12
SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Introduction

Superconducting Magnetic Energy Storage (SMES) exploits advances in materials and power electronics technologies to achieve a novel means of energy storage based on three principles of physics:

- Some materials (superconductors) carry current with no resistive losses.
- Electric currents induce magnetic fields.
- Magnetic fields are a form of energy that can be stored.

The combination of these fundamental principles provides the potential for the highly efficient storage of electrical energy in a superconducting coil. Operationally, SMES is different from other storage technologies in that a continuously circulating current within the superconducting coil produces the stored energy. In addition, the only conversion process in the SMES system is from AC to DC power conversion, i.e., there are none of the thermodynamic losses inherent in the conversion of chemical (battery) and mechanical (flywheel) energy storage to electricity.

SMES was originally proposed [1,2] for large-scale, load leveling, but, because of its rapid discharge capabilities, it has been implemented on electric power systems for pulsed-power and system-stability applications.[18] Figure 12-1 is a picture of the only SMES unit commercially offered at present (American Superconductor's D-SMES). This chapter primarily emphasizes existing SMES applications, but also describes some of the extensive design and development programs for large-scale SMES plants that were conducted in the recent past. Figure 12-2 shows such a plant that is rated at 500 MW_{ac} [3] and stores sufficient energy to deliver this power for 6 to 8 hours. The coil shown is about 1000 meters in diameter and is located at sufficient depth below grade for the surrounding soil to support the magnetic loads from the coil.

[18] A bibliography listing major reports relevant SMES development is included at the end of this chapter.

shown and, SMES units have been proposed over a wide range of power (1 to 1000 MW_{ac}) and energy storage ratings (0.3 kWh to 1000 MWh). Independent of size, all SMES systems include a superconducting coil, a refrigerator, a power conversion system (PCS), and a control system as shown in Figure 12-3. Each of these components is discussed in this section.

The Coil and The Superconductor

The superconducting coil, the heart of the SMES system, stores energy in the magnetic field generated by a circulating current. Since the coil is an inductor, the stored energy is proportional to the square of the current, as described by the familiar equation:

$$E = \frac{1}{2} L I^2, \qquad \textbf{Eq. 12-1}$$

Where L is the inductance of the coil, I is the current, and E is the stored energy.

The total stored energy, or the level of charge, can be found from the above equation and the current in the coil. The maximum practical stored energy, however, is determined by two factors.

- The size and geometry of the coil, which determine the inductance.

The characteristics of the conductor, which determine the maximum current. Superconductors carry substantial currents in high magnetic fields. For example, at 5 Tesla, which is 100,000 times greater than the earth's field, practical superconductors can carry currents of 300,000 A/cm^2.

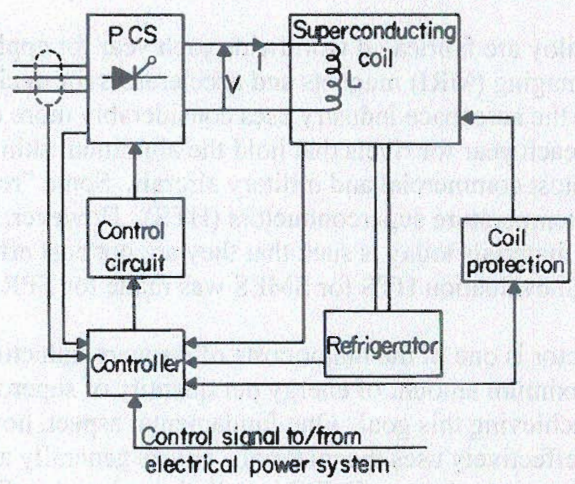

Figure 12-3
Simplified Block Diagram of a SMES System Showing Major Components

Alamos National Laboratory (LANL) and installed by the Bonneville Power Administration at the Tacoma substation. Figure 12-6 is a small, 1 MJ SMES coil.

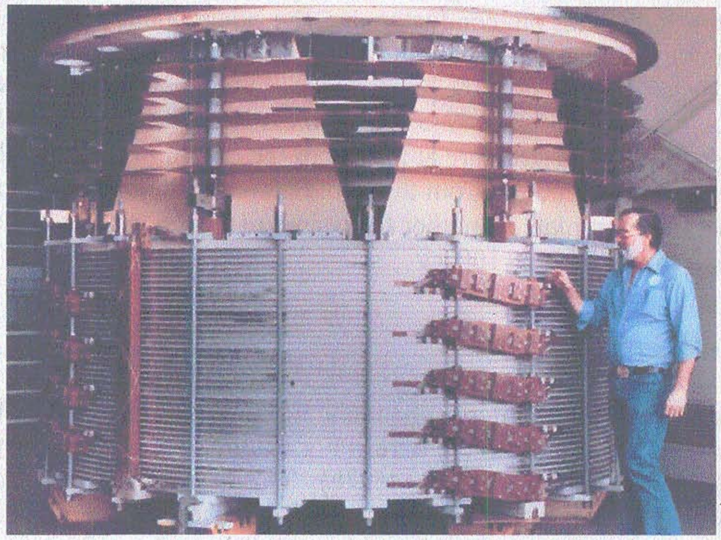

Figure 12-5
30 MJ Superconducting Coil Developed by the Los Alamos National Laboratory (LANL)

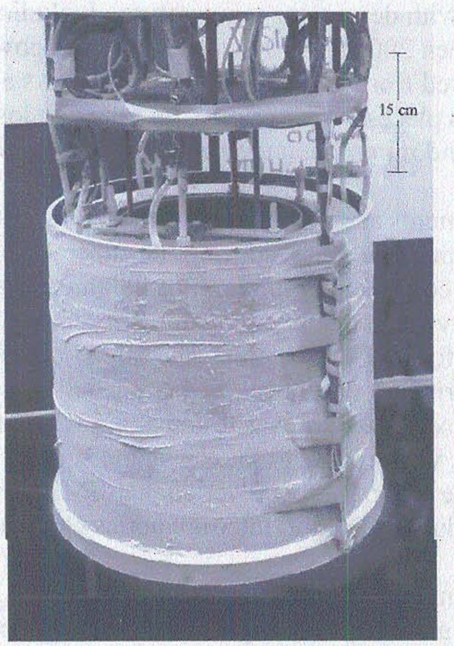

Figure 12-6
1 MJ SMES Coil in a Liquid Helium Vessel (LANL)

helium to cool a superconducting coil are shown. This refrigerator can remove about 5 W at 4.5 K, which is the heat load that might be expected in a micro-SMES for power-quality applications. Such refrigerators usually operate with the cold finger pointing downward but other orientations are possible. Figure 12-8 shows a large liquid helium refrigerator at the Japanese Atomic Energy Research Institute (JAERI). Such a refrigerator would be appropriate for the diurnal SMES installation shown in. It can remove about 10 kW of heat from a large magnet operating at 4.5 K.

Power Conversion System

Charging and discharging a SMES coil is different from that of other storage technologies. The coil carries a current at any state of charge. Since the current always flows in one direction, the power conversion system (PCS) must produce a positive voltage across the coil when energy is to be stored, which causes the current to increase. Similarly, for discharge, the electronics in the PCS are adjusted to make it appear as a load across the coil. This produces a negative voltage causing the coil to discharge. The product of this applied voltage and the instantaneous current determines the power.

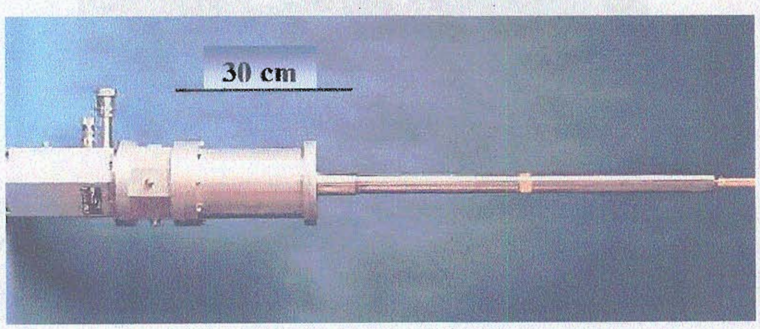

Figure 12-7
Small Cryogenic Refrigerator and Cold-Finger Extension (Cryomech Inc.)

maintains system safety and sends system status information to the operator. SMES systems provide remote observation and control via internet connections.

Technology Attributes

Power Rating

The power of a SMES system is established to meet the requirements of the application, e.g., power quality or power system stability. In general, the maximum power is the smaller of two quantities the PCS power rating and the product of the peak coil current and the maximum coil withstand voltage.

The power rating of commercial micro-SMES installations range from 1 to 3 MW_{ac} as discussed in the next section. A much larger unit is now being installed by the Center for Advanced Power Systems (CAPS) at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, Florida. The PCS for this coil will initially have an installed capacity of 5 MW with planned future enhancement to 25 MW_{ac}. The superconducting coil, however, was designed to deliver 100 MW_{dc}, i.e., the product of the design current and design voltage is 100 MW_{dc}.

Energy Storage Rating

The micro-SMES plants listed above deliver 3 to 6 MJ (0.8 to 1.6 kWh, roughly equivalent to the capacity of a 12 volt, 100 Ah lead acid battery). Because the power rating of these units is so high, this entire quantity of energy can be delivered (i.e., the coil can be fully discharged) in a second or so. The larger, 100 MW_{dc} coil to be installed at NHMFL, mentioned above, was originally designed for a one-second discharge in conjunction with the unified power flow controller (UPFC) operated by American Electric Power (AEP) at its Inez Substation. This coil thus stores about 100 MJ (28 kWh). When the converter at NHMFL is upgraded to 25 MW_{ac}, the coil will be discharged in about 4 seconds.

Physical Dimensions of the SMES Installation

The physical size of a SMES system is the combined sizes of the coil, the refrigerator and the PCS. Each of these depends on a variety of factors. The coil mounted in a cryostat is often one of the smaller elements. A 3 MJ micro-SMES system (coil, PCS, refrigerator and all auxiliary equipment) is completely contained in a 40-ft trailer.

Efficiency

The overall efficiency of a SMES plant depends on many factors. In principle, it can be as high as 95 % in very large systems. For small power quality systems, on the other

Table 12-1
Installed D-SMES Units

Start of Operation	Host	Location	Application
June 2000	Wisconsin Public Service	Northern Wisconsin	Transmission Loop Voltage Stability - 6 Units, installed at distributed locations
July 2000	Alliant Energy	Reedsburg, Wisconsin	Transmission Voltage Stability
May 2002	Entergy	North Texas	Voltage Stability - 2 Units

Micro-SMES

Prior to the development of the D-SMES concept, American Superconductor supplied several small power quality SMES units, which are still operational. Designated "Micro"-SMES, these units have been installed around the world in mostly industrial settings to control voltage sag problems on the electrical grid. These are listed in Table 12-2..

SMES Test and Evaluations

In 1992, the Defense Advanced Research Projects Agency (DARPA) issued a request for proposals to build an intermediate sized SMES system for a utility application. There was some consideration/discussion of dual use [7] with a military pulsed power application. As finally released, there was no requirement for a military application as part of the design. A contract was awarded to Babcock and Wilcox (B&W) to build and then install a 0.5 MWh, 20 MW_{ac} plant in Anchorage, Alaska. However, a variety of factors resulted in several changes in direction of the program. It eventually evolved into a program for BWX Technologies to build a 100 MJ (0.028 MWh) coil for the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, Florida. This coil is expected to be completed in 2003 and will be installed at the Center for Advanced Power Systems (CAPS), a part of NHMFL and Florida State University. The coil will be initially operated with a 5 MW_{ac} converter, which is appropriate for the local power system. It is designed, however, to accommodate power flows of up to 100 MW_{ac}.

SMES Deployment Status

Table 12-3 summarizes the status of SMES deployment.

Table 12-3
Technology Status of SMES

Application	MicroSMES for Power Quality	D-SMES for System Stability
Status	Commercial: several units installed as described in Table 12-1	Demonstration
Funding organizations	Private funding in US. Some government funding of potential applications by Japan and Germany	American Superconductor, Wisconsin Power System
Vendors	American Superconductor	American Superconductor
Major demonstrations	See Table 12-2	Northern Wisconsin power system
Lessons learned	Critical issues in terms of the power output and response time.	Early data indicates that D-SMES is effective in the Wisconsin application. Additional information is required on these and other installations.
Major development trends	American Superconductor has several units in the field at this time. However, they have standardized on the D-SMES installation as the standard product. At present there is only one vendor.	American Superconductor is prepared to deliver additional units and is actively searching for customers
Unresolved issues	Costs of SMES units relative to other PQ technologies.	Cost effectiveness of this application compared to other solutions.

Developmental Costs

The original development of SMES systems was for load leveling as an alternative to pumped hydroelectric storage. Thus, large energy storage systems were considered initially. Research and then significant development were carried out over a quarter century in the US, beginning in the early 1970s. This effort was mainly supported by the Department of Defense, the Department of Energy, and EPRI. Internationally, Japan had a significant program for about 20 years, and several European countries participated at a modest level. The Defense Department -sponsored Engineering Test Model (ETM) program funded $72 M worth of design, engineering and test work between 1988 and 1994. In addition, the total international R&D related labor on SMES for load leveling up to the present is estimated to be about 500 person years, or about $75M. Since no practical devices have been constructed or installed, material and construction costs will not increase this value significantly.

At several points during the SMES development process, researchers recognized that the rapid discharge potential of SMES, together with the relatively high energy related (coil)

FPD, 1 event per hour, 5 events per day, 100 events per year. Valued at the cost of alternative solutions.

Application G: Long Duration Power Quality (LPQ) – SPQ, plus capability to provide several hours reserve power. The reference duty cycle for analysis is standby for infrequent events characterized by SPQ plus standby for 4 hours FPD, 1 event per year. Valued at the cost of alternative solutions.

Application H: 3-hr Load Shifting (LS3) – shifting 3 hours of stored energy from periods of low value to periods of high value. The reference duty cycle for analysis is scheduled 3-hour FPD, 1 event per day, 60 events per year. Valued at market rates.

Application I: 10-hr Load Shifting (LS10) – shifting 10 hours of stored energy from periods of low value to periods of high value. The reference duty cycle for analysis is scheduled 10-hour FPD, 1 event per day, 250 events per year. Valued at market rates.

Combined Function Applications (In the Order Noted)

Application C1: Combined Applications C, A, B, D (GFS +GAS + GVS + RC)

Application C2: Combined Applications F, I, D, E (SPQ + LS10 + RC + SR)

Application C3: Combined Applications F, H, D, E (SPQ + LS3 + RC + SR)

Application C4: Combined Applications G, H, D, E (LPQ + LS3 + RC + SR)

Application C5: Combined Applications I, D, E (LS10 + RC + SR)

SMES System Compliance With Application Requirements

The SMES product performance parameters discussed in the previous section were used to develop approximate sizes and operational parameters for systems meeting the requirements of the applications selected for SMES in the previous section. The key factors in sizing SMES systems are the power and energy requirements of the application. The D-SMES product line can be adapted for increased DC-link voltages and increased discharge durations, and two different configurations have been adapted for the three applications noted above. Performance aspects of SMES systems for the selected applications are described below and summarized in Table 12-4. The reference power for all applications in 10 MW_{ac}.

- Application A: Grid Angular Stability (GAS) – This application requires that the system continuously detect and mitigate infrequent short duration, oscillatory events. D-SMES, adapted to 3000 V_{dc} chopper voltage, was equipped with a Type I PCS and configured for this application to be capable of full power discharges for up to 1 second. The system will spend virtually its entire life in standby mode, for which standby SMES efficiency is calculated at 99.4%, attributed to continuous power for refrigeration and coil current losses at the PCS interface. The net system standby efficiency, including PCS losses, is 97.4%, and the projected life for this application is 20 years.

Table 12-4
SMES System Compliance With Application Requirements

Applications	Single Function		
	App A: GAS – 1 sec FPD equivalent over 20 oscillations per event, 10 events/yr, 1 event/d	**App B: GVS – 1 sec FPD per cycle, 10 events/yr, 1 event/d**	**App F: SPQ – 2 sec FPD per cycle, 100 events/yr, 5 events/d, 1 event/hr**
Model Selection			
Type	DSMES-3KV	DSMES-3KV	DSMES-480V
Pulse Factor	NA	NA	5.0
Chopper Voltage (V_{min})	3,000	3,000	750
Maximum DOD, %	100%	100%	100%
Replacement Interval, yr	20	20	20
PCS Selection			
PCS Type (Chapter 5)	I	I	III
Duty Cycles			
Grid Support or Power Quality (GS or PQ)			
Power, MW	10	10	10
Event Duration, sec	1.0	1.0	2.0
Summary System Data			
Standby Hours per Year	8,760	8,760	8,760
System Net Efficiency, % (See Note)	97.4%	97.4%	96.3%
SMES Standby Efficiency, %	99.4%	99.4%	98.3%
PCS Standby Efficiency, %	98.0%	98.0%	98.0%
System Footprint, MW/sqft (MW/m^2)	0.0051 (0.055)	0.0051 (0.055)	0.0044 (0.047)
SMES Footprint, MW/sqft (MW/m^2)	0.015 (0.16)	0.015 (0.16)	0.01 (0.11)

Note: System net efficiency includes losses for energy conversion and system standby expressed on an annual basis, i.e., one minus inefficiency, where inefficiency equals the ratio of annual energy losses to the product of system rated power times 8760 hours, expressed in percent.

Fixed O&M costs for the PCS are based on $2/kW as required by provisions in Chapter 5, and SMES maintenance is projected at $5/kJ. Representative maintenance activities include:

- Servicing refrigeration equipment
- Confirming the operability of system protective devices
- Calibrating sensors and instrumentation
- Inspecting for unusual vibrations, noise or odors
- Inspecting for abnormal conditions of connecting cables and piping
- Inspecting insulation resistance

No disposal costs are included since all materials can be treated as industrial waste.

Lifecycle Benefit and Cost Analysis for SMES Systems

Further insight to the value of energy storage can be gained through lifecycle cost analyses using a net present value (NPV) methodology and comparison with alternatives. For the convenience of the reader, the financial parameters and electric rate structure set forth in Chapters 4 and 5 and used in the analyses are summarized in Table 12-6 and Table 12-7.

Table 12-6
Financial Parameters

Dollar Value	2003
System Startup	June 2006
Project Life, years	20
Discount Rate (before tax), %	7.5
Property Taxes & Insurance, %/year	2
Fixed Charge Rate, %/year	9.81

Table 12-7
Electric Rates

Load Shifting On Peak Period	3	10
Number Cycles per year	60	250
On-Peak Energy, $/MWh	120	80
Off-Peak Energy, $/MWh	20	
Yearly Average Energy Charge, $/MWh	38	
Regulation Control, $MW-Hour (power), $/MWh	16	
Spinning Reserve, $MW-Hour (power), $/MWh	3	
Transmission Demand Charge, $/kW-mo	5	

The results of lifecycle cost benefit analyses of select SMES applications are summarized in Table 12-8 and discussed below. The bases and methodology used in valuing energy storage applications is described in detail in Chapter 4. The details of the cost benefit analysis for each application are discussed below.

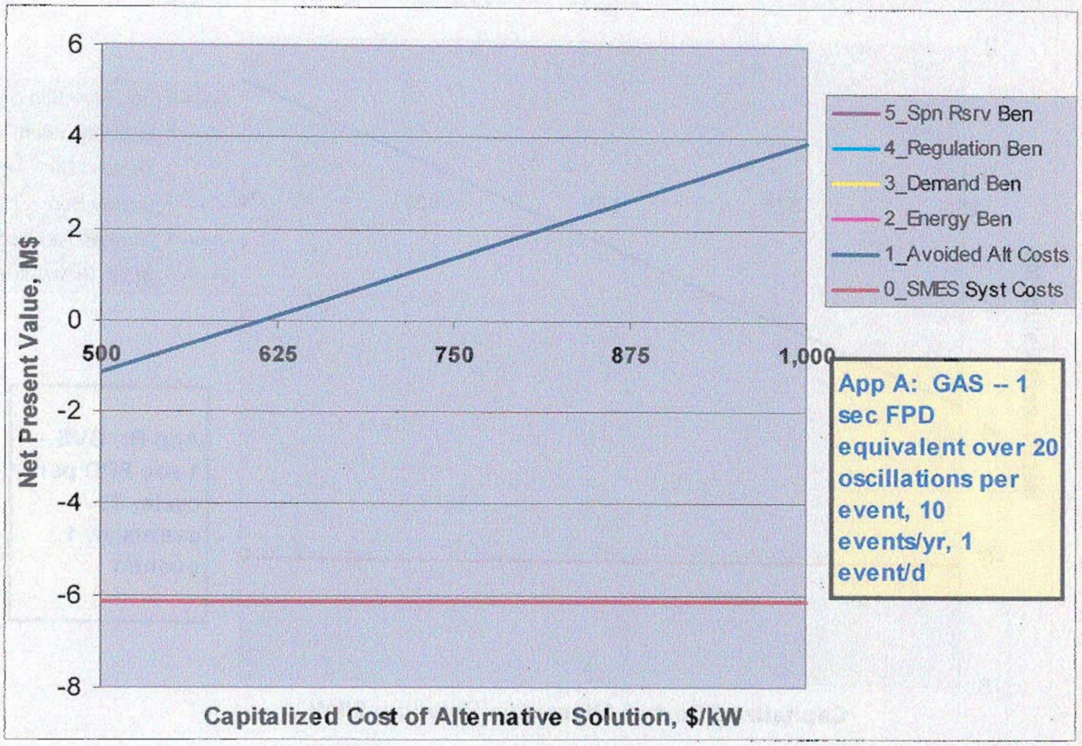

Figure 12-9
Application A: SMES System NPV vs Cost of Alternative Solution

- Application B: Grid Voltage Stability (GVS) – This application was evaluated on the assumption that an alternative solution capable of mitigating GVS events can be obtained for net capitalized costs of about $500/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 12-8, this application yields a negative NPV of ($1.1) million for an initial investment of about $3.8 million on this basis. However, the benefit to cost ratio is about 0.8, and SMES is deemed to be marginally competitive in that it should be considered in circumstances where its intrinsic properties (e.g., its relatively small space requirements) are of high value. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 12-10 illustrates the change in NPV over a range of $250 to $750/kW and shows that SMES systems will compete favorably against alternative solutions with net capitalized costs in excess of about $610/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of DSMES-3KV were decreased from $2.03 to $1.1 million, the NPV would equal zero, i.e., costs and benefits would be equal.

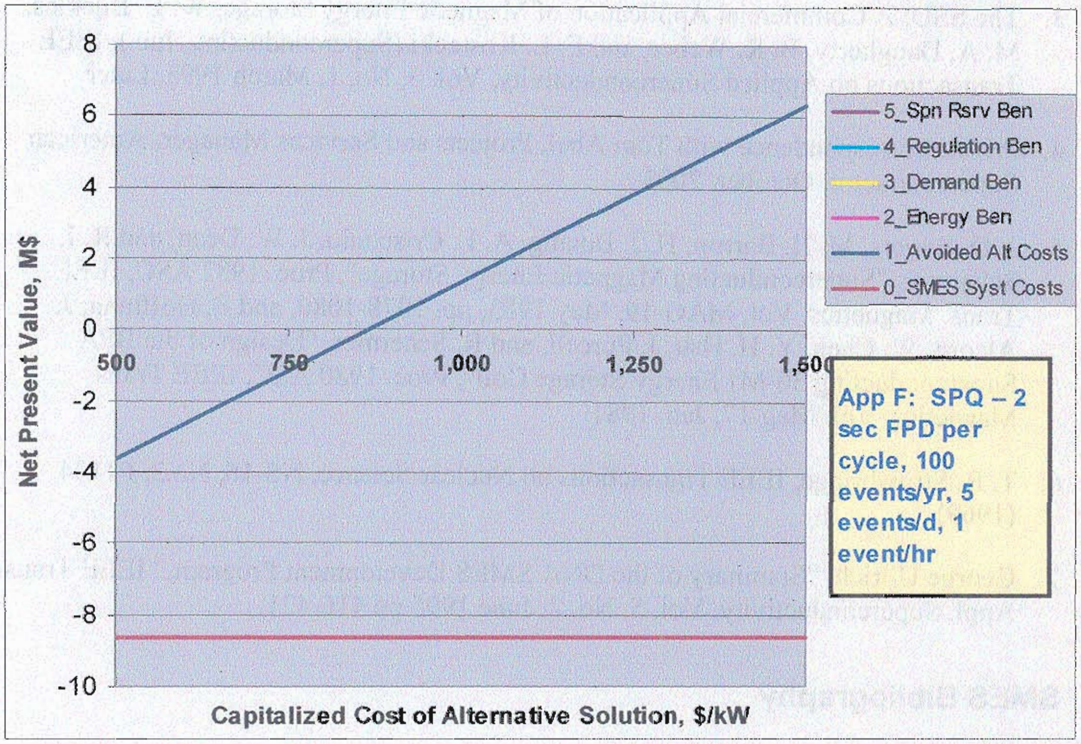

Figure 12-11
Application F: SMES System NPV vs Cost of Alternative Solution

Interpreting Results From Benefit-Cost Analyses

In general, SMES systems are expected to be competitive for grid support applications.

The reader is reminded that the foregoing analyses are intended as a guide to the initial consideration of energy storage options, and that these analyses are based on representative electric rates and costs for alternative solutions as described in Chapter 4. The assumptions used herein should be reviewed in light of project specific applications, alternative solutions, electric rates and financial parameters.

References

1. M. Ferrier, "Stockage d'energie dans un enroulement supraconducteur", in Low Temperature and Electric Power, London, England: 1970, Pergamon, pp. 425-432."

2. E.F. Hammel, W.V. Hassenzahl, W.E. Keller, T.E. McDonald, and J.D. Rogers, "Superconducting Magnetic Energy Storage for Peakshaving in the Power Industry," Los Alamos Scientific Laboratory Report LA-5298-MS, 1973.

- The accepted book that is used to develop magnet and conductor designs is: Martin N. Wilson, Superconducting Magnets Oxford Science Publications, Oxford, UK, 1983.
- The original article that related stored energy and support structure was: R. Clausius, "On a Mechanical Theorem Applicable to Heat," Phil. Mag. S-4, Vol. 40, pp 12-127, 1870.

Early Articles and Papers On SMES

Early articles and papers on SMES include the following:

- H. A. Peterson, N. Mohan, and R. W. Boom, "Superconductive Energy Storage Inductor-Convertor Units for Power Systems", IEEE Trans. Power Systems", IEEE Trans. Power App. Syst., Vol. PAS-94, No. 4, July-August 1975.
- W.V. Hassenzahl, "Will Superconducting Magnetic Energy Storage be Used on Electric Utility Systems?" IEEE Transactions on Magnetics, MAG-11, No. 2, 1975, pp. 482-88 (LA-UR-74-1470).
- J.D. Rogers, W.V. Hassenzahl, and R.I. Schermer, "1 GWh Diurnal Load levelling Superconducting Magnetic Energy Storage System Reference Designs," Los Alamos Scientific Laboratory LA- 7885-MS Vols. I-VIII, September 1979.
- William V. Hassenzahl, "Superconducting Magnetic Energy Storage," Proc. of the IEEE, 71 (September 1983), pp. 1089-98.

The first report that considered a diurnal SMES plant for other utility applications (in this case spinning reserve) was:

- W.V. Hassenzahl, B.L. Baker, and W.E. Keller, "The Economics of the Superconducting Magnetic Energy Storage Systems for Load levelling: a Comparison with Other Systems," Los Alamos Scientific Laboratory Report LA-5377-MS, September 1973.

Early reports on the need for energy storage and the use of SMES for system stability include:

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

EPRI supported a series of studies on SMES in the early 1980's. In 1986, EPRI decided to pursue the design and construction of an engineering test model ETM that stored about 100 MWh. This model stored about 2 percent of the energy of a full-scale diurnal SMES. At about the same time, the Strategic Defense Initiative (SDI) required a pulsed energy storage system with capacities greater than 1000 MWh and with discharge times of about 30 minutes. Much of the development of the diurnal SMES application over the next 6

- Conceptual Design Study of Superconducting Magnetic Energy Storage Using High Temperature Superconductors, S. M. Schoenung (W. J. Schafer Associates), R. L. Fagaly, M. Heiberger, R. B. Stephens, J. A. Leuer, R. A. Guzman, E. R. Johnson (General Atomics), J. Purcell, L. Creedon, J. R. Hull (Advanced CryoMagnetics), Final Report to DOE February 1993, DOE/CE/34019-1
- Superconducting Magnetic Energy Storage (SMES) Using High-Temperature Superconductors (HTS), Susan M. Schoenung, Robert L. Bieri (W. J. Schafer Associates), Final Report for Sandia National Laboratory May 1994, Subcontract AG-5265
- S. S. Kalsi, D. Aided, B. Connor, G. Snitchler, J. Campbell, R. E. Schwall (American Superconductor Corporation), J. Kellers (American Superconductor Europe), Th. Stephanblome, A. Tromm (Gesellschaft für Innovative Energieumwandlung und Speicherung GmbH), P. Winn (Applied Engineering Technologies), "HTS SMES Magnet Design and Test Results", IEEE Transactions on Applied Superconductivity, Vol. 7, No. 2, June 1997.
- R. Mikkonen, M. Lahitnen, J. Lehtonen, and J. Paasi (Tampere University of Technology), B. Conner, S. S. Kalsi (American Superconductor), "Design Considerations of a HTS μ-SMES", European Conference on Applied SC, July 1997

Conference Proceedings

As mentioned earlier, one of the riches sources of information on SMES development are the proceedings of the Applied Superconductivity Conferences. The most recent conference was August 4-9, 2002, and the proceedings will be published by the IEEE in April of 2003. Titles of some of the papers on SMES in this conference are given below.

- A 100 MJ SMES Demonstration at FSU-CAPS, C.A. Luongo, T. Baldwin, FSU-CAPS; C.M. Weber, P. Ribeiro, BWX Technologies.
- Magnet Power Supply with Power Fluctuation Compensating Function Using SMES for High Intensity Synchrotron, T. Ise, Y. Kobayashi, S. Kumagai, Osaka University; H. Sato, T. Shintomi, KEK.
- Impact of Micro-SMES on Power Flow, J. Liu, M.M.A. Salama, R.R. Mansour, University of Waterloo.
- Design of a 150 kJ High-Tc SMES for a 20 kVA Uninterruptible Power Supply System, R. Kreutz, H. Salbert, D. Krischel, A. Hobl, C. Radermacher, ACCEL Instruments GmbH; N. Blacha, AEG SVS GmbH; P. Behrens, EUSGmbH; K. Dütsch, E.ON Netz GmbH.
- Fabrication and Test of a Superconducting Coil for SMES System, H.J. Kim, K.C. Seong, J.W. Cho, S.W. Kim, Y. K. Kwon, Korea Electrotechnology Research Institute.

- S. Schoenung, "Superconducting Magnetic Energy Storage Benefits Assessment for Niagara Mohawk Power Corporation," report prepared for Oak Ridge National Laboratory, DE-AC05-840R21400, 1994.
- Zaininger, SAND98-1904 (SMUD Wind and PV study)
- "The Market Potential for SMES in Electric Utility Applications," prepared by Arthur D. Little for Oak Ridge National Laboratory, Report No. ORNL/Sub85-SL889/1, 1994.
- S. Schoenung, J. Badin, J. Daley, "Commercial Applications and Development Projects for Superconducting Magnetic Energy Storage," Proc. of the American Power Conference, Chicago, 1993.