant line currents representing points of constant apparent power were marked on the power curves. The power loci for the symmetrical firing mode show the circles of constant apparent power as expected from theoretical derivations. The relatively poor power factor for $\alpha_1 = 7°$ is caused by the unusually large commutating reactance of the series connection of transformer and variac. This variac will be unnecessary in a large SMES system which would have a power transformer with the proper winding configuration. The power loci for the asymmetrical firing mode (Fig. 7b) shows clearly the reduction of reactive power for small real power values. The twelve-pulse bridge is not able to operate, for instance, at a power value of 1 kW and 4 kVAr for the given ac voltage because the line currents of the two six-pulse bridges cancel each other.

The line current wave forms were recorded photographically for eight different values of the bridge voltage V_d between V_{max} and $-V_{max}$ for the symmetrically and asymetrically triggered converter. It can be said, in summary, that the line current of the symmetrically triggered converter has fewer harmonics starting with the eleventh and thirteenth harmonic, and that the harmonic content is almost independent of the phase delay angle. The line current of the asymmetrically triggered twelve-pulse converter has a high harmonic content and the current wave form resembles the current of a six-pulse bridge with the fifth and seventh harmonic as the lowest harmonics. In addition, the harmonic content depends heavily on the phase delay angles. Figure 8 shows in a comparison the line voltage, the line current, and the converter voltage of a "coasting" magnet for symmetrical and asymmetrical firing. It is interesting to note that the line currents have a lower harmonic content when the converter is loaded with an inductance than with a resistor.

Initial tests have been performed with the model SMES system, controlled by the feedback power loop. Although stable operation has been reached; the time constants of the different controllers require optimization. Switching times between charge and discharge and vice versa of 25 ms have been measured. Modifications are being made in the control system to improve its performance. The conversion sampling rate of the A/D converter will be increased from its present one per cycle value to 100 per cycle. This will improve the switching time by about half a cycle. Furthermore, a preset voltage demand, computed without any time delay, will be fed directly into the automated digital delay circuit. This demand will be calculated by dividing the power demand signal by the magnet current. The power and current control loops will then be used for vernier regulation, while the preset voltage signal provides the coarse regulation.

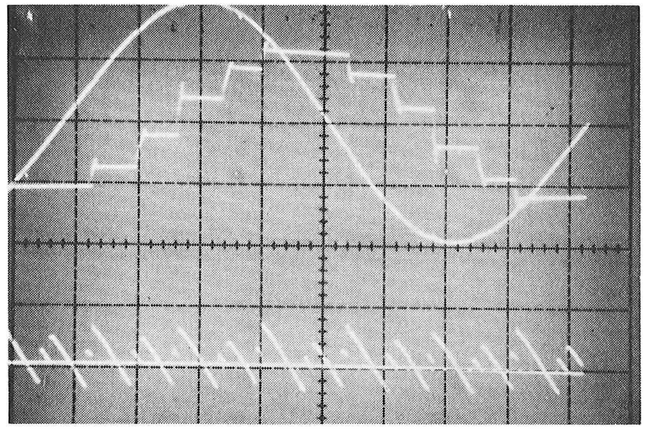
7. CONCLUSION

Model SMES experiments performed at LASL shows that magnetic energy storage in a superconducting magnet is a technically feasible energy storage alternative for electric utility applications. SMES is an efficient method of storage which does not require that electrical energy be converted into mechanical form for storage.

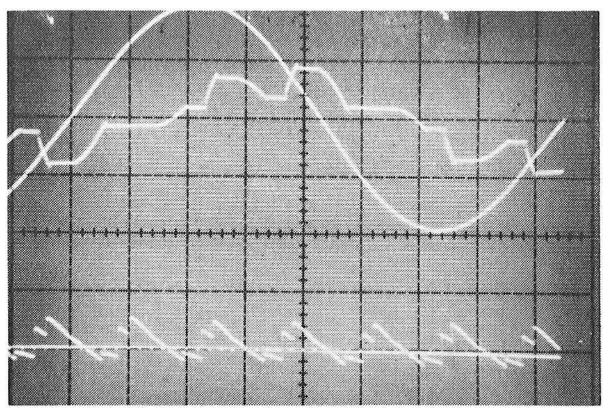
Component tests of a model SMES system includes a twelve-pulse converter and an automatic control system. Tests with the automatic control system show that a SMES system has switching times between the charging and discharging mode of about a cycle and a half. This makes the system very attractive for power system stabilization.

High current superconductors which may be used on the 100 MJ SMES system have been tested. Circuits have been designed and used for nondestructive testing of magnets to determine superconductor performance characteristics.

Further converter tests and studies will be required to clearly identify the best circuits for a SMES system. A converter optimization study must be made to include a cost



a) Symmetrically controlled converter (α_1 = α_2 = 83°). I_{line}= 10A, V_{line}=120V, V_d= 50 V/div.



b) Asymmetrically controlled converter (α_1 7°, α_2 = 131°). I_{line}= 6A, V_{line} = 120V, V_d = 50 V/div.

Fig. 8. Line current, line voltage, and converter voltage wave forms for 12 pulse converter operating with a superconducting solenoid coil.

evaluation of harmonic filter and power factor correction requirements.

8. ACKNOWLEDGEMENT

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