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1

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TITLE PLANT AND OPERATIONAL FEATURES OF THE BPA 30 MJ SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

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ABSTRACT

A 30 MJ superconducting magnetic energy storage (SMES) system was designed and developed for application in the Western U.S. Power System to damp power oscillations that limit high voltage a.c. transmission. The system is in place at the Bonneville Power Administration (BPA) Tacoma Substation and has been in an experimental use for over a year. Extended operations of the unit have been undertaken with success. The physical, electrical, and operational features of the SMES system are given.

INTRODUCTION

The 30 MJ SMES system was devised to modulate the BPA Pacific AC Intertie, a part of the Western U. S. Power System, to prevent undamped power oscillations at 0.35 Hz that were observed to be associated with high power transmission. The concept of using SMES to stabilize utility systems was suggested in 1973.[1] A formal proposal to the Department of Energy to initiate a program for a SMES system to damp oscillations on the BPA Pacific AC Intertie was proposed in 1978.[2] The SMES system was based on a 30 MJ superconducting coil, designed to operate at a frequency of 0.35 Hz with maximum current and field of 4.9 kA and 2.9 T. The system was established to have a power rating of 10 MW. Arrangements were made between the Los Alamos National Laboratory and the BPA to install the SMES system at the Tacoma Substation to interface through a 13.8 kV bus to the Western U. S. Power System. Installation of the SMES system occurred during 1982-83.

The initial objective of the SMES program was to provide a reliable, highly available alternate means to modulate the Pacific AC Intertie to damp unwanted power oscillations. BPA had already devised a means to provide the necessary transmission stability by modulating the Pacific HVDC Intertie at the Celilo converter station, where the d. c. line interfaces with the a. c. grid.[4-6] Clearly, the SMES system was to be an experimental device. The project objectives were altered because both availability and reliability are not sufficient. With this knowledge, BPA uses the system to assess power system dynamics with real and reactive power as variables of the SMES unit; to investigate the variability of power system dynamics with time and operating conditions; to monitor the effects of changes in loads, closely coupled to SMES, upon the power system response to SMES modulation; and to develop stability control techniques.

SYSTEM DESCRIPTION

The SMES facility is organized into three major subsystems, namely, energy storage and transfer, cryogenics and local control and data acquisition. A SMES system is based upon the nondissipative feature of superconducting material carrying d.c. current. For the 30 MJ coil, the superconducting material is the ductile alloy NbTi, imbedded as fine filaments in

a copper matrix. Small eddy current and hysteresis losses do occur in superconducting cables as a result of the magnetic field variation when the SMES coil is charged and discharged. Other heat loads to the 4.5 K liquid helium bath are from radiation and conduction through the containing dewar, heat conduction down the vapor cooled leads, and Joule heating in the helium vapor cooled leads that deliver the power to the coil at 4.5 K from ambient conditions. These heat loads are compensated by a CTI (now Koch Process Industries) Model 2600 helium refrigerator. The refrigerator also cools the storage coil from ambient temperature to 4.5 K and liquefies the helium for the coil immersion bath.

The SMES system interfaces with the utility through transformers and an SCR Graetz bridge converter. The charging-discharging rate and the power flow between the three phase power line or bus and the coil are determined by the amplitude and polarity of the bridge voltage. A phase controlled converter requires reactive power from the a.c. bus. For the 30 MJ system the reactive power compensation requirement can be addressed by operating the converter in the constant Q, buck-boost mode.[7]

The SMES system has current and voltage operating limits. The short sample current or limiting transport current of the superconducting cable and the mechanical structure of the coil determine the highest operating current. Appropriate design factors are provided to assure safe operation. These include ample thermal margin for the superconductor to remove heat from eddy current and hysteresis losses and inadvertent heat pulses that may arise from unplanned but quite small, sudden conductor movement. Stress and strain margins are designed into the coil structure and the superconducting cable. Cyclic stress considerations for 10^8 cycles arising from 100% stored energy changed to 67% and back to 100% at 0.35 Hz were included with component testing done to assure proper performance.[8] The choice of an energy storage coil to operate between 20 and 30 MJ is based upon reducing losses in the superconducting cable with a residual bias of magnetic field. These factors, in turn, determine the desirable lower current level, although, of course, the coil can be completely discharged. Coil protection by rapid energy discharge into a resistive dump circuit requires a higher withstand voltage than does normal operation. The 13.75 MW converter operates between + 2.7 and -2.0 kV, whereas protective energy release requires 5 kV withstand capability and dictates the desired voltage level.

A unique feature of the 30 MJ SMES stabilizer system is the nonconducting dewar. Because of the 0.35 Hz power flow, eddy currents would be induced with resistive heating of a conventional stainless steel dewar and would create an intolerable heat load to the liquid helium bath with an increase in refrigerator requirements. Furthermore, an oscillatory force could be detrimental if the coil were even slightly off axis in a metal dewar. The consequence of this set of conditions was to have a nonconducting fiberglass reinforced epoxy dewar, the largest in the world, made to hold the 30 MJ superconducting coil.

The refrigerator is supported by several major components which are trailer mounted. These are a heat rejection trailer, an evaporative cooler, to remove the compressor waste heat: a high pressure gas recovery trailer with diaphragm compressors to pump excess boil-off helium gas into storage: a railway tube car for the gas supply and storage: and a dewar trailer for storage of liquid nitrogen. The nitrogen is used in a first stage heat exchanger of the refrigerator to cool the helium gas and to trace the radiation shields of the helium transfer lines between the coil dewar and the refrigerator. The completed installation, a show piece and a tribute to the BPA engineering and crafts employees, is shown in Fig. 1. In the far right foreground is the railway tube car for the helium gas supply. Following from the right foreground are the control trailer, liquid nitrogen trailer, gas recovery system trailer and refrigerator, and the heat rejection trailer. In the background are the seismically mounted dewar/coil and the converter, right rear, with its power transformers. Figure 2 shows the 30 MJ superconducting coil in the nonconducting dewar, mounted on the specially constructed seismic foundation adjacent to the helium refrigerator trailer. The helium liquid delivery and cold gas return transfer lines between the dewar and refrigerator run overhead.

SYSTEM OPERATION

The SMES system was placed into operation in the BPA grid in February of 1983. The superconducting coil, vapor cooled leads, nonconducting dewar, and vacuum system all functioned to design specifications.

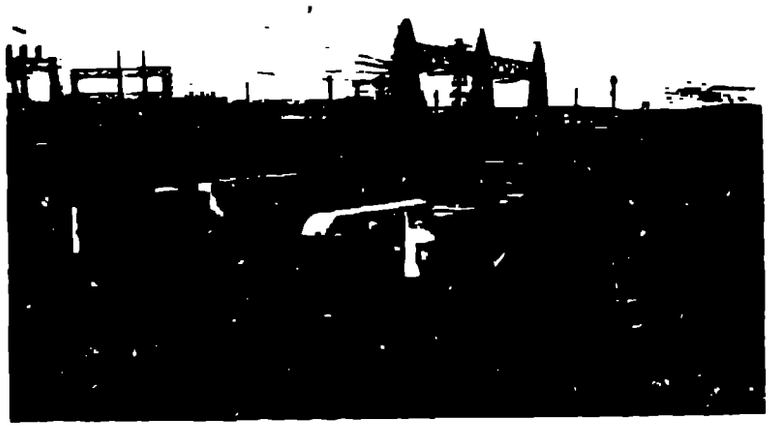


Fig. 1. 30 MJ SMES installation at the BPA Tacoma Substation.

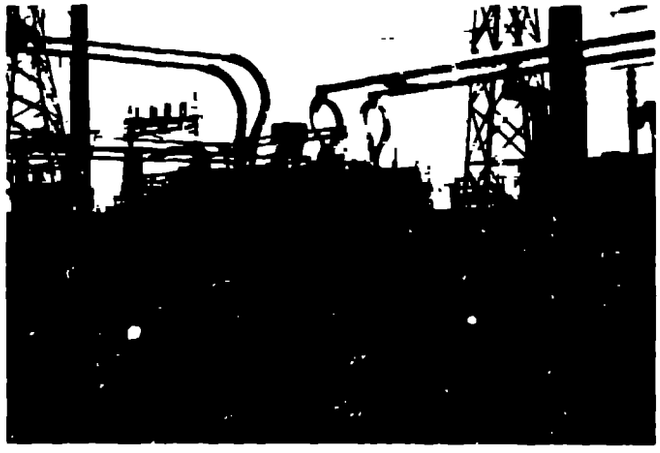
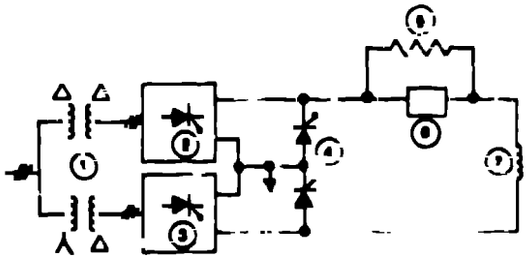


Fig. 2. 30 MJ SMES coil/nonconducting dewar installation at BPA Tacoma Substation.

A coil current of 5.4 kA was reached in contrast to the normal maximum operating current of 4.9 kA. The converter was operated at ±8.3 MW with power to and from the coil at frequencies ranging from 0.1 to 1.0 Hz with parallel modulation of the bridges and at ±4.5 MW real power with up to 9.5 MW reactive power in constant VAR mode.

The converter consists of two 5.5 kA, 1.25 kV 6-pulse bridges in series as shown in Fig. 3. Each bridge is energized by a 6 MVA transformer connected to the BPA 13.8 kV bus, which has a short-circuit capacity of roughly 1000 MVA. A bypass circuit across each bridge provides an alternate current path in case of bridge malfunctions, and a dc breaker, that can



1 CONVERTER TRANSFORMERS, 6MVA 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 (1.0Ω)
6 DC BREAKER
7 SUPERCONDUCTING COIL (2.64 H)

Fig. 3. SMES unit electrical schematic.

insert a 1 ohm resistor in series with the coil, allows stored energy to be dissipated as heat. This energy release circuit is activated upon detection of a.c. line loss or a converter failure.

A test of the system response is shown in Fig. 4, which compares equal amplititude (EA) modulation with constant VAR or constant Q (CQ) modulation. Modulation limits for a 0.3 Hz sinusoidal input and an average current of 4.5 kA are ±8.3MW in EA mode, and ±4.7 MW in CQ mode.

The refrigerator subsystem, composed of the refrigerator itself, the liquid nitrogen storage trailer, the evaporative cooler serving as the heat rejection subsystem, and a high pressure gas recovery system, all operate in essentially manual mode operation. The liquid nitrogen trailer is passive and supplies liquid nitrogen by preset thermostated metering valves. The heat rejection trailer has a main coolant pump, a blower, and a spray water pump, all of which run continuously. The high pressure gas recovery system has two Corblin compressors in parallel that operate to pump helium gas from a low pressure storage tank to the railway tube car by on-off operation between two preset pressure levels detected by pressurstats. The low pressure storage tank is supplied from the refrigerator compressors when the refrigerator valving is set in "Recovery". All three supporting refrigerator subsystems meet functional requirements. The desired computer controlled operation of the refrigerator was foregone because of limited budget and the shortened program period. The refrigerator runs continuously and is monitored regularly with control adjustments made as required. Internal control loops of the gas bearing turbines; some pressure regulator, relief type valves; and a heater in the internal cold box JT valve dewar are used to control the refrigerator.

On several occasions the dewar was isolated from the refrigerator and allowed to vent freely to the atmosphere. The gas vent rate, monitored for up to eight hours, drops sharply for one to two hours and then is stable, with the power leads venting gas equivalent to 15 ℓ/h and the dewar 17 ℓ/h liquid. There are three major contributions to the dewar heat leak in this configuration. Conduction down the coil supports, dewar walls, and, most important, down the helium gas column: - this heat must be intercepted by upflowing helium gas. One dimensional computer calculations predicted a 11 ℓ/h boiloff. Conduction down the power leads, intercepted by upward gas flow: - calculated boiloff rate of 8 ℓ/h for both leads at zero current assumed a lead of constant cross sectional area. The real leads have a very heavy section for the upper 20% of their length. Laboratory measurements yielding 15 ℓ/h were performed in a lossy dewar and are thus as difficult to interpret as the present results. The measurements did show, however, that boiloff rate was independent of current up to 5 kA. Radiation through the dewar sides and bottom was calculated to be 28 ℓ/hr.

These three effects are not additive. Calculations show that helium vaporized by radiation can be used to intercept the conduction loads on almost a one-for-one basis. Radiation cannot be separately estimated unless it is bigger than the total dewar plus lead flow. In that case the dewar lid and lead tops would run unusually cold, contrary to observation.

The separate dewar and lead flows adjust to provide minimum total boiloff consistent with valve settings. Further, we have determined that a dewar vent rate of 12 ℓ/h minimizes the refrigerator load. Thus, each separate vent rate must be close to minimum.

With the refrigerator attached to the coil dewar in closed cycle operation there are three additional heat sources in the system. A calorimeter heater located at the high pressure side of the Joule-Thompson (JT) valve can be adjusted to introduce a known amount of power into the system for calibration. When the coil is modulated, heat is deposited in the helium bath. The heat load at 5 kA d.c. is less than 5 W. The helium transfer lines are liquid nitrogen traced and should have a heat leak of 5 W. Two obvious cold spots at joints, however, seriously affect system performance.

As the load on the system changes the refrigerator automatically adjusts its capacity to meet the changed load. Consider, for instance, an increase in coil modulation that results in a transient excess of helium vaporization over liquefaction. System pressures rise: and because the compressor throughput is directly proportional to the suction pressure, the liquefaction rate rises until it just matches the new vaporization rate. The mass of liquid drops imperceptibly and, in fact, the liquid level rises noticeably due to thermal expansion. The system time constant is very long, due principally to

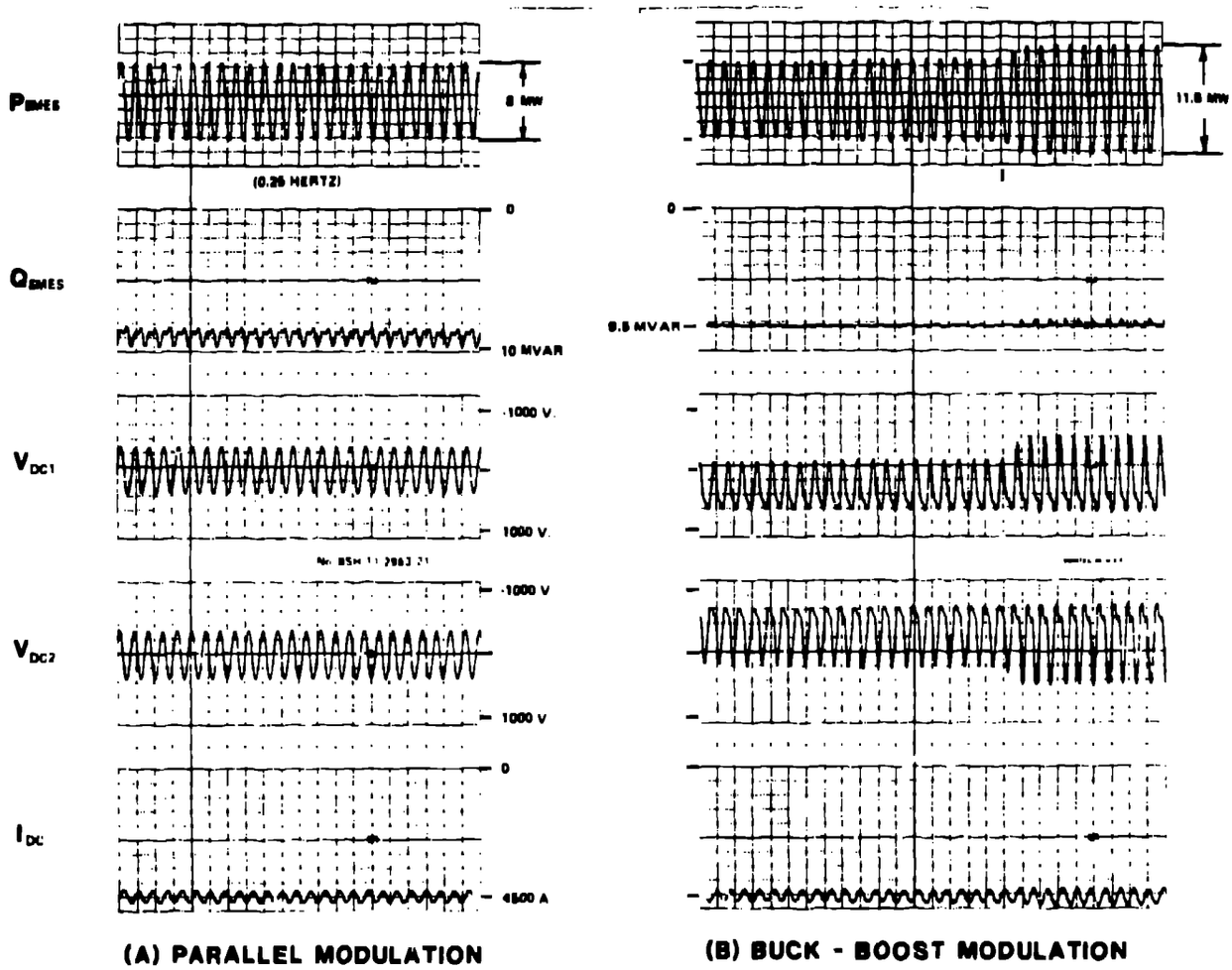


Fig. 4. Test of EA versus CQ modulation.

the presence of 5700 ℓ of liquid helium. Thus, without any operator intervention, the system follows slowly changing loads, ignores rapidly fluctuating loads, and operates very stably at constant load.

Figure 5 shows calibration data in the form of compressor suction pressure as a function of calorimeter power. All points were taken with at least a 12 h equilibration time. Non-linearity may be because system temperatures also change with heat input, leading to changes in turbine and JT valve efficiencies. Figure 5 represents only changes from equilibrium; an absolute calibration results if one accepts the advertized performance of 200 W at 1.29 MPa (18.7 psia) compressor suction pressure with full LN_2 flow. This suction pressure requires 35 W of calorimeter heat. The background heat load of 165 W is comprised of 90 W (27 ℓ/h) for the dewar and leads and 75 W of transfer line losses. Because the

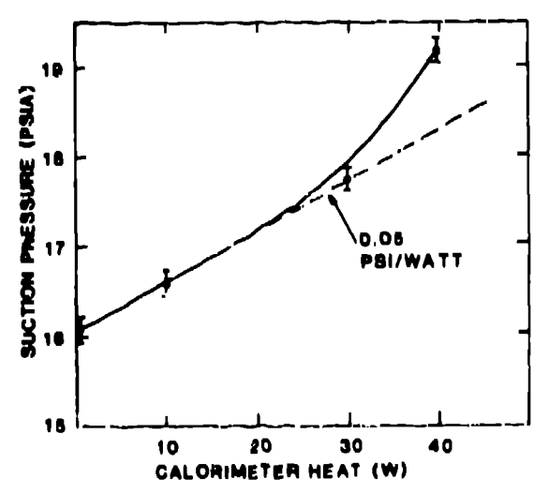


Fig. 5. Refrigerator performance calibration of compressor suction pressure versus electrical power applied to the internal calorimeter.

dewar/lead flow is completely satisfied, any small incremental heat input into the system can be observed. About 220 W refrigeration can be obtained at maximum compressor discharge pressure. With some safety margin, therefore, the system will tolerate 45 to 50 W of incremental, steady state power.

The only technique available for coil loss measurements is to note the steady state change in compressor suction pressure caused by coil cycling at fixed power and frequency and to compare the result with that shown in Fig. 5. These measurements are tedious and error prone due to the long system time constant and the resultant uncertainty caused by slow diurnal drifts in system pressure and temperature. The minimum detectable power increment is about 3 W. Table I gives experimental results at two values of power and three different frequencies, compared to predicted results.

The computer is used to monitor the SMES subsystems. Because it is not used for control of the refrigerator, only a minimum number of data points are monitored. Control of the power side of SMES is through the computer. Both parallel and buck-boost or constant VAR modulation of the converter bridges are accomplished by computer control.

SMES systems have been advocated as efficient energy storage systems for diurnal load leveling. The efficiency of a small SMES unit is not expected to be unusually high because small helium refrigerators are inherently inefficient. Regardless, power losses in the transformers and converter are about 300 kW, and auxiliary power to all other support subsystems is about 400 kW. This latter is for running the refrigerator compressors, the heat rejection subsystem pumps and blower, gas recovery compressors, several fans and vacuum pumps, and numerous small components. Thus, the power loss of 700 kW is only 7% of the 10 MW peak modulation rating of the SMES stabilizing system.

TABLE I

EXPERIMENTAL AND EXPECTED RESULTS FOR CYCLIC LOSSES

P_m (MW)	f (Hz)	Exper. Loss (W)	Predicted Loss (W)
8.4	1.0	54	34
4.4	1.0	32	17
4.4	0.4	33	19
4.4	0.2	34	21

SUMMARY

The 30 MJ SMES system, designed to damp unwanted power oscillations on the BPA Pacific AC Intertie, was completed. The system was installed at the BPA Tacoma Substation and was successfully operated in experiments conducted on the Western U. S. Power System. All major components met the functional design requirements, except the refrigerator capacity is limited, and the computer control of the refrigerator subsystem was not accomplished. Experiments with the SMES system covered a wide range of power levels with frequencies from 0.1 to 1.0 Hz. Both parallel and constant VAR modes of converter bridge modulation were used successfully. Operation of the SMES system was transferred to BPA, and the system has now been operated for long periods.

REFERENCES

1. N. Mohan, "Superconducting Energy Storage Inductors for Power System," Ph.D. Dissertation, University of Wisconsin, Dept. Elec. Eng., Madison, WI (1973).

2. H. J. Boenig, J. C. Bronson, D. B. Colyer, W. V.-Hassenzahl, J. D. Rogers, R. I. Schermer, "A Proposed 30-MJ Superconducting Magnetic Energy Storage Unit for Stabilizing an Electric Transmission System." Los Alamos Scientific Laboratory report LA-7312-P, June 1978.

3. J. D. Rogers, R. I. Schermer, B. L. Miller, J. F. Hauer, "30 MJ Superconducting Magnetic Energy Storage System for Electric Utility Transmission Stabilization," IEEE Proc. 71, 1099 (1983).

4. R. L. Cresap, W. A. Mittelstadt, "Small Signal Modulation of the Pacific HVDC Intertie," IEEE PAS, 95, 536-551 (1976).

5. R. L. Cresap, W. A. Mittelstadt, D. N. Scott, C. W. Taylor, "Operating Experience with Modulation of the Pacific HVDC Intertie," IEEE-PAS Summer Mtg., Mexico City, 1977.

6. R. L. Cresap, D. N. Scott, W. A. Mittelstadt, C. W. Taylor, "Damping of Pacific AC Intertie Oscillations via Modulation of the Parallel Pacific HVDC Intertie," CIGRE, Paris 1978, paper No. 14-05.

7. J. F. Hauer, "Utility Controls for BPA 30-MJ SMES System," 1982 Phys. and Chem. Storage Annual Contractors' Rev. Mtg., Washington, DC, August 23-26, 1982; U. S. Dept. Energy report Conf.-820827, 201-205 (December 1982).

8. R. I. Schermer, H. J. Boenig, M. Henke, R. D. Turner, R. Schramm, "Conductor Qualification Tests for the 30-MJ Bonneville Power Administration SMES Coil," IEEE MAG-17, 356-359 (1981).