A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

LA-UR--83-2516

DE83 017318

CTDF-830971--1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE.
It has been reproduced from the best available copy to permit the broadest possible availability.

TITLE: TESTS OF THE 30-MJ SUPERCONDUCTING MAGNETIC-ENERGY STORAGE UNIT

AUTHOR(S): H. J. Bornig, CTR-9, J. W. Dean, CTR-9, J. D. Rogers, CTR-9
R. I. Schermer, AT-5, J. F. Hauer, Bonneville Power Administration

SUBMITTED TO: 8th Int'l Magnet Conf., September 5-9, 1983,
Grenoble, France

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

MASTER

TESTS OF THE 30-MJ SUPERCONDUCTING MAGNETIC-ENERGY STORAGE UNIT

H. J. Boenig, J. W. Dean, J. D. Rogers, R. I. Schermer
Los Alamos National Laboratory, Los Alamos, NM 87545
J. F. Hauer
Bonneville Power Administration, Portland, OR 97208

Résumé - Un accumulateur d'énergie magnétique supraconductrice (SMES) de 30 MJ (8.4 kWh) avec un convertisseur de 10 MW fut installé durant les derniers mois de 1982 à la sous-station de Bonneville Power Administration (BPA), à Tacoma, Washington. Cette unité, qui est capable d'absorber et de fournir une énergie maximum de 10 MJ à une fréquence de 0.35 Hz, a été conçue pour atténuer les principales oscillations de puissance du Pacific ac Intertie. L'unité a été testée en détail durant la première moitié de 1983. Dans le présent article, les composantes principales de cette unité sont décrites, ainsi que le démarrage et l'opération continue de la bobine, du vase dewar, du réfrigérateur et du convertisseur. L'unité a absorbé un maximum de puissance de 11.8 MW. La puissance réelle fut modulée avec une demande de puissance sinusoïdale de fréquences 0.1 et 1.2 Hz et d'amplitude maximum ± 8.3 MW. Cette unité s'est comportée conformément à ses normes de conception, sans aucun problème majeur.

Abstract - A 30-MJ (8.4 kWh) superconducting magnetic energy storage (SMES) unit with a 10-MW converter was installed during the later months of 1982 at the Bonneville Power Administration (BPA) Tacoma substation in Tacoma, Washington. The unit, which is capable of absorbing and releasing up to 10 MJ of energy at a frequency of 0.35 Hz, was designed to damp the dominant power swing mode of the Pacific AC Intertie. Extensive tests were performed with the unit during the first half of 1983. This paper will review the major components of the storage unit and describe the startup and steady state operating experience with the coil, dewar, refrigerator and converter. The unit has absorbed power up to a level of 11.8 MW. Real power was modulated following a sinusoidal power demand with frequencies from 0.1 to 1.2 Hz and a power level up to ± 8.3 MW. The unit has performed in accordance with design expectations and no major problems have developed.

I - INTRODUCTION

The use of a superconducting magnetic energy storage device as a power system stabilizer was suggested in 1973[1]. Such a unit is suitable for power transmission stabilization because it can provide positive damping by absorbing and releasing energy. A SMES stabilizer has a fast response time of about 10 ms during which a transition from absorbing to releasing of energy can occur.

TABLE I

PARAMETERS OF THE 30 MJ SMES UNIT

Maximum power capability, MW	10
Maximum frequency, Hz	1.0
Maximum energy interchange, MJ	9.1
Maximum stored energy, MJ	30.0
Coil current at full charge, kA	4.9
Maximum coil terminal voltage, kV	2.4
Coil operating temperature, K	4.5
Coil lifetime, cycles	10^8
Heat load at 4.5 K, W	< 150
Mean coil diameter, m	3

Late in 1975, representatives of BPA and Los Alamos National Laboratory developed the concept of installing a small SMES unit for the purpose of providing an alternate method for damping the Pacific AC Intertie power oscillation. Background information on the project has appeared previously[2] and should be consulted for details. Important parameters of the 30 MJ unit are summarized in Table I. The unit was installed in the second half of 1982 in

Fig. 1 - 30 MJ SMES Unit Installation.

Fig. 2 - 30 MJ Dewar and Support Structure.

the BPA Tacoma Substation. Figure 1 is a photograph of the 30 MJ system components. The foreground in Fig. 1 is occupied by the trailers housing major subsystems. From left to right they are: 1 MW cooling tower, 17.25 MPa compressors for gas recovery, refrigerator, liquid nitrogen supply, control/workshop trailer and helium tank car. Beyond the control trailer is the ac-dc converter, flanked by two 6 MVA transformers with the high current buswork visible. In the center background is the coil, contained within its fiber-reinforced plastic, liquid helium dewar and suspended from concrete mounting pillars. A close-up of the dewar and the support structure is given in Fig. 2.

Beginning in the middle of January 1983, the coil and helium vessel were cooled down. The unit was energized for the first time on Feb. 16, 1983, and extensive SMES device tests and power system tests with the unit were performed on a periodic basis until the end of June 1983.

II - DEWAR

The cryostat is the world's largest fiber-reinforced plastic, open-mouthed dewar. It is toroidal in shape, with a room temperature bore. The inner liquid helium vessel is made of fiberglass cloth/epoxy, hand fabricated, using wet layup techniques. The larger diameter wall is 1.78 cm thick, while the smaller diameter wall, which can fail by buckling, is 2.54 cm thick. Design buckling pressure is 0.41 MPa. The outer room temperature vessel is made of polyester/chopped glass and is roughly 4.13 cm thick. The seal for the vacuum space between the two vessels is permanent, made by hand layup of fiberglass cloth and epoxy. The helium space is sealed by two O-rings, with the grooves machined into the steel lid. Thermal insulation in the vacuum space is provided by 100 layers of double-sided superinsulation, interleaved with Nexus cloth.

The distance from the lid to the average liquid level is 96.5 cm. This space is broken by five aluminum foil covered baffles. Openings in the baffles for support structure, piping and wiring have small clearances to reduce radiant heat transfer. Gas that moves upward, extracting heat from the baffles and structure, is collected just under the lid at six circumferential locations. The underside of the lid is

the dewar, measured to the average operating liquid level. These are: 1. Conduction down and heating ($I^2 R$) in the power leads, 2. Conduction down the magnet supports and down the helium gas column, 3. Radiation through the dewar sides and bottom, and 4. Conduction down the dewar walls. The current leads boil-off rate was measured to be 15 l/h at zero current with a very small increase for currents up to 5 kA. The dewar loss was determined to be 12 l/h. Additional information concerning the dewar and its performance is given in Ref. [3].

III - SUPERCONDUCTING COIL

The design and fabrication techniques of the superconducting cable and coil have been reported previously[4]. The coil was mounted into the dewar on site. The coil inductance was determined to be 2.64 H, based on charging voltage and current measurements. The measured value of the inductance agrees well with the calculated value. The critical current limit remains unknown, as the coil has never quenched. In addition, the coil has not shown any signs of voltage breakdown. The coil has been subjected to the following maximum current and voltage conditions: 1. The coil was energized with a constant current of 5 kA for up to 70 min. 2. A maximum coil current of 5.4 kA with a current rise of 880 A/s was measured during overcurrent limit adjustment tests. 3. During power modulation tests, the coil current varied for hours between 4.1 and 4.9 kA, while the coil voltage varied between 2.2 kV and -2.0 kV. 4. The coil has withstood a 5 kV voltage stress during an emergency shutdown operation when the coil current of 5 kA was forced into a 1 Ω resistor.

When the current in the coil is modulated, the coil experiences eddy current and hysteresis losses. The only technique available for magnet loss measurements is to note the steady state change in the refrigerator compressor suction pressure, caused by magnet current cycling at fixed frequency and power modulation level, and to compare the result with data taken without modulation. These measurements were tedious and error prone due to the long system time constant with an uncertainty caused by slow diurnal drifts in system pressure and temperature. The minimum detectable power increment is about 3 W. The measured losses, for instance, 54 W of cyclic losses at a coil power modulation level of ± 8.3 MW and 1 Hz determined over an 8 h period, are higher than were previously calculated. These losses are higher than the refrigerator can sustain continuously. The maximum estimated continuous load the refrigerator could provide would be ± 7.5 MW. Test observations indicate that the cyclic losses are predominantly hysteretic. At any constant current the bridge generates 1280 V peak-to-peak voltage pulses at a repetition rate of 720 s^{-1} . This ripple voltage becomes close to zero at maximum positive bridge voltage and appears in modulated form when the bridge supplies a sinusoidal voltage. Thus the predicted loss is greatest at constant current and is attributable to ripple. The additional Joule heating loss at 5 kA is less than 5 W.

IV - CRYOGENIC SYSTEM

The cryogenic system[3] comprises a helium refrigerator, high pressure gas recovery compressors, a gas storage railroad tank car and a cooling tower. The refrigerator is a CTI Model 2800 with three variable flow screw compressors, two Sulzer gas bearing turbines and liquid nitrogen precooling. The system was rated for a capacity of 90 l/h or near 300 W, but undersized turbine nozzle rings limit gas flow through the high pressure side of the cold box. To date a maximum liquefaction rate of 60 l/h into a 500 l dewar has been achieved. During cooling of the system at the Tacoma Substation, the refrigerator suffered initially from absorption of approximately 10 to 20 kg of water from the coil and the dewar. This water entered the cold box, forcing it to shut down. The accumulated moisture in the cold box has been slowly trapped in the liquid nitrogen absorbers, from which it can be evacuated by routine purging procedures without shutdown.

With the refrigerator attached to the coil dewar in closed cycle operation there are three additional heat sources in the system: 1. A calorimeter heater located at the JT valve can be used to introduce a known amount of power into the system for calibration. 2. When the coil current is modulated, heat is deposited in the helium

bath, and 3. The helium transfer lines are liquid nitrogen traced and were expected to have a heat leak of 5 W. There are two obvious cold spots at joints that seriously affect system performance. The transfer line losses were determined to be 75 W. At maximum compressor discharge pressure the refrigerator supplies 220 W. With the 27 l/h, or roughly 90 W, for the dewar and lead loss and the 75 W for the transfer line loss, the system can sustain 45 to 50 W of steady state power losses, caused by current modulation.

V - ELECTRICAL SYSTEM

The electrical system[5] consists of two 6 MVA, 13.8 kV/0.92 kV transformers, each feeding a six-pulse, line-commutated bridge. The two bridges, as shown in Fig. 3, are connected in series, forming a 12-pulse converter, which can provide a continuously variable terminal voltage between +2.2 kV to -2.0 kV. A bypass circuit across each bridge provides an alternate current path in case of bridge malfunctions. A dc breaker, that can insert a 1 Ω resistor in series with the coil, allows stored energy to be dissipated as heat. The two bridges regulate the power flow between the supply ac bus and the dc coil. The power level during charging and discharging can be regulated continuously by voltage control of the converter. The converter no load output voltage is 2.40 kV in the rectifier mode and -1.84 kV in the inverter mode. The inversion end stop has been set to 140°, explaining the discrepancy between maximum positive and negative voltage.

A series connection of two bridges allows for many control options by obtaining the desired real power output of the unit with the reactive power as a variable[6]. For example, a real power output of 4 MW, with a coil current of 5 kA, is achieved with a converter voltage of 800 V. A total converter output of 800 V can be obtained by the sum of a combination of individual bridge voltages, for instance by 300 V plus 500 V, 1000 V plus -200 V, or so on. Each voltage setting results in the same real power value with a different reactive power level. Of special interest is a control mode with equal bridge voltages, called equal α (EA) mode, because it gives the maximum real power output. A disadvantage of the EA mode, when used for sinusoidal real power modulation, is the associated reactive power modulation with twice the frequency. A variable real power variation with constant reactive power (CQ) mode decouples the effects. Also of interest is a constant real power (CP) mode with only reactive power variations.

VI - TESTS

Prior to the commissioning tests at Tacoma, the major components of the 30 MJ SMES unit, such as the refrigerator and converter, had been only partially tested, while the coil and dewar had not been tested at all. Initially the unit was tested to determine its operating limits. During the startup procedure, the current in the coil was increased by steps of a 1000 A up to 3000 A. The current was held constant at 1000 A and 2000 A for approximately 5 min while the proper functioning of the converter, such as 12-pulse symmetry, was determined. Then the current was kept

1. Converter transformers, 6 MVA each;
2. 6-pulse bridge (± 1.25 kV, 5.5 kA);
3. 6-pulse bridge (± 1.25 kV, 5.5 kA);
4. Bypass SCRs;
5. Dump resistor (1.0 Ω);
6. DC breaker;
7. Superconducting coil (2.64 H).

Fig. 3 - Block Diagram of 30 MJ Electrical System.

Fig. 4 - Charging and Discharging Cycle of 30 MJ Coil.

constant at a level of 3000 A for two hours and 4000 A for one hour. During the tests the converter, refrigerator, current leads and coil performance were monitored. A slight increase in the heat load on the refrigerator was observed, starting at 3000 A and measured by the increase in the refrigerator compressor suction pressure. In the next step the current was increased to 5000 A at a low rate of 500 A/min and was kept constant at this level for 70 min. This test verified the thermal loading of the converter, transformers and current leads. No external indications, such as acoustical noise, possibly being a sign of conductor movement or shifting of the support structure, were noticed for the dewar-coil assembly, even at temporary currents up to 5.4 kA. At 5.4 kA the coil stores 38.5 MJ of energy, at a field strength of 3.2 T, well exceeding the design requirements.

The unit was then subjected to dynamic testing by increasing and decreasing the coil current at different rates, up to the maximum rate of 880 A/s ($dB/dt = 0.52$ T/s) during the charging mode and 715 A/s ($dB/dt = 0.42$ T/s) during the discharging mode. Figure 4 shows results from a maximum charging and discharging cycle with the converter switched between full voltage limits. The top two traces depict the individual bridge voltage V_{DC1} and V_{DC2} of the converter, the middle trace indicates the coil current I_{DC} , reaching a peak of 5.1 kA, and the lower two traces show the reactive and real power Q_{SMES} and P_{SMES} of the unit measured at the 13.8 kV line. The current of 5 kA is reached in 5.7 s. The 30 MJ SMES unit input power at 5 kA is 11.48 MW and -9.50 MW during coil charge, and discharge, respectively, whereas the coil power is 11.16 MW and -9.80 MW. This implies that the combined losses for the transformers and the converter are approximately 300 kW at

this operating point. The cryogenic system absorbs about 400 kW, so that the total system loss is near 7% of the throughput power.

The next tests determined the behavior of the 30 MJ SMES unit in the BPA transmission system. For that purpose the power of the SMES unit was modulated with random noise and sinusoidal power demand signals. The frequency for the sinusoidal power variations ran from 0.1 Hz to 1.2 Hz. Power system parameters, such as the AC Intertie power, were metered and analyzed to determine what frequency would cause oscillations. The power modulation tests were performed for different converter control modes, such as EA, CQ and CP modes. Figure 5 shows some typical results for the EA and CQ modes. The five traces from the top to bottom show the real (P_{SMES}) and active (Q_{SMES}) power of the SMES unit, the two bridge voltages (V_{DC1} and V_{DC2}), and the coil current (I_{DC}). Note that for the EA modulation the bridge voltages are identical and that the lowest harmonic of the reactive power variation has twice the frequency of the real power variation. In the CQ modulation scheme the individual bridge voltages are different, which results in no reactive power variation. Preliminary evaluations of the effect of the power modulation on the BPA transmission system reveal that a sinusoidal power variation of the SMES unit causes

Fig. 5. Power modulation tests with 30 MJ unit; EA mode (left), CQ mode (right).

modulation of the SMES unit results in AC Intertie noise which cannot be easily distinguished from the normal line noise caused by load changes.

The refrigerator was capable of maintaining the liquid level constant for power modulation levels up to ± 7.5 MW. It is expected that for stabilizer operation the refrigerator output is adequate, because the average power level will be below ± 7.5 MW.

REFERENCES

- [1] Mohan, N., Ph. D. Thesis (1973) Madison, WI.
- [2] Rogers, J. D., Boenig, H. J., Bronson, J. C., Colyer, D. B., Hassenzahl, W. V., Turner, R. D., Schermer, R. I., IEEE Trans. Mag., MAG-16(1979) 820.
- [3] Schermer, R. I., and others, invited paper, Cryogenic Engineering Conference, Colorado Springs, CO, (1983).
- [4] Hoffmann, E., Alcorn, J., Chen, W., Hsu, Y-H., Purcell, J., Schermer, R., IEEE Trans. Mag., MAG-17, (1981) 521.
- [5] Boenig, H. J., Turner, R. D., Neft, C. L., Sueker, K. H., Proc. 9th Symp. Eng. Prob. of Fusion Res., IEEE 81 CH 1715-2 NPS, (1981) 452.
- [6] Hauer, J. F., U. S. Dept. of Energy report Conf-820827 (1982) 201.