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Superconducting Magnetic Energy Storage (SMES) Program

January 1—December 31, 1984

Compiled by
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ABSTRACT

The 30 MJ, 10 MW superconducting magnetic energy storage (SMES) system was devised to interact in the Western U.S. Power System as an alternate means to damp unstable oscillations at 0.35 Hz on the Pacific HVAC Intertie. The SMES unit was installed at the Tacoma Substation of the Bonneville Power Administration (BPA). The operating limits of the 30 MJ SMES unit were established, and different means of controlling real and reactive power were tested. The unit can follow a sinusoidal power demand signal with an amplitude of up to 8.6 MW with the converter working in a 12 pulse mode. When the converter operates in the constant VAR mode, a time varying real power demand signal of up to 5 MW can be met. Experiments showed that the Pacific AC Intertie has current and reactive power variations of the same frequency as the modulating frequency of the SMES device. Endurance tests were run to assess the reliability of the SMES subsystems with a narrow band noise input, which is characteristic of the modulation signal for stabilizer operation. In this mode, the energy of the power spectrum is not concentrated at one frequency to avoid exciting a resonance frequency of the ac transmission system. During the endurance tests, parameters of the ac power system were determined. Converter short circuit tests, load tests under various control conditions, dc breaker tests for coil current interruption, and converter failure mode tests were conducted. The experimental operation of the SMES system was concluded and the operation was terminated in early 1984.

A study was funded at Bechtel to devise major cost reductions for a 5000 MWh diurnal load leveling SMES system. A cost savings of 26% was developed with some design simplifications as compared to the Bechtel-GA Technologies study funded earlier by the Electric Power Research Institute (EPRI). The indicated saving makes SMES cost competitive for energy storage.

I. SUMMARY

The goal of the Los Alamos National Laboratory's SMES program has been to develop electrical units to store energy in the magnetic field of a coil or inductor. The magnetic field is created by an electric current flowing in a superconductor. A 30 MJ (8.3 kWh) SMES unit was built to damp the short term power oscillations in the Bonneville Power Administration (BPA) electrical grid.

The Pacific Northwest and southern California are part of the Western U.S. Power System and are connected by two 500 kV, ac power transmission lines, collectively called the Pacific AC Intertie, and one ± 400 kV dc transmission line, the Pacific HVDC Intertie. The two ac lines have a conductor thermal rating of 5500 MW and the dc line has a rating of 1600 MW. Upgrading of the dc line to 2000 MW is in progress. The 900 mile long Pacific AC Intertie separation of the major load and generation centers produces a low frequency instability. In 1974, negatively damped oscillations on the ac line with a frequency of 0.35 Hz (21 cpm) and amplitude of about 300 MW were observed.

BPA installed equipment on the HVDC Intertie to modulate power flow between the interties, damping the oscillations and increasing the stability limit of the Pacific AC Intertie from about 2100 MW to 2500 MW. Subsequent system growth appears to have lessened the instability problem, but the nature of that growth may be combining with higher intertie loads to bring the problem back in a more complex form. At BPA these considerations have engendered continued interest in means for monitoring, predicting, and improving dynamic stability. The 30 MJ SMES unit installed at the Tacoma Substation was used to study these issues.

The dynamics of the power system are much more complicated now than when the project started, and recent evidence suggests that they are prone to abrupt changes which the available study tools cannot predict. There is some risk that disturbances or switching operations on major ties may suddenly bring the power system to a poorly damped condition with attendant high level oscillations. In such cases, the large signal damping capability of HVDC Modulation may prove necessary, and the SMES unit might also provide its most valuable services in directly supporting roles.

The availability of the HVDC Intertie is about 90% under normal conditions. Unusual conditions (an earthquake disabled the line for six months at one time) also take the line out of service occasionally.

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 dc line interfaces with the ac grid.[1-3] Clearly, the SMES system was to have been an experimental device. The program was paced in its last years by monetary limitations, with the consequence that the need to have a fully remote computer controlled system at the Tacoma Substation with only part-time staffing was not met. The complicated refrigerator system was not so controlled. Thus, the project objectives were altered because both availability and reliability are not sufficient. With this knowledge, BPA used 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.

Some of the work reported here was conducted in late 1983 but developed into a cohesive analysis in 1984. 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 spectrum. Over 10^6 cycles of power to and from the coil were accumulated. The experiment was terminated in March 1984. Extensive tests of the coil also constituted converter tests. The converter performed to its design characteristics and was found to adapt to a number of control functions with real and reactive power variations.

Large SMES systems have the potential for diurnal load leveling application in a utility system. The EPRI funded study[4] was based upon a SMES system concept developed by the Unviersity of Wisconsin. That study identified a number of areas where cost savings might be made. The follow-on study by Bechtel and GA Technologies,[5] reported here, addressed these areas and proposes some design simplifications with the consequence of a 26% cost savings. Diurnal load leveling SMES systems for large utility application now appear to have a competitive position for energy storage.

II. 30 MJ BPA SMES OPERATION

The use of a superconducting magnetic energy storage (SMES) unit for power system damping was suggested in 1973.[6] The 30 MJ unit was designed for such service as the modulated control element similar to HVDC Modulation.[3,7,8] 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 midterm 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 these components is addressed in detail in three recent publications.[9-11]

The coil stores energy in its magnetic field. Energy exchange between the coil and the ac system is controlled by a line commutated 12-pulse converter. Each of the two 6-pulse bridges is fed by a 13.8/0.93 kV transformer provided with a ± 5% tap changer.

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 equal or different phase delay angles. 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.[12] Figures 1,2, and 3 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 13.8 kV bus. In Fig. 1 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. 2, the SMES unit output shows sinusoidal real power, but the two bridges are controlled independently and provide a constant reactive power absorption. In Fig. 2, 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. 3, 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.

Auxiliary equipment - pumps, compressors, blowers, electronics - consumed about 210 kW of power. The measured converter and transformer power losses were established to be 230 kW at a coil current of 4.5 kA. Thus, the SMES system efficiency is about 86%.

The only technique available to make the coil loss measurements was to note the change in compressor suction pressure caused by coil cycling at fixed

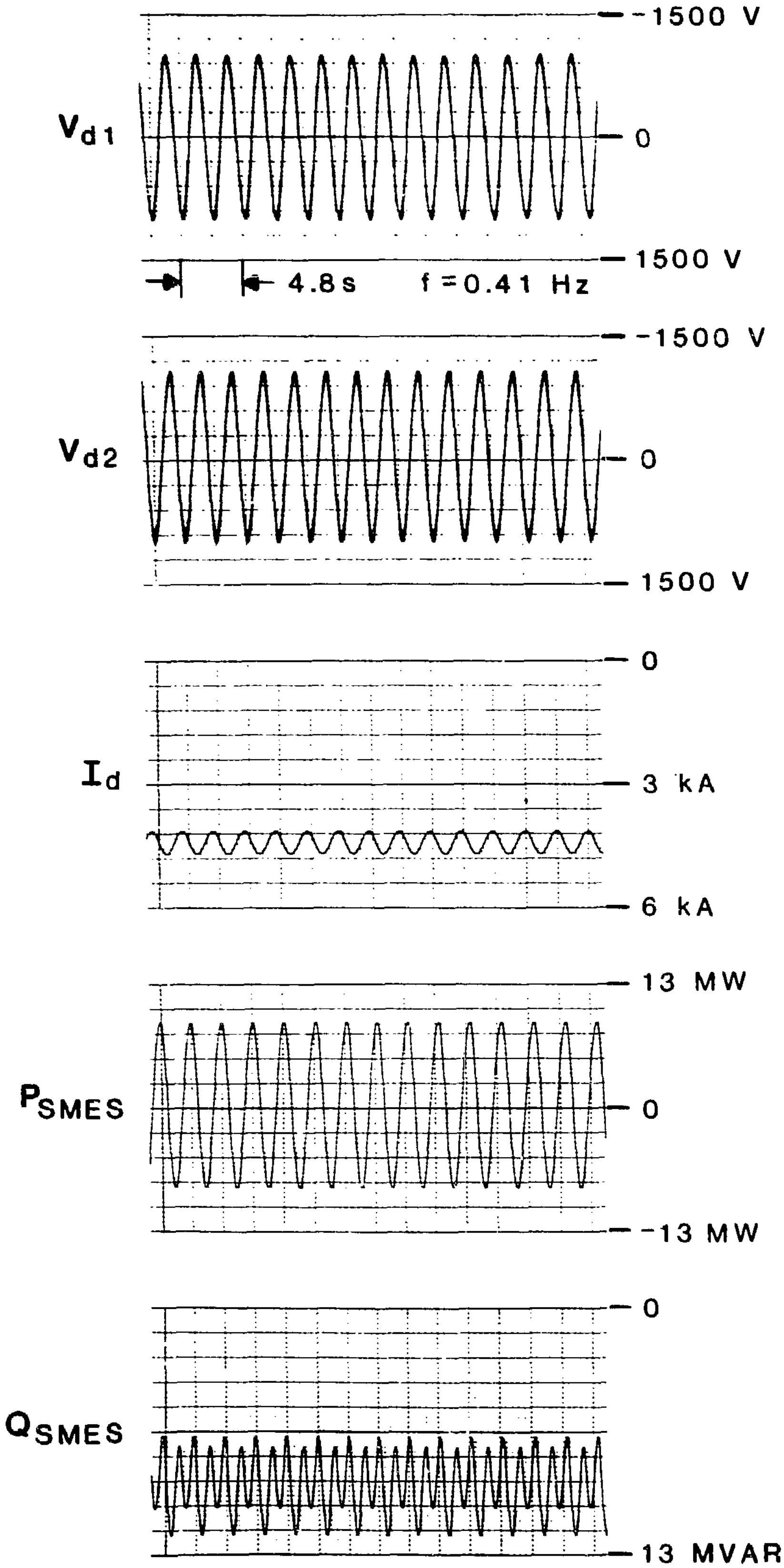

Fig. 1. Electrical parameters of SMES system with sinusoidal power output and equal voltage control.

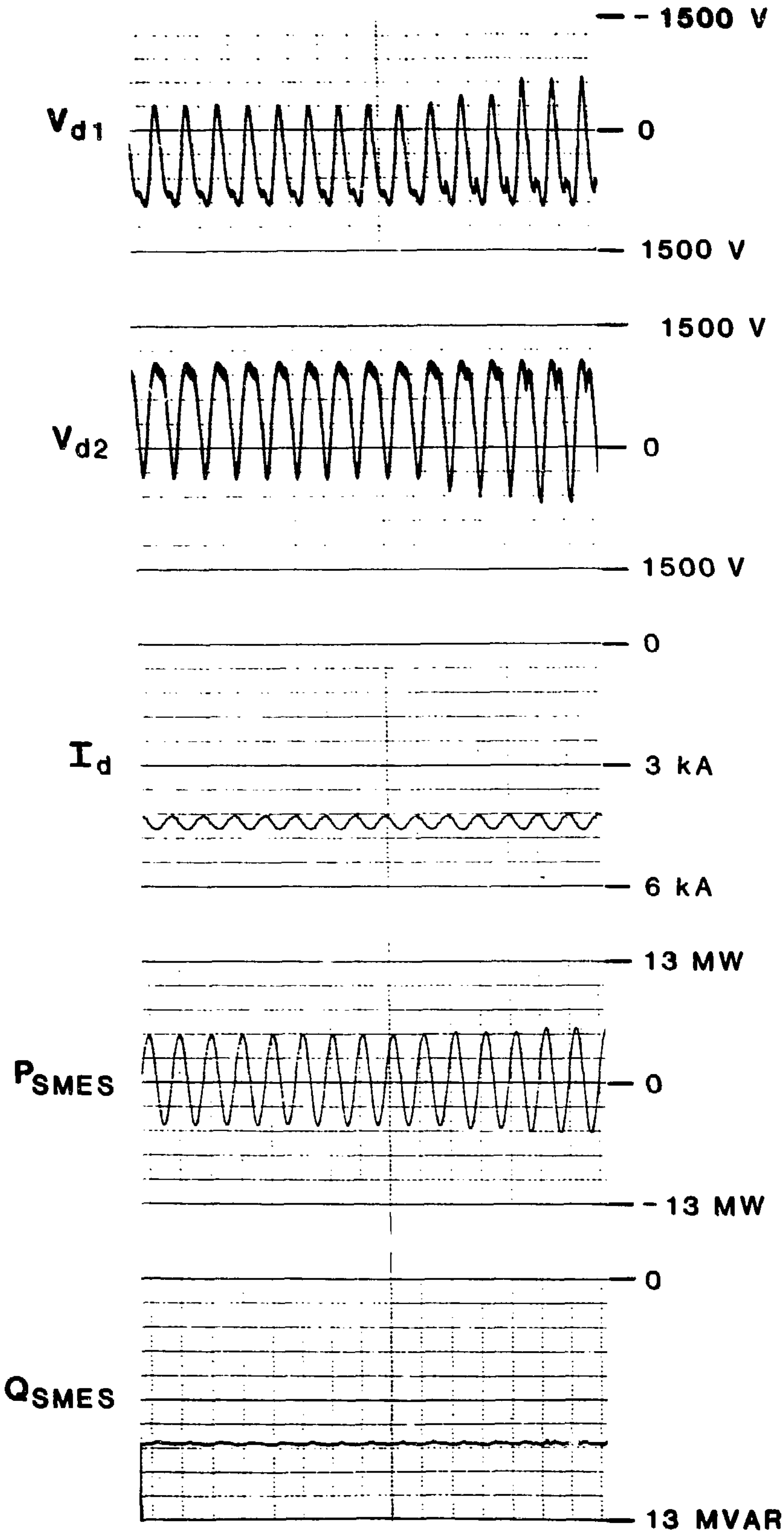

Fig. 2. Electrical parameters of SMES system with sinusoidal power output and constant Q control.

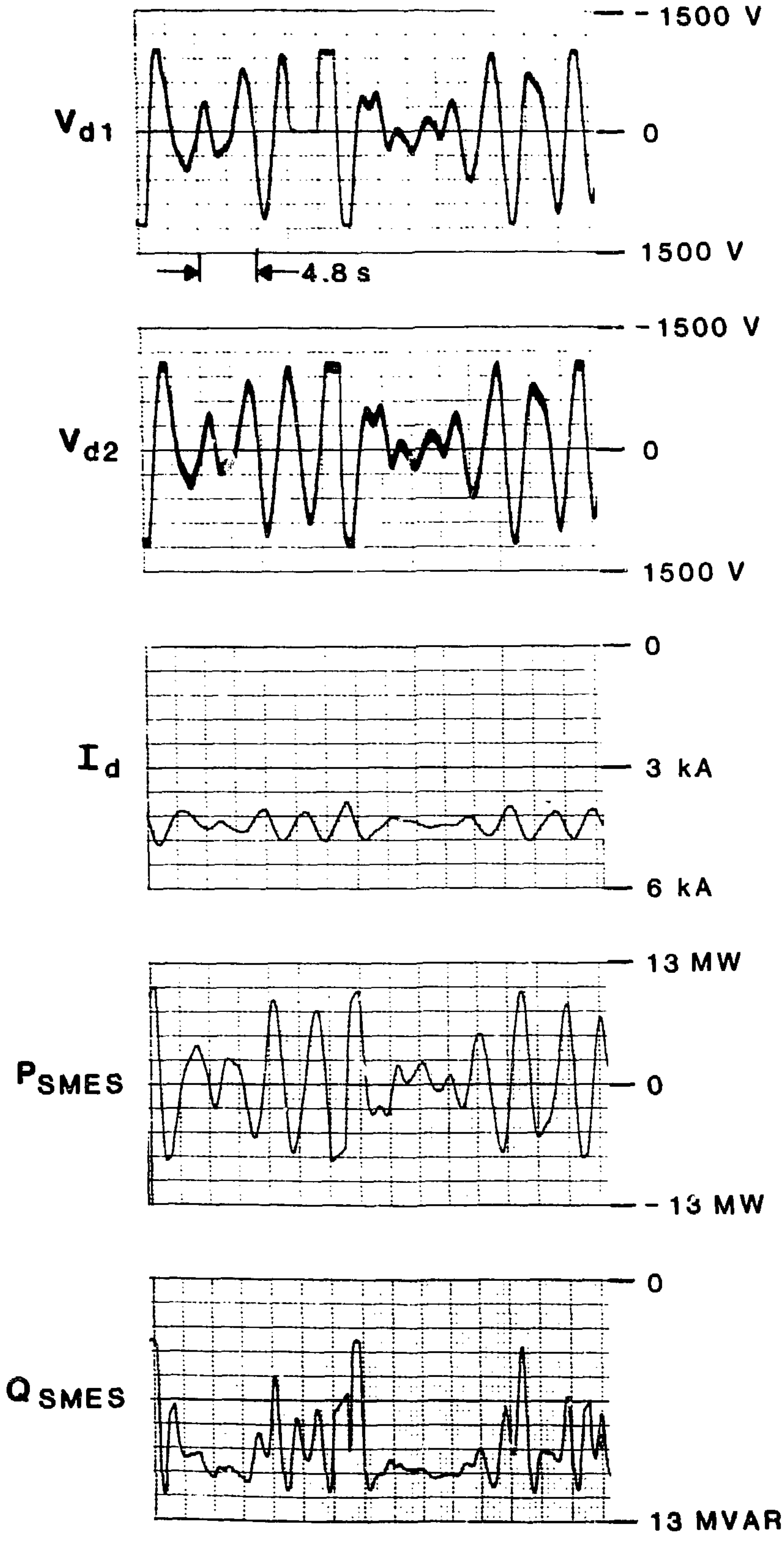

Fig. 3. Electrical parameters of SMES system with random noise signal power output and equal voltage.

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.[13] These losses varied from 32 to 34 W for a modulation power of 4.4 MW at frequencies of 1.0 to 0.2 Hz, respectively, and increased to 54 W at 8.4 modulation power at 1.0 Hz.

Though strong, the connection of the SMES unit to the center of Pacific Northwest generation was a long one involving several lines. The unit also shared the Tacoma bus with Tacoma City Light, a large aluminum reduction plant, and lines extending toward two large thermal generation plants. These factors increased the likelihood that the influence of SMES modulation would change with area operating conditions.

Figure 4 shows the response of various ac system quantities to a ±4.5 MW SMES CQ modulation at 0.29 Hz. The first trace is the real power for the SMES unit, and the second trace is for the constant 9.5 MVAR SMES reactive power. The third trace of the figure shows the variation of the current and the fourth trace of the reactive power of the Pacific AC Intertie. The fifth trace shows the 230 kV bus variation at the Tacoma Substation. The sixth trace gives the real power variation of a line going to Tacoma City Light. The signal-to-noise ratio is less unfavorable for most area quantities, but degrades at frequencies further away from 0.3 Hz. This is consistent with system noise characteristics.[8,14] Good results require a mixture of procedures in system testing, signal analysis and model construction.[15]

The converter performed well during continuous duty operation as evidenced by the figures and the accumulated 1000 hours with over 10^6 cycles of operation. At full power rating, the converter ran cool with an average temperature difference of 15° C between the incoming and exiting air. Three of the 96 converter SCRs failed during the initial tests. Additional SCRs failed during experiments in which the inversion end stop was increased beyond 140°. In one instance, a mechanical malfunction in the 13.8 kV breaker mechanism caused contact bouncing during a breaker closing operation, which resulted in destruction of the converter RC filter networks and MOV transient suppression devices. However, during this severe voltage transient none of

Fig. 4. Response of ac system to SMES unit modulation.

the converter SCRs was damaged. The electronic logic and relay logic appeared to be quite immune to electromagnetic noise. Although some difficulty was expected with the digital circuitry in a noisy converter environment, none was experienced in the field. The converter operation was not interrupted by routine operation of adjacent 230 kV power circuit breakers or disconnect switches within the substation. Misfiring of bypass SCRs occurred when both 6-pulse bridges were controlled in a constant reactive power mode with bridge 1 operating primarily in the rectifier mode and bridge 2 in the inverter mode. Misfiring occurred when the other bridge was at its inversion end stop. Experiments showed that misfiring could be avoided by choosing a more conservative inversion end stop.

The dc energy dump breaker had to operate during a double fault condition, when an electrical system failure was concurrent with a cryogenic system failure. Although such a condition never occurred during the lifetime of the 30 MJ SMES system, the breaker was nevertheless tested up to 5 kA. Tests began at a low current rating, 1 kA, and then increased by 1 kA to 4 kA. Several tests at 4.5 kA and 5 kA were conducted. Initially, the commutation capacitor charging voltage was adjusted so that the peak commutation current was always approximately 1.6 times the dc current. All breaker tests were successful in that the commutation current extinguished the arc and the magnetic coil energy was deposited in the dump resistor. However, some of the tests at coil currents of 4 kA and above caused a failure in one, two, or all the commutation SCRs. Initially, an improper design of the SCR MOV protection devices was blamed for the failures. Unfortunately, a visual inspection of wafers of the damaged SCRs revealed no definite conclusions. Some of the SCRs seemed to have failed because of excessive voltage, others from excessive di/dt. The cause of the failures was finally determined as time differences in the gate pulses of up to 15 μs, caused by LED deterioration in the optical links.

A complete discussion of the ac-dc converter design and operational experience is given in reference 16.

The results established that the Tacoma SMES unit was 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.

III. SMES DESIGN AND COST REDUCTION STUDY

The EPRI study[4] undertaken by Bechtel and GA Technologies Inc. identified eight potential cost reduction features of the diurnal load leveling SMES system concept that was used for that work. These were

1. Development of higher current density and/or a lower cost alternative superconductor material,
2. Optimization of the conductor configuration,
3. Use of an alternate to the aluminum for energy absorption during a coil scram and/or alternate to aluminum for coil support,
4. Reduction of helium requirements,
5. Optimization of the overall system parameters,
6. Improvements in the power conditioning system (PCS),
7. Matching the PCS and switchyard to utility requirements, and
8. Reducing the minimum stored energy level.

The near term (5 year) and long term (15 year) obtainable cost reductions were estimated to be about 21 and 35%, respectively. Bechtel and GA, in the DOE funded study for FY84, were given a free hand to consider substantial design modifications as well as to address the listed features. Specifically, the scope of work for the study was to consider item 2,3,4, and 5. In addition; items 7 and 8 were also assessed peripherally. The result of the study was an indicated cost reduction of 26.8% with a simplified design that eliminates some of the most difficult to fabricate aspects of the design that formed the basis of the EPRI study. This is not to say that all the details of the new design are entirely understood to assure 100% fabricability. Regardless, the redirection has considerable merit and creates a possibility for a truly competitive energy storage system. About one-half of the cost reduction is generally applicable to any large SMES system.

The overall project objectives were to improve the design and reduce the cost of a nominal 5000 MWh, 1000 MW SMES plant using the design concept reported in reference 4 as the starting point. Specific areas of emphasis were system configuration that would improve constructibility and reduce capital costs and to establish a minimum cost or near minimum cost combination of coil parameters and minimum coil residual charge.

The objective of identifying an alternative system configuration was approached first from the requirement for technical feasibility. The high current, 765 kA, field fabricated conductor and the conductor support system presented in reference 4 were considered to be quite difficult to fabricate and install. The premise that technical feasibility requires factory fabrication of the conductor, at a size that can be shipped to the SMES site on spools, led to use of a rectangular conductor capable of carrying a more modest 200 kA.

For the reduced current conductor, more coil turns are required to store a given amount of energy. This fact led to consideration of multi-layer designs. The project first attempted to define a multi-layer design concept using radial ripples to accommodate thermal contraction from cooldown that at the same time would prevent relative motion between the radial coil layers during normal operation. This latter requirement is very difficult to achieve with a rippled geometry. However, that a rippled geometry is unnecessary quickly became apparent. Numerous aluminum alloys are capable of withstanding the thermal stresses encountered when the coil is cooled to operating temperature.

The above considerations led to a four layer coil design supported from both sides by struts. The design was further developed to decouple the magnetically induced axial stresses from other stresses in the coil winding structure and to include inexpensive material to supplement the capacity of the coil structure to absorb heat during a coil scram.

Consistent with the above system configuration, the second objective to establish a minimum cost system was partially met by evaluating a range of coil diameters to obtain a cost minimum for the conductor and coil winding structure materials.

In addition to establishing a technically practical conceptual design, economic siting criteria were established and general areas of the U.S. that could meet these criteria were identified. The most important economic siting criterion was that the coil should be located in near surface rock capable of withstanding 1.92 MPa (20 tons/ft^2) of radial loading. A second desirable criterion was that the water table should be below the bottom of the trench which houses the coil.

The total capital requirement at startup for the design detailed in the baseline EPRI study[4] was estimated at $1,118 million for storage related items and $194 million for power related items, both in 1982 dollars. The new design is estimated to cost $820 million and $141 million for storage related and power related items, respectively, in 1984 dollars.

Thus, without inflating the 1982 estimates, the estimated cost of a SMES plant capable of delivering a nominal 5000 MWh daily at a nominal power of 1000 MW has been reduced from a total of $1,312 million to $961 million, a decrease of $351 million, or 27 percent. About 34 percent of this cost reduction is attributable to actual and near term improvements in superconductor performance, 15 percent to modified operating limits for the power transfer equipment, 28 percent to changes in the coil design concept, and 23 percent to a reduction in coil diameter for the new coil design concept.

To determine the economic merit of SMES for utility scale load leveling was beyond the scope of the DOE funded study. However, a 1982 EPRI funded study by Energy Management Associates[17] states that there would be at least a small market for a nominal 5000 MWh, 1000 MW SMES plant costing $1000/kW in

1981 dollars. When computed on the same basis, the design reported here is estimated to cost $988/kW in 1984 dollars. Futhermore, because SMES has a net roundtrip energy efficiency in excess of 90 percent, the value of SMES relative to other energy storage technologies should increase with the cost of charging energy.

Estimated capital costs are presented in Table I. For comparison, the costs estimated for the design given in the baseline EPRI study[4] are included. The costs assume construction of an n^{th}-of-a-kind plant of a mature SMES technology. All construction labor was costed at $25/man-hour and no allowance was made for construction delays that could be caused by labor problems or inclement weather. The cost of SMES is still dominated by materials, and material costs remain dominated by the conductor and coil structure. However, due to design changes and improved superconductor performance, the coil structure, rather than the conductor, is now the largest cost item.

The major cost reductions arise from use of a lower current conductor with multiple radial layers; improved superconductor performance; elimination of the radial ripples, originally conceived to reduce thermal stresses; the smaller coil diameter; and a more realistic charge-discharge power profile for the power conditioning equipment.

The cost reductions include use of $2,000/acre instead of $5,500/acre for the cost of land; lower costs for the conductor that result from eliminating its structural component, made possible by revising the conductor support method; use of four radial conductor layers that permit the superconductor to be graded to the magnetic field; improved superconductor performance; and the elimination of the radial ripples that further reduce the field seen by the superconductor. The savings for the conductor are partially offset by a cost increase for the coil structure. Elimination of the radial ripples in the conductor and coil structure is a significant design simplification. This feature and a reduction of coil diameter from 1568 m (5143 ft) to 1000 m (3280 ft) are contributing factors to savings for other storage related capital costs. The charge-discharge power profile selected requires that power delivery during the late portion of the SMES discharge operation decline so that the peak coil voltage is limited to 9.4 kV. Such performance is

TABLE I

TOTAL CAPITAL REQUIREMENT
(Millions of Dollars)

	Reported in Ref. 4, 1982 Dollars			Current Design, 1984 Dollars		
	Storage Related Costs	Power Related Costs	Totals	Storage Related Costs	Power Related Costs	Totals
Direct Process Capital:						
Materials and Offsite Fabrication	569.9	122.8	692.7	407.6	79.0	486.6
Construction	115.5	24.4	139.9	93.7	24.4	118.1
Total Direct Process Capital	685.4	147.2	832.6	501.3	103.4	604.7
Indirect Process Capital	30.8	7.8	38.6	21.2	7.8	29.0
Total Process Capital	716.2	155.0	871.2	522.5	111.2	633.7
General Facilities	3.7	-	3.7	2.4	-	2.4
Engineering and Home Office	28.8	6.2	35.0	26.2	5.6	31.8
Geotechnical	2.2	-	2.2	2.1	-	2.1
Licensing	2.5	-	2.5	2.5	-	2.5
	753.4	161.2	914.6	555.7	116.8	672.5
Contingency	188.4(25 %)	24.2(15 %)	212.6	138.9(25 %)	17.5(15 %)	156.4
Total Plant Investment	941.8	185.4	1,127.2	694.6	134.3	828.9
AFDC*	112.5	6.9	119.4	83.0	5.0	88.0
Total Plant Investment At Startup	1,054.3	192.3	1,246.6	777.6	139.3	916.9
Preproduction	10.8	2.1	12.9	7.9	1.4	9.3
Inventory and Refrigerants	25.7	-	25.7	26.5	-	26.5
Land	26.7	-	26.7	7.9	-	7.9
Total Capital Requirement	1,117.5	194.4	1,311.9	819.9	140.7	960.6

Cost Reduction from Ref. 4 = $1,311.9 - $960.6 = $351.3 (26.8%)**

* Allowance for funds during construction, used same percentage as calculated in Ref. 4.
** This percentage reduction would be larger if the effects of inflation from 1982 to 1984 were included.

realistic in that a SMES plant would probably be operated to track the usual diminishing end-of-day peak load demand. The savings in construction costs are more nominal. They result primarily from the reduction in coil diameter and to some extent from factory, rather than field fabrication of the conductor and from elimination of radial ripples in the coil. Indirect construction costs closely track the modest reductions in construction costs.

The total capital requirement at startup is summarized in Table I. The costs compiled therein show the important result of a 27 percent reduction. This reduction more than captures the savings suggested in reference 4 after an intensive 5 year development program performed at considerable cost. Thus, the resulting total capital requirement of $961 million (1984 dollars) versus $1,312 million (1982 dollars) of the prior study represents a greater reduction than had previously been anticipated. The content of each line item in Table I is given in reference 5.

When considered in combination with the high net energy efficiency of SMES (about 92%) and higher dispatch efficiency (about 94%), this reduced capital requirement shows SMES to have a real competitive position with other large scale electrical energy storage technologies.

The technical feasibility of SMES would benefit from additional research and development in a number of areas. However, the most pressing issue is that of coil protection during an emergency discharge. In this area, analyses are required to establish the extent and effects of temperature nonuniformities in the coil during an emergency discharge from full coil current.

IV. CONCLUSIONS

Several major conclusions can be drawn from the results of this most recent Bechtel-GA study and the work of others. They are

1. The SMES conceptual design developed during this project is technically feasible.
2. The estimated cost of a SMES plant capable of storing and delivering nominal 5000 MWh at a nominal 1000 MW has been greatly reduced and is now estimated at $961 million in 1984 dollars in contrast to $1,312 million

in 1982 dollars as previously estimated,

3. The merit of SMES has been greatly improved and will continue to improve as the costs of charging energy and premium fuels rise,
4. Additional anaylsis is required to demonstrate that, in an emergency, the coil can be discharged without causing damage to the SMES plant, and
5. Additional development is required to refine the new concept into a fully optimized conceptual design.

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