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SUPERCONDUCTING MAGNETIC ENERGY STORAGE FOR ELECTRIC POWER SYSTEM STABILIZATION

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ABSTRACT

A Superconducting Magnetic Energy Storage (SMES) system is being developed at the Los Alamos Scientific Laboratory (LASL) for a dynamic stabilizer to be installed in the Bonneville Power Administration (BPA) power system at Tacoma, Washington, by 1982. This unit will be an alternate stabilization method to the dc modulator now used to stabilize the 900 mile, ac intertie between BPA and Southern California. The generation control systems' response to the constantly occuring, small-load and voltage changes can result in negatively damped, low-frequency power oscillations. The dc modulator provides stabilization by fast load control of the High-Voltage dc (HVDC). The SMES unit consists of a 30-MJ solenoid, a 10-MW convertor, a liquid helium dewar, and auxiliary systems which operate independent of the HVDC system. The SMES dynamic stabilizer design is presented herein, and status information is given about the superconducting coil, the converter, and other components of the SMES dynamic stabilizer.

ADVANCES IN SUPERCONDUCTING TECHNOLOGY HAVE PROGRESSED in recent years to indicate that its utilization by the electric power industry will soon become a reality. The zero ohmic resistance of a superconductor makes it unique. In solenoid form, a superconducting coil is essentially a classical inductor that can be utilized to store energy through a high dc current with a very long L/R time constant. Any resistance arises from joints in the superconducting cable. Other small losses arise from ac effects (hysteresis and eddy currents) during charge and discharge of the coil.

A SMES unit is being developed at LASL for electric power system dynamic stabilization. This unit will be installed in the BPA power system at Tacoma, Washington(1*) by 1982 and will be an alternative to the 40 MW-dc modulator which is now being used to compensate for the HVAC intertie's underdamped characteristics. The SMES unit will operate independently of the HVDC system to provide damping to the ac system.

The Pacific Northwest-Southern California power intertie consists of two very large generator-load complexes located at the ends of a 900 mile, relatively weak transmission system, Fig. 1. This transmission system is made of three separate transmission lines which are electrically parallel. Two 3-phase, 500-kV ac lines, which also have some 230-kV sections, have a thermal design rating of 2000 MW each. The HVDC intertie is the third system which has a 1440-MW transmission capacity and is

*Numbers in parentheses designate References at end of paper

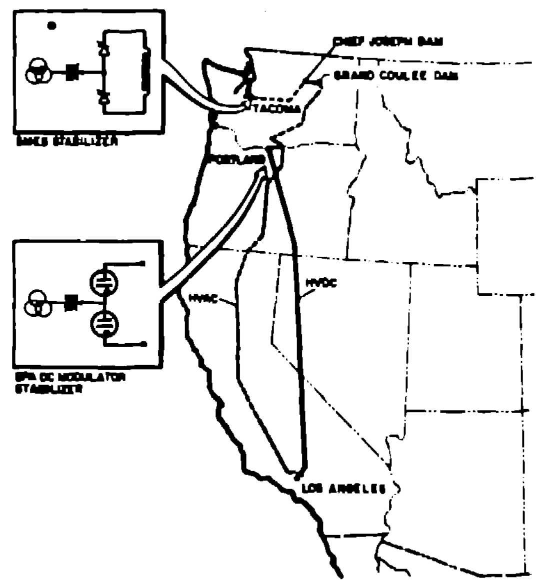

Fig. 1. - Pacific intertie transmission system routes and dynamic stabilizers

operated at ± 400 kV. This transmission system, because of its size and length, is an interregional intertie which characteristically requires more extensive stabilization than is commonly needed by radial intertie power systems(2). Operation of the intertie provides for the export of power to Southern California during periods of excess capacity and the day-to-day off-peak energy exchange between power regions required for load profile economic dispatch.

Before the initial energizing of the ac intertie, studies had shown that under some load-generation conditions negatively damped power oscillations were likely to occur. These would prevent the designed operating power transmission capacity from being realized (3). Initial operation confirmed the predictions, and a transmission power limit of 1700 MW was used until Power System Stabilizer (PSS) control systems were installed on the generators (4). The PSS improved the system's dynamic stability, and stable power transmission at 2100 MW was achieved until mid-1974 when spontaneous, negatively damped, power oscillations of about 300 MW peak-to-peak amplitude at 0.35 Hz frequency were observed several times throughout the Western Interconnected Power System,(3) Fig. 2. In 1975, a 40-MW, dc modulator was installed by BPA to provide additional damping to the ac intertie by means of fast load control of the HVDC system. This improved the ac system's stability to allow the 2100 MW transmission operating limit to be increased to 2500 MW (5).

Representatives of BPA and LASL met in 1975 to explore the feasibility of a small SMES unit for use as a dynamic stabilizer on the ac intertie to provide an alternate system to the dc modulator that would not be subject to the HVDC system's unavailability. As of now, two iterations of the SMES dynamic stabilizer design have been completed (6). Tacoma, Washington, has been chosen as the location for the installation of the stabilizer unit, and some component fabrication contracts have been placed with commercial manufacturers.

SMES DYNAMIC STABILIZATION SYSTEM

A SMES dynamic stabilizer consists of five major components--a superconducting solenoid, an ac-dc-ac solid-state converter, a liquid-helium dewar, a liquid-helium refrigerator, and auxiliary and control systems. The functional relationship of these components is shown in Fig. 3.

The technology base needed for these components currently exists in the various industries' state-of-the-art. With the exception of the superconducting coil and the dewar, design adaptations of currently manufactured equipment can be utilized for the system. Both the superconducting coil and its dewar must be designed for the requirements of each application. BPA has performed studies using a modeled SMES unit in their system as an alternate dynamic stabilizer for the HVAC intertie. They have recommended that the SMES stabilizer's power-absorption, power-delivery capacity be ± 10 MW. A ± 5-MW power range of operation provides essentially all the stabilization needed by the HVAC intertie. Purdue University has

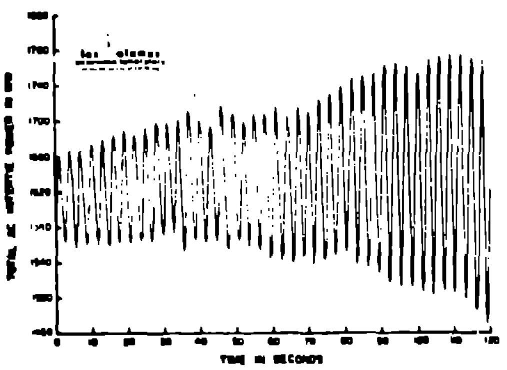

Fig. 2. - Negatively damped ac intertie oscillation recorded August 2, 1974.

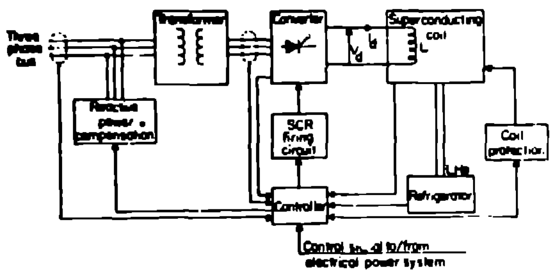

Fig. 3. - Major system components of a SMES unit

confirmed the previous BPA work through power system simulation studies of the SMES unit stabilizer's storage capacity, its power level and time response, and the expected control system behavior.

Table I is a summary of the superconducting solenoid's design and operating parameters together with the preliminary dimensions.

SUPERCONDUCTING COIL

Most superconducting solenoids that have been designed in recent years and reported in the literature are for applications that need large energy storage capacity such as fusion power experiments and daily load-leveling of electric utility power profiles (8,9). In contrast, the SMES dynamic stabilizer requires relatively small quantities of energy storage that will be cycled in and out of the coil many times on a daily basis for periods of a few seconds' duration. The economics associated with coil geometry optimization (9) favor a solenoidal aspect ratio (diameter-to-height) of approximately 3. The coil's stored energy, when fully charged, is to be 30 MJ. A maximum energy transfer of 9.1 MJ to the ac power system is the designed discharge limit. Limiting the depth-of-discharge minimizes the cyclic strain and magnetic field variations on the coil and system components, reduces the refrigeration heat load, and reduces the structural fatigue load as compared to operation at greater dept-of-discharge limits. During a discharge cycle, the coil current decreases from 4.9 kA to 4.17 kA. At the same time, the magnetic field maximum at the conductor decreases

TABLE I - DESIGN PARAMETERS OF A 30-MJ SYSTEM STABILIZING SMES UNIT

Maximum power capability, MW	10
Operating frequency, Hz	0.35
Energy interchange, MJ	9.1
Maximum stored energy, MJ	30.0
Coil current at full charge, kA	4.9
Maximum coil terminal voltage, kV	2.13
Maximum field at full charge, T	2.8
Inductance, H	2.5
Operating temperature, K	4.5
Mean radius, m	1.53
Height, m	1.15
Radial thickness, m	0.4
Number of turns	900

TABLE II - PARAMETERS OF A 30-MJ SYSTEM STABILIZING COIL (6)

Energy stored at full charge, MJ	30
Energy stored at end of discharge, MJ	20.9
Current at full charge, kA	4.9
Insulation standoff voltage, kV	10
Maximum field at full charge, T	2.8
Inductance, H	2.5
Operating temperature, K	4.5
Mean radius, m	1.53
Height, m	1.15
Radial thickness, m	0.4
Number of turns	900
Conductor length, m	8650
NbTi volume, m^3	2.34×10^{-2}
NbTi mass, kg	131
Composite core mass, kg	756
First subcable mass, kg	5750
Second subcable mass, kg	6750
Strap mass, kg	3850
Current density in copper at 4.9 kA, A/m^2	6.7×10^7
Current density in superconductor, A/m^2	1.3×10^9

from 2.8 T to 2.3 T. Table II is a summary of the superconducting coil parameters.

The maximum axial stress in the coil 7.2 MPa (1050 psi) occurs at the axial midplane at the mean coil radius. If this stress is carried entirely by the conductor support strap, the resulting stress in the strap is 25 MPa (3700 psi). The maximum radial stress, which occurs near the average radius in the axial midplane, is 20 MPa (2900 psi) compressive in the strap. The hoop stress maximum of 303 MPa (44 000 psi) also occurs at the coil midplane in the strap. The main structural material in the coil structure will be G-10 epoxy-fiberglass.

A contract has been awarded to Gulf General Atomic Co. for the detail design of the coil.

SUPERCONDUCTOR DESIGN

The conductor design and its support are patterned after the Westinghouse coil constructed for the LASL/Magnetic Energy Transfer Storage (METS) program. This coil was repeatedly cycled from an initial 300-kJ energy level to a complete discharge without experiencing a premature or unexpected loss of superconductivity. For the BPA application, the METS superconductor has a modified filament composition with added copper to improve its cryostability and maintain its low loss characteristics. Figure 4 is a photomicrograph with 500x magnification of the superconductor to be used in the cable for the coil.

The first subcable, the fundamental unit of the cable composite, is an insulated, array of six, 0.51-mm-diam copper conductors spiral wrapped around a central superconducting strand of the same diameter. Kapton* film is proposed as an insulating wrap for the first-level subcable. Six, first-level subcables will be cabled about an inactive central copper or superconducting core, which will be used to detect resistive regions. Ten of the second-level subcables are spiral wrapped around a supporting strap to form the complete conductor, see Fig. 5.

*duPont trademark

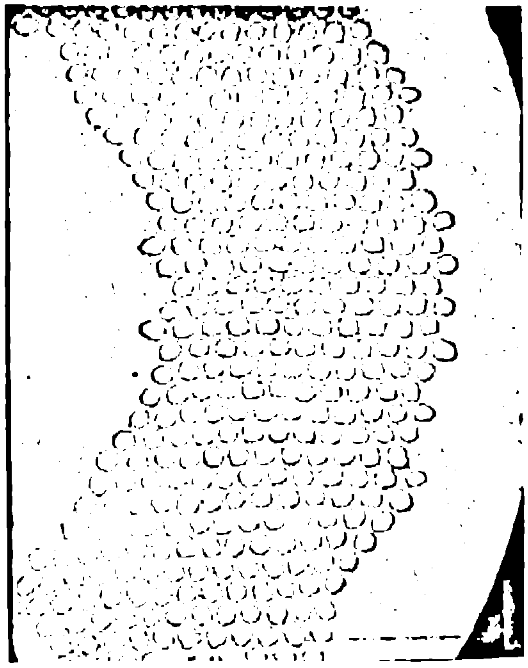

Fig. 4. - A photomicrograph of NbTi/Cu superconductor with a 500x magnification

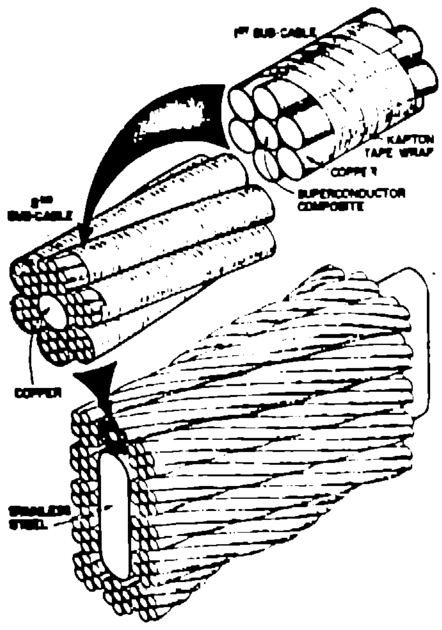

Fig. 5. - Superconductor cable composite

Fabrication of the 0.51-mm-diam superconductor has been completed and short sample testing has been done to develop statistics for the mean critical current-background magnetic field characteristics. Also, the standard deviation and other statistical parameters have been evaluated to determine if there are significant differences among lots of the superconductor.

The manufacture of the BPA superconductor required nine, heat-treated batches to produce the complete order. Seven random samples were taken from each heat-treated unit and a short sample critical-current test was performed on each. The critical-current mean is approximately normally distributed for the entire population. At 4.5 K, $I_{critical}$ = 123 A (J_c = 2.42 x 10^5 A/cm^2), with a standard deviation of 5.6A. This provides an adequate design margin for the I_c value used in the coil design.

CONVERTER SYSTEM

A line-commutated converter, Fig. 6, provides the electrical interface between the superconducting coil and the BPA power system. It is a Graetz bridge circuit in which the semiconductors are silicon controlled rectifiers (SCR), which can be operated in either rectifier or inverter modes. The converter provides three basic functions; to provide a dc link between the converter and the superconducting coil, to provide ac coupling between the converter and the ac power system, and to provide the needed isolation between the ac and dc circuits, Fig. 6. In the rectifier mode, the converter absorbs power from the ac system and converts it to dc for charging the superconducting coil. Conversely, in its inverter mode, stored energy is reconverted from dc to ac power and returned to the ac power system. A twelve-pulse converter will be used for the BPA stabilizer, in which the transformer's dual-secondary, Δ-Y windings provide a 30° phase shift of the 3-phase line power for 6-phase ac to the converter's ac terminals. Twelve-pulse converters provide dc with a lower ripple content and lower harmonic content which reduces the filter requirement needed over what can be obtained from a 3-phase, 6-pulse converter.

The converter design parameters are determined from the maximum sinusoidal power demand with the operating frequency of 0.35 Hz and the coil characteristics. For a maximum power of 10 MW, the energy exchange required is 9.1 MJ. The maximum coil current of 4.9 kA, determined because of superconductor considerations, is also the maximum converter current. The maximum converter voltage will be 2.13 kV at a current of 4.6 kA. The converter has to be designed for the maximum voltage. For a 10% commutation reactance and load currents of approximately 5 kA, the no-load voltage of the converter should be 2.5 kV. The installed converter thus has a power rating of 12.5 MW.

The Robicon Corp., Pittsburgh, Pennsylvania, has been awarded the contract to build the SMES 10-MW converter, which is scheduled to be completed October, 1979. Figure 7 is the 12-pulse converter circuit showing the electrical components that it will contain. The converter SCRs as shown in Fig. 7 are Westinghouse 53-mm cells which have a 3200 peak inverse voltage rating and are mounted on air cooled heat sinks. Eight SCRs must be mounted in parallel for each of the 12 sections in the converter and each will be equipped with current-balancing inductors and protective fusing. The SCR gate drive will be a dual, hard-gate drive impulse combined with a pulse sustainer "back porch" current. Converter control will be by analog input for SCR conduction between 10° and 165° phase angle delay range.

COIL STABILITY, PROTECTION AND LOSSES

Although the proposed coil and conductor will be self-protecting under regular operation, there may be circumstances which require a backup protection system to discharge the coil quickly. If the ac-to-dc converter were used to discharge 30 MJ the decay time period will be 5.5 s. A discharge of coil energy through the converter to the ac line at the wrong time might trigger an instability of the type the unit is designed to control. Further, if emergency situations such as dewar vacuum loss are considered, which would result in a sudden superconducting to normal state transition (quench) of the coil, it might be desirable to reduce the discharge time below 5.5 s. Therefore, the coil energy is to be dissipated in a 1-ohm external resistor, with a terminal voltage of 5 kV and an L/R decay time of 2.5 s, Fig. 7. Laboratory experience indicates that the quench detection sensitivity against a background 2-kV operating voltage would

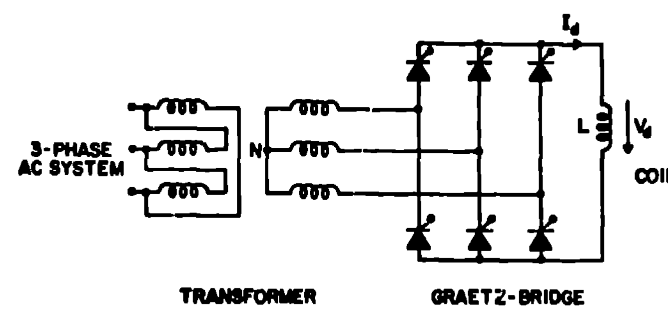

Fig. 6. - SMES converter system basic circuit

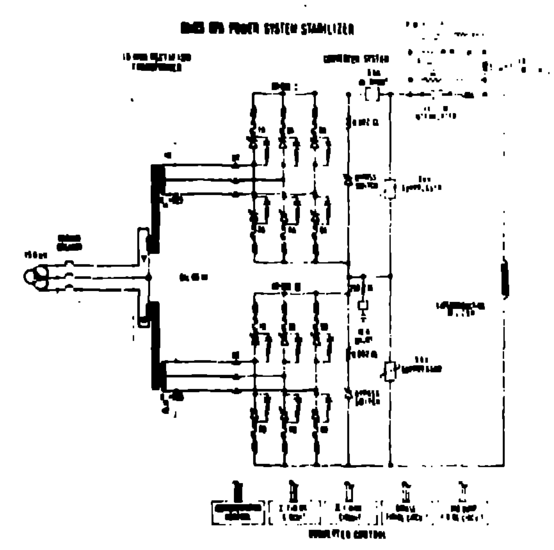

Fig. 7. - SMES BPA power system dynamic stabilizer converter circuit

correspond to approximately one normal turn. A thermohydraulic analysis shows that if the heat transfer does not change with time, the conductor will simply remain at a temperature of approximately 10 K. The additional boiloff caused by the increased heat load of 33 W per normal turn could be used to trigger the protection circuit. If a number of adjacent turns in the same layer are normal, the volume of gas generated may reach a critical vapor fraction which could cause vaporlocking. Calculations show that the electrical protection system should detect a considerably smaller normal region and would trigger well before such a situation occurs.

CRYOGENIC COMPONENTS

The liquid helium dewar, refrigeration system, and associated peripherals provide the 4 K temperature environment for the superconducting coil. Dewar design is contingent upon the completion of the final coil design. It will be fabricated of an insulating material to avoid eddy current heating and most likely will be a fiberglass-reinforced plastic material. The dewar will be cylindrical with the coil structure suspended from the removable top closure. Table III is a summary of the calculated losses that occur during the charge-discharge cycle of the stabilizer.

A CTI Cryogenics/Sulzer Model TCF-50 liquid helium refrigerator has been purchased and will be delivered in mid-1979. The refrigerator is equipped with two screw-type compressors to improve its long-term reliability. The compressor helium flow can be controlled from 30% to 100% by a slide valve arrangement. An estimate of the dewar and coil heat loads is given in Table IV. Both the mechanical and electrical losses of the coil are conservative and will probably be reduced.

TABLE III - CALCULATED HEATING OR LOSSES IN THE 30-MJ COIL DURING THE CHARGE-DISCHARGE CYCLE

<u>Conductor Losses</u>	
Hysteresis, W	39.4
Self-field, W	2.5
Coupling, W	8.3
Eddy currents, W	3.4
	53.6
<u>Structure Losses</u>	
Eddy currents, W	0.2
Mechanical, W	50.0

TABLE IV - SUMMARY OF CALCULATED REFRIGERATOR REQUIREMENTS FOR 30-MJ SYSTEM STABILIZING SMES UNIT

Conductor ac losses, W	59
Mechanical losses, W	50
Dewar heat leak, W (radiation and conduction)	33
Transfer line losses, W (liquid nitrogen shielding)	3
Total, W	145
Liquefaction loads, power leads, l/h, W	15

CYCLIC EFFECTS

The most difficult area of design, for which the least knowledge exists, is that of mechanical and electrical integrity. The concern arises from the expected minimal life of 10^7 to 10^8 cycles for the stabilizing unit. Only limited information exists on cyclic, cryogenic properties for fiberglass-epoxy laminates and electrical insulating materials. Abrasion, wear, and cracking can be serious problems.

An experiment will be undertaken to determine the life expectancy and/or design limits in terms of stresses and bearing loads that can be imposed on the conductor, the cable, and the insulation to maintain mechanical and electrical integrity.

ENVIRONMENTAL CONSIDERATIONS

All SMES units will produce magnetic fields beyond the cryogenic enclosure. For the 30-MJ coil, the field beyond the dewar will be a few gauss. At 40 m (133 ft) the field due to the coil should be below the average value of the earth's magnetic field, 0.3 G. Forty meters is expected to be well within the fence that defines the site boundary and surrounds the transformer, converter, refrigerator, and coil. Consequently, no environmental impact is expected from the magnetic field.

CONCLUSIONS

Superconducting magnetic energy storage systems for power transmission line stabilization are well within the present state of the art. A 30-MJ superconducting storage system with a 10-MW power rating can be built to modulate, at 0.35 Hz, the HVAC Intertie betweeen the Pacific Northwest and Southern California to damp the power system oscillations.

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