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OPERATION OF THE 30 MJ SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM IN THE BONNEVILLE POWER ADMINISTRATION ELECTRICAL GRID*

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Abstract

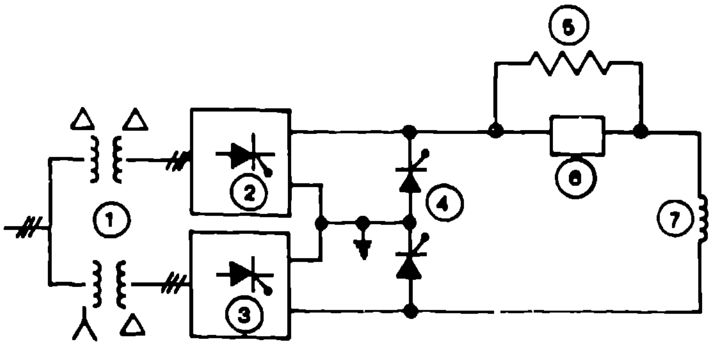
The 30 MJ superconducting magnetic energy storage (SMES) system was installed in the Bonneville Power Administration (BPA) Tacoma Substation in 1982-83. Operation of the unit since that time has been for over 1200 hours. Specific tests to explore the SMES system's thermal and electrical characteristics and the control functions were conducted. The coil heat load with current modulation was determined. A converter with two 6-pulse bridges interfaces the superconducting coil to the power bus. Equal bridge voltage amplitude and constant reactive power modes of operation of the system were run with computer control of the SCR bridge firing angles. Coil energy dump tests were performed. Electrical grid system response to SMES modulation was observed, and full power SMES modulation was undertaken.

Introduction

The use of a superconducting magnetic energy storage (SMES) unit for power system damping was suggested in 1973.[1] The 30 MJ unit was designed for such service as the modulated control element similar to HVDC Modulation.[2-4] As with HVDC Modulation, fluctuations of the Pacific AC Intertie current I_{ac} are sensed, and the SMES unit can respond with power variations to damp oscillatory intertie current components, when the 30 MJ unit operates in the closed loop stabilizer mode. The unit was first energized in February 1983. The short term operational capabilities of the unit were established, and endurance tests were performed to assess the mid term reliability of the superconducting coil as well as that of the helium refrigerator and other supporting subsystems. During the endurance test period, the unit was driven by a narrow band noise input, characteristic of the modulation signal for stabilizer operation, that also provided a useful test signal for gathering the power system response data needed for tuning of the SMES Modulation system.

The major components of the SMES unit are its superconducting coil, the nonconducting vacuum vessel, the cryogenic system with its liquid helium refrigerator, the ac/dc converter and the local control system. The engineering of these components is addressed in detail in three recent publications.[5,6,7]

The coil stores energy in its magentic field. Energy exchange between the coil and the ac system is controlled by a line commutated 12-pulse converter, shown in Fig. 1. Each of the two 6-pulse bridges is fed by a 13.8/0.93 kV transformer provided with a ±5% tap changer. The bridges maintain a unidirectional current I_d, so that positive converter voltage V_d produces a positive power output, charging the coil; and negative



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

Fig. 1. Electrical circuit diagram of 30 MJ SMES unit.

V_d produces negative power, discharging the coil. The bypass thyristors in Fig. 1 provide a path for I_d in the event of a converter failure. The dc breaker allows I_d to be diverted into a 1 ohm energy dump resistor, should a converter failure occur followed by a cryogenic system failure.

The solenoidal coil has an inductance of 2.6 H, a current rating of 5 kA, and a peak field of 3.0 T. Factors such as fatigue, mechanical forces, and superconductor stability dictate that stored energy during normal operation should be managed between about 20 MJ and 30 MJ, corresponding to currents of 4.0 kA and 4.8 kA. Figure 2 shows the housing of the coil, a

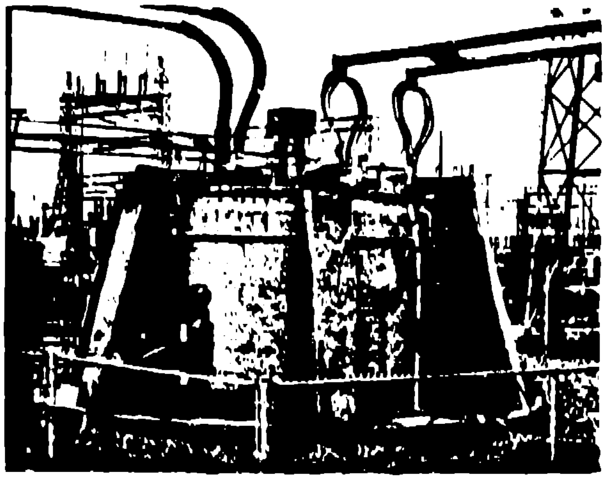


Fig. 2. Dewar and support structure of 30 MJ coil.

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fiber reinforced plastic dewar, along with its supporting structure. The dewar has an outer diameter of 3.9 m and a height of 2.7 m. The two 5.0 kA current conductors from the converter to the coil are in the upper right of the picture. The transfer lines for helium to the helium refrigerator are shown in the upper left of the picture. Two 6 MVA transformers feed the two 6-pulse bridges mounted on each side of the air cooled converter unit.[7] The dc breaker is also contained in the converter unit, while the dump resistor is mounted on top of the converter in a weather resistant compartment. The no load output voltage of the converter can be varied continuously between +2.4 kV and -1.9 kV with both bridges operating in series. The unequal limits are due to an inversion end stop that has been set to 140°. The protective energy release in the dump resistor requires 5 kV withstand capability and dictates the voltage design level.

The refrigerator is supported by components that 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 vaporized helium gas into storage; a railway tube car for the 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.

SMES System Operation

Charging and Discharging

The 30 MJ coil was first charged and discharged in the manual control mode. The coil power at 5 kA was 11.16 MW and -9.80 MW for charge and discharge, respectively. The peak current in the coil was 5.4 kA.

Protective Discharge

The protective circuit tests began with coil currents of 1 kA and then increased by 1 kA to 5 kA. All tests were successful with the coil energy deposited in the dump resistor and an exponential decay time constant of 2.6 s.[8] Voltages of 5 kV were developed across the coils, and no spurious switching or strong resonant voltage transients were observed.

Operating Modes

During normal operation, the coil current I_d plus the complex load $S_{ac} = P + jQ$, that the SMES unit presents to the power system, are established by local controller logic, where P and Q are the real and reactive powers, respectively. For the unit to operate as a stabilizer, one or more inputs to the controller must be generated remotely, according to a feedback control law that uses Pacific AC Intertie current I_{ac} as its primary input.[4] The controller permits some independence in the choice of P and Q and thus affords several modes for modulation.

If the converter fails or the ac supply relays out, then the stored energy cannot be returned to the power system. The coil current can be circulated through the converter bypass thyristors. Thyristor and busbar losses in this free wheeling mode of operation bring I_d to zero within an hour.

The converter bridges present associated complex loads S_1, S_2 to the ac system. For each S_i the power factor cos ϕ_i can be adjusted by means of the bridge firing angle α_i, and $|S_i|$ varies automatically as I_d changes.

Line commutated converters cannot be operated across a full 180° firing angle. Control for the SMES unit is between $\alpha_{min} = 5°$ and $\alpha_{max} = 140°$. End stop settings past 140° are possible but risk commutation failure.[7] This precaution reduces the ranges of constant reactive power (CQ) and constant real power (CP) modulation.

The SMES system was used for injecting and absorbing real power pulses into the high voltage electrical grid to identify system parameters. Tests were performed by injecting either sinusoidal, low frequency (0.1 to 1.2 Hz), real power pulses or a narrow band noise power signal into the electrical system. When sinusoidal power pulses are injected, the two independently controlled 6-pulse bridges of the converter can assume either an equal or a different phase delay angle. With equal phase delay angles (EA), a real power variation also causes a reactive power variation, while with independent bridge control, the reactive power can be kept constant.[8] Figures 3, 4, and 5 show three different converter loading conditions. Each recording depicts the bridge 1 voltage (V_{d1}), bridge 2 voltage (V_{d2}), the converter output current (I_d), which is the coil current, and the real (P_{SMES}) and reactive (Q_{SMES}) power of the SMES unit measured at the 13.8 kV bus. In Fig. 3, the SMES unit follows a sinusoidal power demand signal and both bridges have equal voltage output. The fundamental and second harmonic reactive power variations are significant. In Fig. 4, the SMES unit output shows sinusoidal real power, but the two bridges are controlled independently and provide a constant reactive power absorption. In Fig. 4 the SMES real power slowly increases and one bridge operates almost exclusively in the rectifier mode, while the other bridge operates in the inverter mode. In Fig. 5, the SMES unit follows a narrow band noise signal demand. The bridges are controlled with equal phase delay angle. Both positive and negative maximum voltages are reached. Limits for a 0.3 Hz sinusoidal input are ±8.3 MW in EA mode and ±4.7 MW in CQ mode. The CP modulation range with I_d = 4.5 kA is 7.3 to 11.3 MVAR, regardless of frequency. EA and CQ mode power levels of ±8.6 and ±5.0 MW, respectively, are attained with the transformer taps set for a higher output voltage.

Power Consumption and Losses

Auxiliary equipment - pumps, compressors, blowers, electronics - consumed about 300 kW of power. The measured converter and transformer power losses were established to be 250 kW at a coil current of 4.5 kA. Thus, the SMES system efficiency is about 94%.

The only technique available to make the 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 obtained by calibration data for the refrigerator in the form of compressor suction pressure as a function of known heat inputs from a calorimeter.[9] Table I gives experimental results at two values of power and three different frequencies for coil losses, as deduced from the comparative calorimeter measurements, and the predicted losses.

Operating Experience

Except for a few brief intervals, the SMES coil was kept at superconducting temperatures since it was first energized February 16, 1983. Until October 31, 1983, the coil was energized only during staged tests, which usually exercised the unit for some ten hours per day. The cumulative testing time with power modulation was approximately 120 hours. An estimated 30% of this time the SMES unit ran at power outputs of ±8 MW and above. Since November 1, 1983, the unit was run over 1000 hours with a narrow band white noise modulation

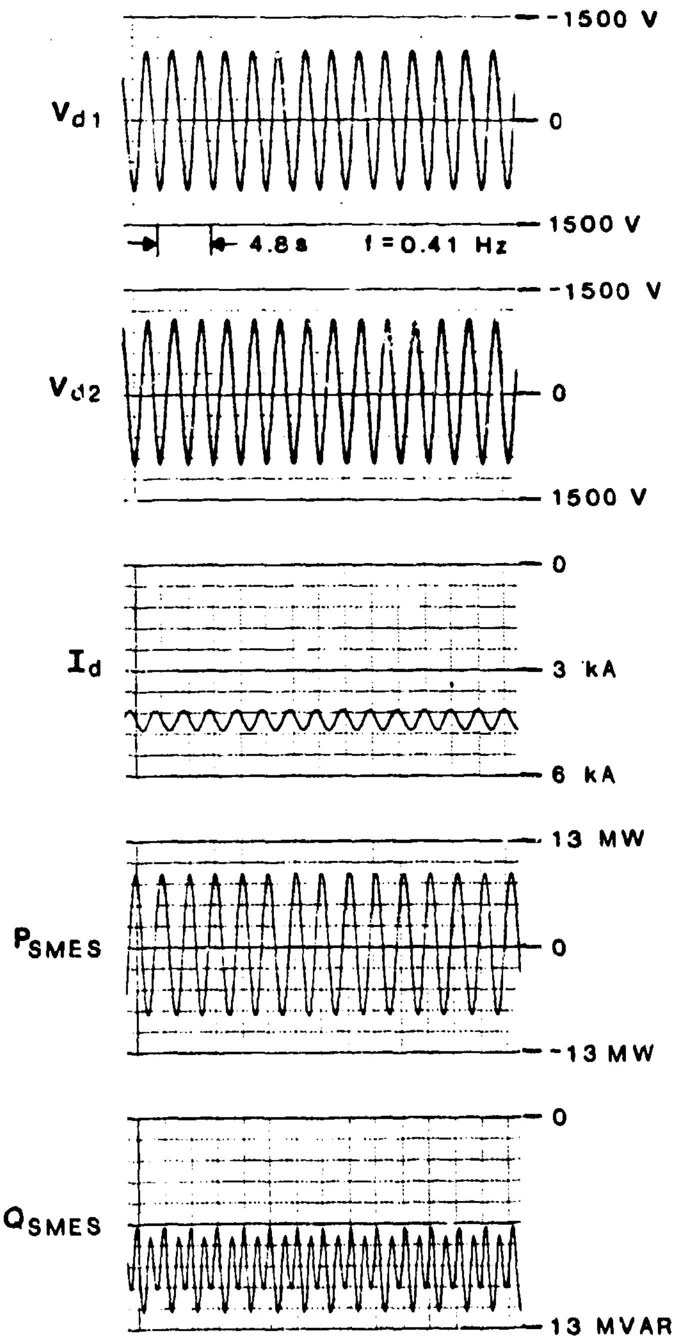

Fig. 3. Electrical parameters of SMES system with sinusoidal power output and equal voltage control.

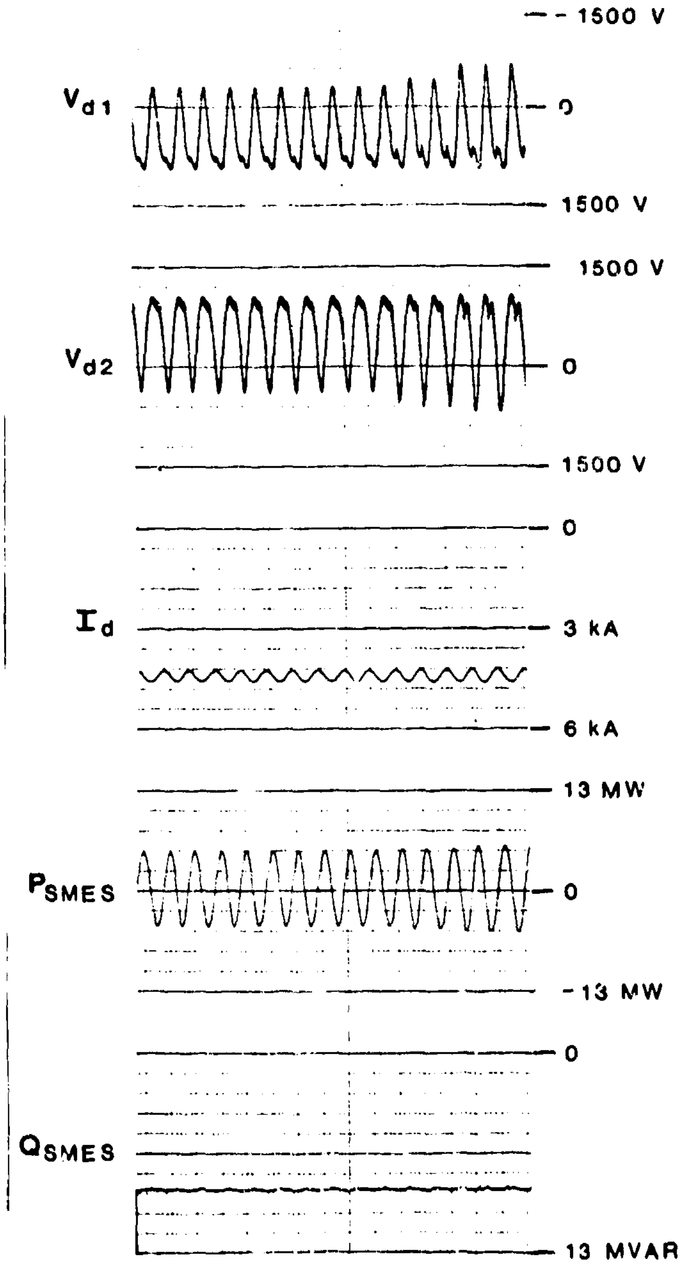

Fig. 4. Electrical parameters of SMES system with sinusoidal power output and constant Q control.

spectrum. Over 10^6 cycles of power to and from the coil were accumulated.

During the early tests the converter required modest repair and maintenance.[7] The coil and dewar functioned to full specifications. Within the cryogenic system, however, the helium refrigerator was a persistent source of hardware and operating problems. Some of the problems were anticipated because funding limitations of the project prevented the refrigerator to be fully automated. The refrigerator responds very slowly to adjustments, with time constants of up to 12 hours in the control loop and with enough backlash and other nonlinearities to render dial settings not very informative. The heat load varies strongly with the level of SMES real power modulation and can necessitate considerable refrigerator adjustment. Recovery from a protracted refrigerator outage, as caused by a power outage, is tedious and complex. These problems were compounded initially by overly sensitive protection logic, inadequate alarms, and emerging protocols for alarm servicing. The problems associated with protection were alleviated substantially.

The refrigerator and cooling tower experienced some mechanical component failures. These were usually repaired within hours by BPA personnel. The consequences of two mechanical design defects, one within the refrigerator and one in a helium transfer line, were more serious.[9] The first derates the refrigerator

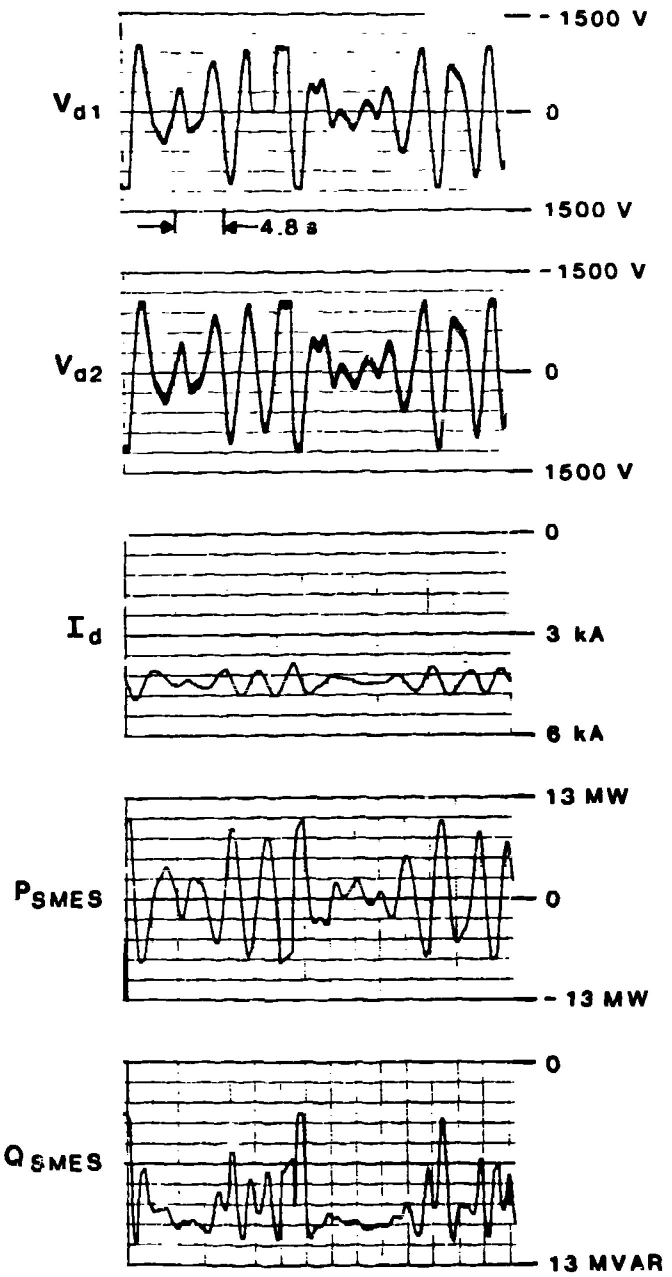

Fig. 5. Electrical parameters of SMES system with random noise signal power output and equal voltage control.

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

by about 30% and the second increases the heat load to the point that sustainable SMES power is about 4 MWrms instead of the expected 7 MWrms.

Conclusion

The results establish that the Tacoma SMES unit is a versatile and responsive device for power system testing and control. Its electrical operating range, though modest, satisfied design requirements and could be extended. From November 1, 1983 until March 8, 1984, with the exception of brief staged tests, it was continuously modulated by a narrow band noise signal, representative of stabilizer operation. Over 1200 hours of operation with modulation were accumulated. The continuous modulation addressed an objective of the project to acquire an initial base of operating experience for estimating the cost effectiveness and special requirements of superconducting power equipment and to provide an opportunity for gathering power system data, useful for tuning the modulation algorithm, for measuring long term refrigerator capabilities, and for refining operational procedures. The experiment has conclusively demonstrated that SMES can operate successfully in a complex utility system.

Acknowledgement

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References

1. N. Mohan, "Superconductive Energy Storage Inductors for Power Systems," Ph.D. Dissertation, University of Wisconsin, Dept. Elec. Eng., Madison, WI (1973).
2. 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 Paper No. 14-05, Paris, 1978.
3. R. L. Cresap, J. F. Hauer, "Power System Stability Using Superconducting Magnetic Energy Storage: Dynamic Characteristics for the BPA System," Proc. of the 1978 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, U.S. DOE Pub. CONF 781046, pp. 1254-1262.
4. J. F. Hauer, "Utility Controls for BPA 30-MJ SMES System," Proc. of the DOE Physical and Chemical Energy Storage 1982 Contractors' Review Meeting, U.S. DOE Pub. CONF 820827, pp. 201-205.
5. W. V. Hassenzahl, "Superconducting Magnetic Energy Storage," Proc. of the IEEE, Vol. 71, September 1983, pp. 1089-1098.
6. J. D. Rogers, R. I. Schermer, B. L. Miller, J. F. Hauer, "30-MJ Superconducting Magnetic Energy Storage System for Electric Utility Transmission Stabilization," Proc. of the IEEE, Vol. 71, September 1983, pp. 1099-1107.
7. H. J. Boenig, R. G. Nielsen, K. H. Sueker, "Design and Operating Experience of an AC-DC Power Converter for a Superconducting Magnetic Energy Storage Unit," IEEE Industry Applications Soc. 1984 Mtg., Chicago, IL, October 1-4, 1984.
8. H. J. Boenig, J. F. Hauer, "Commissioning Tests of the Bonneville Power Administration 30 MJ Superconducting Magentic Energy Storage System Unit," IEEE, Power Apparatus and Systems Summer Power Mtg., July 1984, Seattle, WA.
9. R. I. Schermer, et al., "Design and Operation of the 30 MJ Superconducting Magnetic Storage System on the Bonneville Power Administration Bus," Cryog. Eng. Conf., Colorado Springs, CO, August 1983.