CONF-780952--26

MASTER

LA-UR 78-2435

TITLE: 30-MJ SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES) UNIT FOR STABILIZING AN ELECTRIC TRANSMISSION SYSTEM

AUTHOR(S): J. D. Rogers, H. J. Boenig, J. C. Bronson,
D. B. Colyer, W. V. Hassenzahl, R. D. Turner,
and R. I. Schermer

SUBMITTED TO: 1978 Applied Superconductivity Conference
Hilton Hotel - Pittsburgh, PA
September 25-28, 1978

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

An Affirmative Action/Equal Opportunity Employer

Form No. 836 R2
St. No. 2629
1/78

DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

30-MJ SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)
UNIT FOR STABILIZING AN ELECTRIC TRANSMISSION SYSTEM*

J. D. Rogers, H. J. Boenig, J. C. Bronson, D. B. Colyer,
W. V. Hassenzahl, R. D. Turner, and R. I. Schermer

ABSTRACT

Electric power systems that have major loads and generation centers separated by large distances may experience low-frequency power oscillations. This type of oscillation has occurred on the Pacific AC Intertie that connects southern California and the Pacific Northwest. A separate, almost parallel, dc-transmission line also connects these areas. The Bonneville Power Administration, which operates this transmission system, has overcome the instability by controlling the power transmitted on the dc-transmission line. A 30-MJ (8.4-kWh) superconducting magnetic energy storage unit with a 10-MW converter could also provide damping for this instability. The conceptual design of the 30-MJ coil and the cryogenic and electrical components of the system are described. The system is to operate at a maximum current of 5 kA and will modulate the AC Intertie at 0.35 Hz. Discharge will be controlled to retain a minimum stored energy of 20 MJ to limit cyclic strains in the coil and ac losses in the conductor. The conductor will be made of multistrand-copper and copper-matrix, multifilament NbTi superconducting wires on a stainless steel mandrel.

I. INTRODUCTION AND SUMMARY

The Pacific Northwest and southern California are part of the Western US Power System and are connected by two 500-kV, ac-power transmission lines, collectively referred to as the Pacific AC Intertie, and one ± 400-kV dc-transmission line, the Pacific HVDC Intertie.[1] The two ac lines have a thermal rating of 3500 MW, and the dc line has a rating of 1440 MW.

The stability of the Western Power System is affected by relative weakness of the tie provided by the 905-mile-long Pacific AC Intertie. In fact, according to Cresap and Mittelstadt,[2] "Studies made before energization of the Pacific AC Intertie showed that negatively damped oscillations with a frequency of about 20 cpm were likely to occur." In 1974 negatively damped oscillations with a frequency of 21 cpm (0.35 Hz) were observed. The peak-to-peak oscillation on the Pacific AC Intertie was about 300 MW. Subsequent to these instabilities, the Bonneville Power Administration (BPA) installed equipment[3] to modulate the power flow on the HVDC Intertie as a means of damping the oscillations. The maximum possible power modulation on the HVDC Intertie is 40 MW, about 3 percent of the HVDC power rating. The modulation of the HVDC Intertie has increased the stability limit of the Pacific AC Intertie from about 2100 MW to 2500 MW whenever the HVDC Intertie is operating. However, the HVDC Intertie does not operate continuously. The line availability is 89.6%, and the southern terminal was down for six months as a result of earthquake damage. A back up stabilizing system could be used. The idea that SMES systems could serve as system stabilizers was proposed by Mohan,[4] and its economics were analyzed by Hassenzahl, Baker, and Keller.[5] Late in 1976, representatives of BPA and the Los Alamos Scientific Laboratory (LASL) developed the concept of installing a small SMES unit for the purpose of providing system damping similar to that now available through modulation of the Pacific HVDC Intertie. The design parameters of the unit to be installed at the Chief Joseph Substation near the Grand Coulee Dam are summarized in Table I.

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	5
Maximum coil terminal voltage, kV	2.13
Coil operating temperature, K	4.5
Coil lifetime, cycles	$>10^7$
Heat load at 4.5 K, W	<150
Coil diameter, m	2.7

The coil will be immersion cooled in liquid helium at 4.5 K and will have an open wound construction very similar to that employed in existing coils. The unusual features of the coil are the very low heat generation allowed, despite the unusually short cycle time, and the very large number of operating cycles expected over its life. The conductor proposed for this application is a modification of the conductor used by Westinghouse[6] in a pulsed superconducting coil constructed for the Controlled Thermonuclear Reactor development program at LASL. The conductor will be cabled from a number of superconductors made into subcables. It will consist of superconducting composite strands surrounded by six copper or perhaps aluminum strands forming an insulated, first-level subcable. Six of the first level subcables will be wrapped around an inactive core to form a second-level subcable. Finally twelve second-level subcables will be wrapped on a structural element to form the complete conductor.

Most of the other components of the unit are well within the state of the art. The converter will be a scaled-down version of the thyristor units now used on high-voltage dc-transmission lines.

The control system for regulating the power flow between the ac system and the SMES system has been developed and demonstrated in the laboratory.[7] An analysis just completed by P. C. Krause, Purdue University, confirms work done by the Bonneville Power Administration on the energy storage requirement and power rating of the unit and its expected control behavior. The refrigerator is a standard unit available from several manufacturers. Some redundant components may be required to bring the refrigerator up to the performance level expected for an electric power system. The dewar, similar to one that has operated successfully for a period of several years,[8] must be made of a nonconductive material such as epoxy fiber glass to avoid eddy current heating as the coil is charged and discharged.

II. SUPERCONDUCTING COIL

Previous studies[9] show that SMES coils will be most economical if they are built as solenoids with a height-to-diameter ratio of about one-third

Manuscript received September 29, 1978

*Work performed under the auspices of the U. S. Department of Energy. Los Alamos Scientific Laboratory of the University of California, Los Alamos, NM 87545 and with a maximum field, B_{max}, at the windings in the range of 4 to 5 T. The stored energy, when fully charged, is to be 30 MJ, even though a maximum of only 9.1 MJ is to be exchanged with the ac-power system on each cycle. Storing more energy than is needed for discharge limits the cyclic strain and the magnetic field variation experienced by the coil components and results in better fatigue performance and sharply decreased heat load compared with storing, for instance, 20 MJ. The current drops from 5 kA to 4.17 kA during the magnet discharge, and the maximum field at the conductor drops from 3.92 T to 3.27 T. Parameters for the proposed coil are given in Table II. The inductance was calculated by using the tables of Grover,[10] and the magnetic fields and resulting forces were calculated by using the computer program CSYD.[11]

TABLE II
PARAMETERS OF A 30-MJ SYSTEM STABILIZING COIL

Energy stored at full charge, MJ	30
Energy stored at end of discharge, MJ	20.9
Current at full charge, kA	5
Insulation standoff voltage, kV	10
Maximum field at full charge, T	3.92
Inductance, H	2.4
Operating temperature, K	4.5
Mean radius, m	1.29
Height, m	0.86
Radial thickness, m	0.34
Number of turns	918
Winding pattern	layer
Number of layers	24
Number of turns per layer	38
Turn-to-turn separation axial and radial, mm	2
Conductor length, m	7450
NbTi volume, m^3	2.27×10^{-2}
NbTi mass, kg	127
Composite core mass, kg	724
First subcable mass, kg	5520
Second subcable mass, kg	6450
Strap mass, kg	3060
Current density in copper at 5kA, A/m^2	6.2×10^7
Current density in superconductor, A/m^2	1.8×10^9

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 occurs near the average radius and in the axial midplane. It is 10.5 MPa (1520 psi) compressive, or 20 MPa (2900 psi) in the strap. The maximum hoop stress, which also occurs at the coil midplane, is [illegible]0 MPa (41,000 psi) in the strap. All stresses will decrease by a factor of 0.335 during the discharge portion of the magnet operating cycle. The main coil structural material will be epoxy fiber glass G10 CR, and the highest fault mode voltage across the coil will be 10 kV.

III. CONDUCTOR DESIGN

The design of the conductor and its support are patterned after that of the Westinghouse coil constructed for the LASL/METS program. This coil was discharged repeatedly at 40 kV from 10 kA to 0 A without any premature, unexpected losses of superconductivity. It is possible to start with a slightly different strand composition from that used for the METS conductor and add sufficient copper to have it be cryostable while still having low losses. Specifications for the proposed conductor are given in Table III.

The conductor is designed to operate at 90% of critical current along the load line. Six copper wires are to be cabled about the copper and NbTi composite core to form the first-level subcable. This structure was suggested by Wang.[12] 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 superconducting core that will be used to detect resistive regions. Twelve of the (6 + 1) second-level subcables are cabled about a supporting strap to form the complete conductor. Figure 1 shows the proposed conductor.

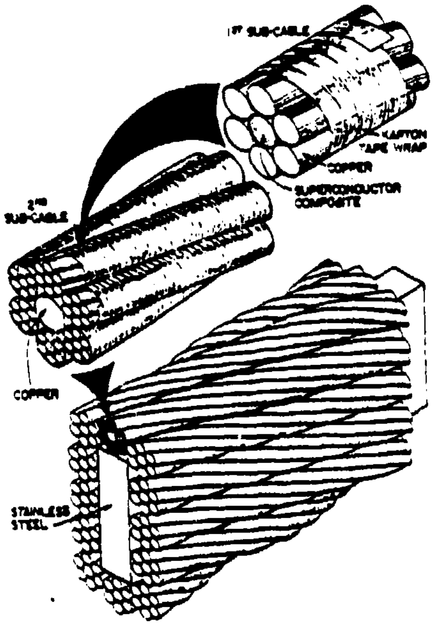

Fig. 1.
Low-loss superconductor for the 30-MJ coil.

TABLE III
SPECIFICATIONS FOR A CRYOSTABLE CONDUCTOR
FOR A 30-MJ SYSTEM STABILIZING COIL

Superconductor Composite Core	
Area of NbTi, mm^2	4.24×10^{-2}
Filament diameter, µm	8
Number of filaments	844
Strand diameter, mm	0.462
Cu to NbTi ratio	2.95:1
Twist pitch, mm	3.69
First Subcable	
Six copper wires cabled about a core	(6 + 1)
Uncompacted diameter, mm	1.39
Overall Cu to NbTi ratio	26.7:1
Insulation	Kapton
Second Subcable (Uninsulated)	
Six first subcables around a core	6 x (6 + 1) + 1
Uncompacted diameter, mm	4.16
Finished Conductor	
Twelve second subcables around a supporting strap	
Strap dimension, mm	4 x 13
Uncompacted conductor dimension, mm	12 x 21

---

*DuPont trademark.

IV. STABILITY, PROTECTION, AND LOSSES

The Joule heating per unit length of conductor is calculated to be 92 W/m. For reasonable values of heat flux and surface area, recovery from Joule heating will occur.

Although the proposed coil and conductor will be self-protecting under regular operation, there may be system emergencies which require a back-up protection system that will discharge the coil quickly. If the 2.18-kV capacity of the ac-to-dc converter were used to discharge 30-MJ at 5 kA, the decay constant will be 5.5 s.

A discharge of coil energy through the converter back into the ac line at the wrong time might trigger an instability of the type the unit is designed to control. Therefore, the coil energy is to be dissipated in a 2-ohm external resistor, with a terminal voltage of 10 kV and a discharge time of 1.2 s. Laboratory experience indicates that the quench detection sensitivity against a background 2 kV operating voltage would 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 boil-off 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 of 0.30 by mass and vapor-locking could occur.[6] Calculations show that the electrical protection system should detect a considerably smaller normal region and should trigger well before such a situation occurs.

The loss calculations were performed by using the formulas of Walker and Murphy[13] averaged over the volume of the coil and over the time variation of field during the charge-discharge cycle. The hysteresis loss was overestimated by assuming $j_c = 2.1 \times 10^9$ A/m^2 at 4 T, rather than the value $j_c = 1.8 \times 10^9$ A/m^2 used in designing the conductor. The transverse resistivity of the conductor was taken as the average value for copper over the coil volume, $\rho = 2 \times 10^{-10}$ Ω-m. Results of these calculations are presented in Table IV.

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

Conductor Losses	Watts
Hysteresis	39.4
Self-field	2.6
Coupling	8.3
Eddy currents	8.4
	58.7
Structure Losses	
Eddy currents	0.2
Mechanical	50

V. ELECTRICAL INTERFACE

A line-commutated converter is the electrical interface between the 230-kV ac bus and the superconducting coil. This type of converter, with fast control, is ideally suited for bidirectional power flow in the coil. The coil absorbs power from the ac system and acts as a load during one half-cycle when the converter voltage is positive. During the next half-cycle the converter [illegible]ltage is made negative and the coil operates as [illegible]ator sending power back into the ac systems. [illegible]verter design parameters can be determined fro[illegible] [illegible]ximum [illegible]usoidal 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 5 kA, determined because of superconductor considerations, is also the maximum converter current. The maximum converter voltage will be 2.18 kV at a current of 4.55 kA. The converter has to be designed for the maximum voltage. For a 10% commutation drop for load currents close to 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. A 12-pulse converter, consisting of two Graetz bridges, was chosen for this application instead of a single 6-pulse converter because it requires less filter capacity and less installed transformer power. A single, 12.75-MVA transformer with a delta primary winding and two secondary windings (one in delta, one in star) connects the converter to the 230-kV bus.

Figure 2 shows the laboratory results of a small-scale SMES system. The power demand is sinusoidal with a frequency of 0.3 Hz. The converter or coil power meets this demand perfectly. Figure 2 also shows the time dependence of current and voltage expected for the BPA unit.

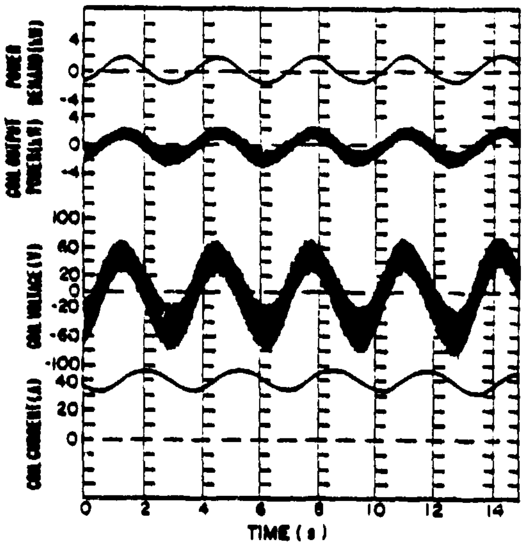

Fig. 2.
Oscillograms of the response of coil voltage, current, and power of a 3.8-H SMES system subjected to a 0.3-Hz sinusoidal power demand signal.

VI. CRYOGENIC COMPONENTS

To avoid eddy-current heating, a helium dewar made of an insulating material must be used. The simplest dewar configuration obtainable, a top opening cylindrical vessel of liquid helium in which the coil is suspended from the upper lid, is proposed. The dewar material is to be fiber glass-reinforced plastic.

A CTI Cryogenics/Sulzer, Model TCF-50 refrigerator is being purchased. The refrigerator has screw compressors for long-term reliability and a slide valve arrangement for adjustment of the compressor throughput from 30 to 100%. Two compressor assemblies provide maximum capacity and reliability. The refrigerator has gas-bearing turboexpanders.

The refrigeration requirements are given in Table V. Those for the coil are probably high because a conservative value was assumed for mechanical losses and the hysteresis loss can be reduced by using a smaller NbTi filament.

TABLE V

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

Refrigeration loads at 4.5 K	Watts
Conductor ac losses	59
Mechanical losses	50
Dewar heat leak (radiation and conduction)	8
Transfer line losses (liquid nitrogen shielding)	3
Total	120
Liquefaction loads, Power leads, ℓ/h	15

VII. 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 the cryogenic environment for fiber glass-epoxy laminates and electrical insulating materials. Abrasion, wear, and cracking can be serious problems. An experiment, still to be devised, 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.

VIII. ENVIRONMENTAL CONSIDERATIONS

All SMES units will produce magnetic fields beyond the cryogenic enclosure. For the 30-MJ coil, the field outside the building will be only a few gauss. At 30 m (100 ft) the field should be below the average value of the earth's magnetic field, 0.3 G. Thirty 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.

IX. CONCLUSIONS

Superconducting magne[illegible] energy storage systems for power transmission l[illegible]bilization are well within the present state [illegible] art. A 30-MJ superconducting storage system [illegible] 10-MW power rating can be built to modulate, at 0.35 Hz, the AC Intertie between the Pacific Northwest and s[illegible]hern California to damp oscillations.

REFERENCES

1. G. Hingorani, "Operating Experience of the Pacific Northwest-Southwest HVDC Intertie," Proc. Am. Power Conf. 35, 1160-1169 (1973).
2. R. L. Cresap, W. A. Mittelstadt, "Small Signal Modulation of the Pacific HVDC Intertie," IEEE-PAS, 95, 536-541 (1976).
3. R. L. Cresap, W. A. Mittelstadt, D. N. Scott, C. W. Taylor, "Operating Experience with Modulation of the Pacific HVDC Intertie," paper presented at IEEE-PAS Summer Meeting, Mexico City (1977).
4. N. Mohan, "Superconductive Energy Storage Inductors for Power System," Ph.D. Thesis, University of Wisconsin, Department of Electrical Engineering, Madison, Wisconsin (1973).
5. W. V. Hassenzahl, B. L. Baker, W. E. Keller, "The Economics of Superconducting Magnetic Energy Storage Systems for Load Leveling: A Comparison With Other Systems," Los Alamos Scientific Laboratory report LA-5377-MS (August 1973).
6. C. J. Mole, P. W. Eckels, H. E. Haller, III, M. A. Janocko, S. A. Karpathy, D. C. Litz, E. Mullan, P. Reicher, Z. N. Sanjara, "A Superconducting 0.54-MJ Pulsed Energy Storage Coil," Paper CE-2 presented at the CEC/ICMC, Boulder, Colorado, August 2-5, 1977.
7. W. V. Hassenzahl, H. J. Boenig, "Superconducting Magnetic Energy Storage," paper presented at World Electrotechnical Congress, Moscow 1977.
8. C. R. King, K. D. Williamson, Jr., W. Goree, "Development of Large Fiber Glass Reinforced Plastic Dewars for Superconducting Magnets at 4 K," 1976 Winter ASME Meeting, New York, New York, November 28-December 3, 1976.
9. See, for instance Los Alamos Scientific Laboratory Report LA-6004-PR, compiled by W. V. Hassenzahl (July 1975).
10. F. W. Grover, Inductance Calculations, Van Nostrand, New York 1946.
11. R. F. Holsinger, "Coil System Design," University of California, Berkeley, report UCRL-16958 (1966).
12. S. T. Wang, S. H. Kim, L. R. Turner, K. M. Thompson, W. F. Praeg, C. I. Krieger, R. L. Kustom, "Design and Development of Cryostable Superconducting Ohmic Heating Coils for a Tokamak," Paper IC-6 presented at the CEC/ICMC, Boulder, Colorado, August 2-5, 1977.
13. M. S. Walker and J. H. Murphy, ONR Contract N00014-73-C-0461, (September 1975).