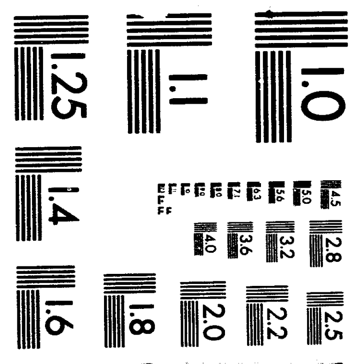

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Battery Energy Storage and Superconducting Magnetic Energy Storage for Utility Applications: A Qualitative Analysis

Abbas A. Akhil
Paul Butler
Storage Batteries Department

Thomas C. Bickel
Photovoltaic Technology Research Department

Sandia National Laboratories
Albuquerque, New Mexico 87185

Abstract

This report was prepared at the request of the U.S. Department of Energy's Office of Energy Management for an objective comparison of the merits of battery energy storage with superconducting magnetic energy storage technology for utility applications. Conclusions are drawn regarding the best match of each technology with these utility application requirements. Staff from the Utility Battery Storage Systems Program and the Superconductivity Programs at Sandia National Laboratories contributed to this effort.

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I. EXECUTIVE SUMMARY

This report compares the merits of battery energy storage (BES) and superconducting magnetic energy storage (SMES) for utility applications. Although pumped-hydro is the only mature energy storage technology currently available to utilities, it has not been considered in this report because of severe siting, environmental, and size constraints. Based on this BES/SMES comparison, recommendations are made to the U.S. Department of Energy (DOE) regarding possible DOE involvement in development of the two technologies for specific utility applications. Developmental needs for each technology and its interface to the utility grid (the power conditioning subsystem) are also identified.

As a result of demonstration projects and system studies, utilities have realized that energy storage can be used for many applications. Table 1 shows representative utility applications and preliminary energy storage requirements that have evolved from these demonstrations and studies. More important, utilities have realized that they can use one energy storage device for more than one application. This makes energy storage an option to attain higher efficiencies and reduce operating costs for utilities. If suitable energy storage systems are developed to meet these application requirements, they can satisfy the needs of a potentially large segment of the electric utility market and have a significant impact on utility operations nationally.

Table 1. Utility Applications and Corresponding Preliminary Energy Storage Requirements

Utility Application	Energy Storage Requirements		
	Energy Capacity (MWh)	Avg. Discharge Time (h)	Max. Discharge Rate (MW)
Load Leveling	> 40	4 - 8	> 10
Spinning Reserve	< 30	0.5 - 1	< 60
Frequency Regulation	< 5	0.25 - 0.75	< 20
Power Quality	< 1	0.05 - 0.25	< 20
Substation Application (e.g., transformer deferral, feeder/customer peak shaving, etc.)	< 10	1 - 3	< 10
Renewables	< 1	4 - 6	< 0.25

The ability of BES and SMES technologies to meet these needs depends on their basic characteristics (energy density, round-trip efficiency, and rate of charge and discharge) and their performance. An estimate of the suitability of BES and SMES technologies for specific utility applications is presented in Table 2. The suitability estimate is based on technical merit, recognizing that BES is further developed. Consideration has been given to the potential for overcoming technical hurdles facing SMES before it achieves a mature status. Economic issues were not addressed in this analysis.

Table 2. Utility Applications and Storage Technology Suitability

Utility Application	BES		SMES	
	Current Tech	Advanced Tech	Current Tech*	Advanced Tech**
Load Leveling	UN	ND	UN	NA
Spinning Reserve	SA	ND	ND	ND
Frequency Regulation	SA	ND	SA	ND
Power Quality	SA	ND	SA	ND
Substation Applications	SA	ND	ND	ND
Renewables	SA	ND	ND	NA

UN = Unsuitable ND = Needs Development
SA = Suitable, Available NA = Needs Assessment
*Low Temperature Superconductors **High Temperature Superconductors

BES could meet the performance requirements for most of the applications in Table 1. The concerns of utilities about reliability, life, and energy density for particular applications have driven development of improved lead-acid and advanced batteries. SMES could meet the requirements for applications that require rapid charging and discharging. If significant advances are made, then SMES could be used in other applications. The required materials for large superconductors have driven the development needs.

Both BES and SMES systems require future development. The concerns of utilities about BES reliability, life, and energy density for particular applications have driven development of improved lead-acid batteries. For SMES systems, the required materials for large superconductors have driven development needs.

For either SMES or BES to be useful to a utility, an interface between the storage device and the grid must be present. The interface is the power conversion subsystem (PCS). PCSs are commercially available, but current designs are not cost-effective. Advances in technology such as the resonant frequency power converter suggest that the major development needs are to provide manufacturers with standardized requirements and to demonstrate PCS capabilities to utilities as part of integrated system demonstration programs.

Results

In general, BES is well suited for applications that require fast response as well as storage capacities up to approximately three hours. Present BES systems based on lead-acid batteries can meet all the utility application requirements except load leveling. In the near term, the primary needs of this technology are for developing standardized, integrated system designs that can be purchased by utilities on a turn-key basis. Further support for field demonstrations at utility sites to validate performance is highly desirable. In the longer term, sustained development of advanced battery technologies, such as sodium/sulfur and zinc/bromine, is needed to ensure that improved-performance battery systems will be available to meet anticipated utility needs.

SMES offers rapid charge/discharge capabilities, but is limited by storage capacity. Considerable development effort will be required to increase SMES capacity beyond its present capability of a few seconds to approximately three hours in order to meet certain utility application requirements.

Widespread application of both technologies requires development of off-the-shelf PCS hardware and vendor capability. The one-of-a-kind PCS that was built for earlier battery projects will not be able to meet the needs of the energy storage market as it grows. Cost-effective PCS hardware with higher functionality will be needed.

Recommendations

This analysis suggests that both SMES and BES are storage technologies that can meet specific needs of the electric utility industry. The deployment of these technologies will result in better asset utilization in the utility network. To facilitate efficient deployment of these systems, SNL recommends the following course of action for consideration by the DOE:

- Assist the utility industry, component manufacturers, and system suppliers to develop and demonstrate standardized BES systems for specific applications using commercially available and near-term batteries.
- Continue development of BES systems with advanced batteries to meet the performance needs of high-capacity, small-footprint applications.

- Develop and validate cost models for SMES including further refinement of cold support/warm support trade-offs, magnet geometries, and refrigeration systems.
- Pursue development of SMES technologies for intermediate-to-long discharge duration applications, if warranted by the cost models.
- Assess the feasibility of SMES for large-scale energy storage and, if warranted, initiate a core-technology development program to address critical technology needs.
- Determine the research and development issues related to power conditioning subsystems that would facilitate the development of cost-effective, standardized PCSs for energy storage and renewable energy applications. Initiate a DOE-supported program for PCS technology improvements, if warranted.

II. BES AND SMES APPLICATIONS

Background

Utilities have traditionally thought of BES systems only for load-leveling applications. Recent studies[1,2] have identified at least five other applications, which are shown in Table 1. Benefit studies have shown that energy storage systems can satisfy more than one of these applications, thereby greatly increasing their economic value to a utility network.

There has been an effort to demonstrate the feasibility of using BES and SMES energy storage technologies. Table 3 lists most of the BES systems that are in use or planned by utilities. This list covers a broad range of applications in which BES offers benefits to utilities. However, it does not include BES systems used on the customer side of the meter, such as UPSs, or those used with industrial customers for peak shaving to reduce their demand charges. It also excludes a large number of battery systems at military bases that are used as a UPS or as a supplement for special needs such as pulse power for experimental submarines or other experiments that cannot be supplied with commercial utility power.

Table 4 lists SMES projects that are completed or planned. The Superconductivity, Inc., devices are leased to selected demonstration sites and tested. The other projects are in the planning or conceptual stage.

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[1] *Four system studies performed in FY91-92 with San Diego Gas & Electric, Oglethorpe Power Corporation, Chugach Electric Association and Bonneville Power Administration, SAND93-1754.*

[2] *SMES Utility/Industry Applications Workshop, September 2-3, 1992.*

Table 3. Utility Battery Projects — Existing & Planned

Company Name	MW/MWh	On-Line or Planned
I. Projects Completed		
Crescent Electric Coop.	0.5 / 0.5	1983, Operating
Southern California Edison (Chino)	10 / 40	8/86, Operating
Berlin Power and Light (BEWAG)	8.5 / 8.5 17 / 5.7	2/87, Operating
San Diego Gas & Electric Trolley Load-Leveling Project	0.20 / 0.40	11/92, Operating
Tatsumi Substation (Kansai Electric)		
Lead-acid	1 / 4	1986, Operating
Sodium/sulfur	1 / 8	1991, Completed
Imajuku Energy Storage Test Plant (Kyushu Electric Power Co.)		
Zinc/Bromine	1 / 4	1991, Completed
Puerto Rico Electric Power Authority, 1st of 5 Planned Installations	20 / 14.1	11/93 (Under Const.)
II. Committed to Conceptual Design		
Chugach Electric Association, Anchorage, AK	10 / 20	7/94, Planned
Hawaii Electric Light Company	10 / 10	4/94, Planned
Puerto Rico Electric Power Authority, 2nd Planned Installation	20 / 14.2	1/95, Planned
Metlakatla Power & Light, Metlakatla Village, AK	1 / 1/60	1/94, Planned
Tlingit, Haida Regional Electrical Authority, Kasaan Village, AK	0.03/0.09	1/94, Planned
Pacific Gas & Electric Utility Scale Battery Demonstration	2 / 4	3/94, Planned
III. Completed System Study		
Oglethorpe Power Corporation	6 / 19	?
San Diego Gas & Electric, System-Wide Benefits	20 / 60	?
Consolidated Edison	?	?
New York Power Authority, Metro North Railway Application	2 / 4	?
Bonneville Power Authority, Puget Sound Area Study	?	?

Table 4. Utility SMES Projects — Existing & Planned

Project Name	Power Rating/Stored Energy	Status On-Line or Planned
Superconductivity, Inc.	460 - 2500 KVA 140-550 Wh	Commercial Product
Los Alamos National Laboratory/ Bonneville Power Authority	10 MVA 30 MJ (8.3 kWh)	1983-1984
ABB, Zurich Swiss National Railroad	1.2 MW 210 MJ (50 kWh)	1993-1995 (Demonstration Unit)
ABB, Zurich Swiss National Railroad	25 MW 3600 MJ (1 MWh)	Awaiting Demonstration Results
Hydro Quebec	10 MVA 33 MJ (9 kWh)	1993-1995 (Demonstration Unit)
Hydro Quebec	300 MVA 360 MJ (100 kWh)	2000
MITI-ISTEC	20 MW 420 MJ (120 kWh)	1994
ETM - DNA	10 - 400 MW 20 MWh	????

ABB = Asea Brown Boveri
MITI = Ministry of International Trade and Industry (Japan)
ISTEC = International Superconductivity Technology Center
DNA = Defense Nuclear Agency
ETM = Engineering Test Model

Requirements and Applications

Based on the demonstrations and studies, requirements and applications for energy storage systems have been summarized in this section.

Six utility applications of BES and SMES and corresponding preliminary system-performance requirements are shown in Table 1. A brief description of each application and the feasibility of using either a BES or SMES in each application follows.

Load Leveling. Utilities in the size range of 2,000 to 3,000 MW typically need 300 to 400 MW of generation capacity for at least 4 hours to meet their peak demand. Any form of storage capacity used to displace this peaking generation capacity must be fully capable of carrying this load until the peak period passes. Thus, the commonly accepted requirement for a storage system is at least 40 MWh of storage capacity, capability for diurnal discharge, and displacement of 10% or more of the peak demand.

Load leveling requiring more than 40 MWh is not easily attained with current lead-acid battery technology. Typically, this size of battery plant requires more than 8,000 batteries, and such a large number of batteries in one facility poses several design problems. These problems include ground fault detection and an unacceptably high number of parallel strings, leading to unbalanced charging. Even if these issues were successfully overcome, utilities are hesitant to accept the maintenance burden perceived with the operation of such a large battery plant. The development of improved and advanced batteries that reduce the size and complexity of the plant could make BES a favorable option for load leveling at some future time.

SMES has been proposed as a candidate for load-leveling applications, and the concept of SMES for large-scale load leveling has progressed to the point of engineering design of an Engineering Test Model (ETM). Originally designed for dual military/civilian use, the ETM has been designed for 20.4 MWh with a military power requirement of 400 MW and a civilian requirement of at least 10 MW for utility load leveling. The objective of the ETM is to validate the engineering design of an advanced SMES. However, the small size and experimental nature of the device leads to an inefficient unit, and its daily energy consumption may exceed its diurnal storage capacity. System sizes in excess of several hundred MWh for an efficient advanced SMES may be necessary to overcome the inefficiencies of the smaller sized systems.

Spinning Reserve. Utilities are required by law to have 15 to 20% of their generating capacity readily available. Because this capacity is commonly held ready in rotating turbines, it is known as spinning reserve. Energy storage systems with nominal power capabilities of up to 60 MW, with a half-hour to an hour of storage capability, could meet the needs of a broad spectrum of utility sizes. Lead-acid batteries that are available or being developed are capable of meeting the spinning-reserve performance requirements.

Existing flooded-cell lead-acid batteries have been successfully demonstrated in this application in Berlin with a battery that has been operational for over six years in a combined spinning reserve and frequency regulation mode. In the U.S., there is a growing interest in BES systems. The Puerto Rico Electric Power Authority has undertaken construction of a 20 MW/14 MWh battery to meet its spinning reserve needs. This battery is scheduled for commercial operation in the fall of 1993.

Frequency Regulation. Fast-response energy storage systems can be used effectively to correct the frequency deviations that normally occur on the utility network as a result of momentary differences between system load and available generation resources. The requirements for a frequency regulation storage system are for rapid cycle-to-cycle discharge and rapid charge capability to compensate for a drop or rise in frequency on a continuous basis. The current lead-acid system being built by the Puerto Rico Electric Power Authority will also be used for this application, and other systems are planned.

The application of SMES for frequency regulation was demonstrated by an 8.3-kWh Los Alamos National Laboratory/Bonneville Power Administration (LANL/BPA) device in 1983. Operated intermittently for one year, the system accumulated over 106 cycles. This application demonstrated the rapid charge/discharge capability of the SMES system and its suitability for frequency regulation applications.

Power Quality. Industrial loads with large motors or other processes that require intermittent, sharp surges of power during their routine operation create brief voltage sags that affect power quality at the customer site and, depending on their severity, can also affect the power quality of neighboring customers. Voltage fluctuations and the resulting deterioration of power quality are becoming an increasingly important service issue as the use of sensitive electronic equipment increases. Power quality requires minimal energy storage. Both battery and SMES storage can be used effectively to provide this short-duration "pulse" discharge that lasts only a few seconds.

Power quality applications require high power and low storage capacity, and commercially available SMES systems are technically suitable to meet the requirements. The key characteristic of the SMES system is its ability to charge and discharge rapidly at high efficiency (>95%) with virtually unlimited life. The power quality application utilizes this characteristic to its greatest advantage, and small SMES systems have been demonstrated at utility customer sites. Lead-acid batteries can also be used for this application, and their feasibility has been demonstrated in UPS applications.

Substation Applications. Substation energy storage requires systems in approximately the 2-to-10-MW power range, with up to 10 MWh of storage capability. If the storage system is transportable, utilities can move the energy storage system to different sites as substation needs change in response to load-growth patterns over time.

Presently available lead-acid batteries can meet the needs of stationary substation energy storage. Transportability introduces new requirements for the system design. Improved lead-acid batteries and advanced batteries with small footprints are particularly desirable. Since substation-upgrade applications require storage capabilities of up to three hours, SMES is presently limited by its energy storage capacity and will require significant development to meet the needs of this application.

Renewables. Energy storage systems can potentially be an enabling technology that would facilitate the integration of renewable resources into the electric utility of the future. The value of renewable resources, especially photovoltaics and wind, is heavily dependent on their ability to generate energy when the utility system load peaks. The variability and unpredictability of these resources make it uncertain that their generation capability will be available to the utility on demand. If energy storage is available to a utility, however, the generation capacity of renewable resources is decoupled from the real-time energy needs of the utility network, and the energy generated can be stored for dispatch at any time.

Initially, for small penetration levels of renewable resources, the role that energy storage plays will be small. As the penetration level of renewable resources increases, the value and importance of energy storage to the utility network will be greatly enhanced. The performance characteristics required for renewable support are met by battery technology. SMES may not be suitable for this application at this time, and developing its capability to satisfy this application in a cost-effective manner will be a significant challenge.

III. TECHNOLOGY STATUS AND DEVELOPMENT NEEDS

This section describes BES and SMES technology along with the development needs. Energy storage systems require a storage system (a battery or a superconductor) and the associated hardware to allow the storage system to interface with the utility grid. The most important piece of hardware is the power conversion system. Figures 1 and 2 show complete BES and SMES systems.

Storage Systems

Battery Systems. Battery systems store energy electrochemically, and the storage capacity of batteries depends on the electrochemical couple chosen. The energy stored in lead-acid batteries is approximately 30 to 40 Wh/kg or 60 to 100 Wh/l. The energy conversion efficiency of lead-acid batteries is typically about 80 to 85%. Lead-acid batteries are most readily available because of their other uses with proven reliability and low cost. Advanced batteries have the potential of doubling the capacity of lead-acid batteries and have a footprint that may be 25% of the size of lead-acid batteries.

The major concerns of utilities are the reliability (including lifetime) of battery systems, the maintenance requirements, and the footprint of the system. Lifetimes of batteries should be enhanced for improved lead-acid batteries like the VRLA and advanced batteries. Footprints can be decreased by 75% and energy densities at least doubled by advanced batteries. Demonstrations of standard designs of BES should demonstrate reliability and real maintenance rather than perceived maintenance requirements.

To enhance demonstration projects, development is needed in standardizing system designs for both stationary and transportable systems for both lead-acid and advanced batteries. Transportable systems would meet short-term demonstration needs and also allow the utility to move the storage where it is most needed. Demonstrations will provide performance data needed for utility planners to consider battery energy storage as a viable option in their planning.

Superconducting Magnetic Energy Storage (SMES). This technology is based on storing energy in the magnetic field of a superconducting coil. Because direct current flows with negligible losses in superconductors, SMES systems can be used for small- and large-scale energy storage and rapid charge/discharge applications.

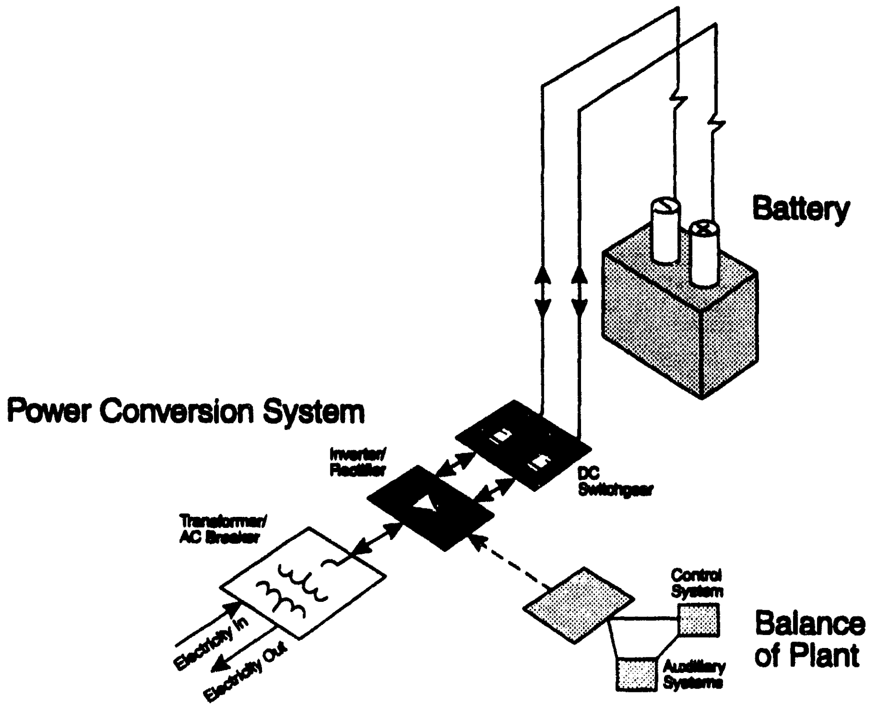

Figure 1. Schematic of a BES System

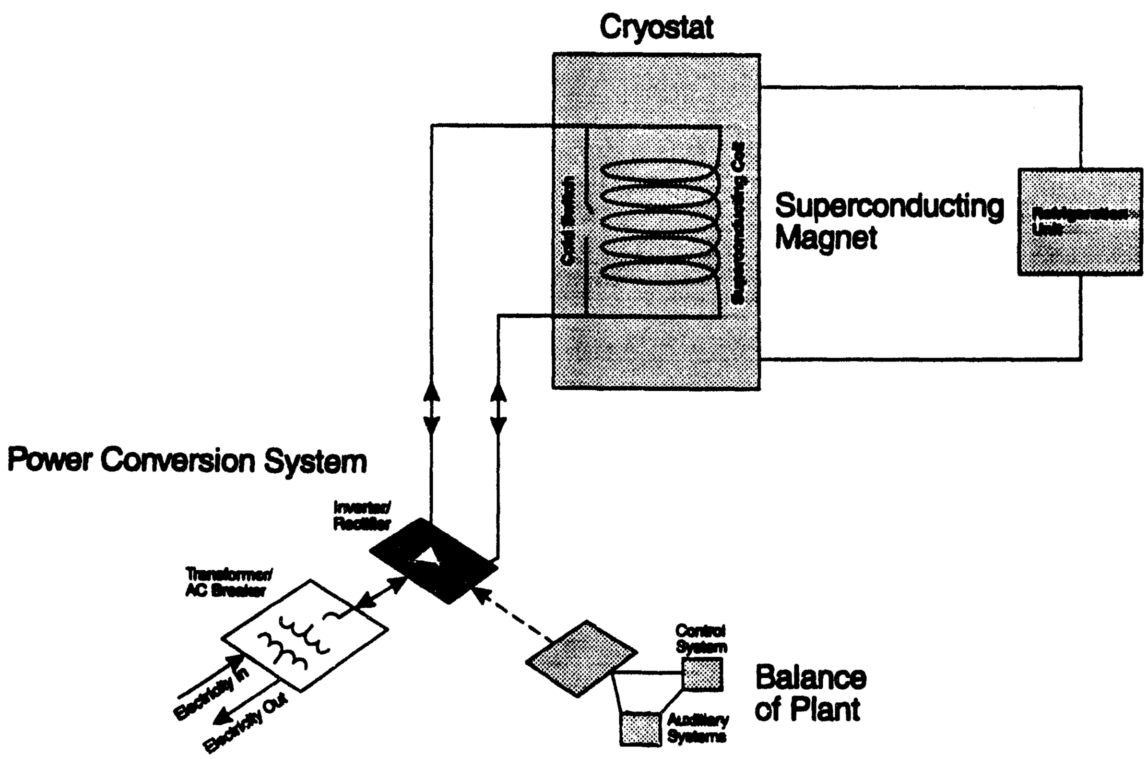

Figure 2. Schematic of a SMES System

The primary components of a SMES system are

1. A magnet manufactured using either high-temperature or low-temperature superconducting wire.
2. A cryostat/refrigerator that maintains the superconducting materials at cryogenic temperatures. Typically, this is liquid helium (4.2 K) for low-temperature superconductors (LTS), and it is projected to be liquid nitrogen (77 K) for high-temperature superconductors (HTS).
3. A structural support to contain the magnetic field (Lorenz forces, IxB), which can be warm-supported (generally buried in the ground) or cold-supported (structural steel inside the cryostat).

Although few superconducting systems have been built for energy storage, commercially available low-temperature superconductors are used in medical and scientific instrumentation. They have also been proposed for use in the Supercollider. Development needs are minimal for low-temperature superconductors, but their use is limited by the high cost of helium and their refrigeration requirements.

High-temperature superconductors need significant development. One major hurdle is a method for processing the superconducting materials into the long flexible lengths of wire needed for the coils. This is particularly difficult because the superconductivity depends not only on the exact formulation of the oxides, but the alignment of the crystals. Another priority is the development of very efficient refrigeration units.

Power Conversion for BES and SMES

A brief discussion of PCS basics is included here for completeness and to highlight the equally important development needs for this subsystem in the commercialization of both battery and SMES technologies.

Both batteries and SMES are dc power sources that require conversion to ac for interconnected or parallel operation with electric utilities. This conversion is performed by the PCS. The key component of the PCS is the inverter that converts the dc output of the storage device to ac during discharge and the ac to dc for recharging the storage device. Inverter design for either BES or SMES systems could be substantially similar except for its interface with the storage device. The battery, as seen by the PCS, behaves as a voltage source. The SMES coil, on the other hand, appears as a current source to the PCS. At present, there are no domestic or foreign PCS suppliers in the 40+ MW power rating. The self-commutated PCS sold to date for BESs have been one-of-a-kind, special-order units sold at premium cost.

Both battery and SMES PCSs can be subdivided into two generic types. One type is switched or commutated by an external circuit, and the other type is switched of its own accord. The externally switched PCS, which relies on the electric utility line for switching or commutation, is called a line-commutated PCS; the internally switched PCS is called a self-commutated PCS. Power quality and frequency regulation are stand-alone operations isolated from the utility network and require self-commutated PCS capability.

Rapid advances in power conversion technology could have significant impact on self-commutated PCS designs. Until recently, Gate Turn Off (GTO) switches were preferred for high-rate PCS designs because of their higher power ratings. Integrated Gate Bipolar Transistors (IGBT), which were previously available only for lower power ratings, are now being designed for higher power ratings and offer operational as well as cost advantages over GTOs. Eventually, IGBTs or similar devices could replace GTOs as the preferred device for large PCSs. The fundamental circuit design of power conversion devices is also changing, and new circuits, such as the resonant frequency power converter, are being designed that have higher power capabilities and promise lower costs.

The development need is for a "commercial," self-commutated PCS for power quality, frequency-regulation applications, and renewables. Demonstrations of energy storage systems with this PCS are needed to establish its reliability.

Distribution

ABB Power T&D Co., Inc. (2)
630 Sentry Parkway
Blue Bell, PA 19422
Attn: P. Danfors
H. Weinrich

AC Battery Corporation
P.O. Box 325
East Troy, WI 53120
Attn: R. Flemming

Alaska Energy Authority
P.O. Box 190869
Anchorage, AK 99519-0869
Attn: D. Denig-Chakroff

American Electric Power Service Corp.
1 Riverside Plaza
Columbus, OH 43215
Attn: C. Shih

Argonne National Laboratories (3)
CTD, Building 205
9700 South Cass Avenue
Argonne, IL 60439
Attn: C. Christianson
W. DeLuca
K. Myles

Arizona Public Service
P.O. Box 5399
Phoenix, AZ 85072
Attn: R. Hobbs

AT&T Energy Systems
3000 Skyline Drive
Mesquite, TX 75149
Attn: M. Bize

Bechtel
P.O. Box 193965
San Francisco, CA 94119-3965
Attn: W. Stolte

Bonneville Power Administration
Routing EO
P.O. Box 3621
Portland, OR 97208
Attn: J. Ray

C&D Charter Power Systems, Inc.
3043 Walton Road
P.O. Box 239
Plymouth Meeting, PA 19462-0239
Attn: S. Misra

California State Air Resources Board
Research Division
P.O. Box 2815
Sacramento, CA 95812
Attn: J. Holmes

Chugach Electric Association, Inc.
P.O. Box 196300
Anchorage, AK 99519-6300
Attn: T. Lovas

Consolidated Edison (2)
4 Irving Place
New York, NY 10003
Attn: M. Lebow
N. Tai

Corn Belt Electric Cooperative
P.O. Box 816
Bloomington, IL 61702
Attn: R. Stack

Decision Focus, Inc.
650 Castro Street, Suite 300
Mountain View, CA 94041
Attn: S. Jabbour

Delco-Remy
7601 East 88th Place
Indianapolis, IN 46256
Attn: R. Rider

Doug Danley
18131 Metz Dr.
Germantown, MD 20874

Eagle-Picher Industries
C & Porter Street
Joplin, MO 64802
Attn: J. DeGruson

East Penn Manufacturing Co., Inc.
Deka Road
Lyon Station, PA 19536
Attn: M. Stanton

Electric Power Research Institute (6)
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, CA 94303
Attn: J. Birk
S. Chapel
S. Eckroad
R. Schainker
P. Symons
R. Weaver

Electrotek Concepts, Inc.
P.O. Box 16548
Chattanooga, TN 37416
Attn: H. Barnett

Eltech Research Corporation
625 East Street
Fairport Harbor, OH 44077
Attn: E. Rudd

Energetics, Inc. (5)
7164 Columbia Gateway Drive
Columbia, MD 21046
Attn: J. Badin
D. Baker
J. Hurwitch
C. Matzdorf
P. Taylor

Energy Systems Consulting
41 Springbrook Road
Livingston, NJ 07039
Attn: A. Pivec

Exxon Research Company
P.O. Box 536
1900 East Linden Avenue
Linden, NJ 07036
Attn: P. Grimes

Firing Circuits, Inc.
P.O. Box 2007
Norwalk, CT 06852-2007
Attn: J. Mills

General Electric Company (2)
Building 2, Room 605
1 River Road
Schenectady, NY 12345
Attn: E. Larson
D. Swann

General Electric Drive Systems
1501 Roanoke Blvd.
Salem, VA 24153
Attn: C. Romeo

Giner, Inc.
14 Spring Street
Waltham, MA 02254-9147
Attn: A. LaConti

GNB Industrial Battery Company (3)
Woodlake Corporate Park
829 Parkview Blvd.
Lombard, IL 60148-3249
Attn: S. Deshpande'
G. Hunt
J. Szymborski

Hawaii Electric Light Co.
P.O. Box 1027
Hilo, HI 96720
Attn: C. Nagata

Hughes Aircraft Company
P.O. Box 2999
Torrance, CA 90509-2999
Attn: R. Taenaka

Integrated Power Corp.
7524 Standish Place
Rockville, MD 20855
Attn: J. Adelman

ILZRO
P.O. Box 12036
Research Triangle Park, NC 27709
Attn: R. Nelson

Johnson Controls Battery Group, Inc. (4)
5757 N. Green Bay Avenue
P. O. Box 591
Milwaukee, WI 53201
Attn: P. Eidler
R. Miles
T. Ruhlmann
W. Tiedeman

Johnson Controls Battery Group, Inc.
12500 W. Silver Spring Drive
P. O. Box 591
Milwaukee, WI 53201-0591
Attn: J. Zagrodnik

Lawrence Berkeley Laboratory (3)
University of California
One Cyclotron Road
Berkeley, CA 94720
Attn: E. Cairns
K. Kinoshita
F. McLarnon

Jo Meglen
P.O. Box 3232
Oakton, VA 22124

N.E.T.S.
P.O. Box 32584
Juneau, AK 99803
Attn: T. Neubauer

National Renewable Energy Laboratory (3)
1617 Cole Blvd.
Golden, CO 80401-3393
Attn: R. McConnell
J. Ohi
N. Rau

New York Power Authority
1633 Broadway
New York, NY 10019
Attn: B. Chezar

Northern States Power
414 Nicollet Mall
Minneapolis, MN 55401
Attn: M. Rogers

Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831
Attn: B. Hawsey, Bldg. 3025, MS-6040
J. Stoval, Bldg. 3147, MS-6070
J. VanCoevering, Bldg. 3147, MS-6070

Oglethorpe Power Company (2)
2100 E. Exchange Place
P.O. Box 1349
Tucker, GA 30085-1349
Attn: K. Scruggs
C. Ward

Omnion Power Corporation (2)
P.O. Box 879
East Troy, WI 53120
Attn: H. Meyer
F. Ruf

Pacific Gas & Electric (3)
3400 Crow Canyon Road
San Ramon, CA 94583
Attn: G. Ball
B. Norris
R. Winter

Pacific Northwest Laboratory (2)
Battelle Blvd.
Richland, WA 99352
Attn: J. DeSteese, K5-02
K. Drost

Power Technologies, Inc.
1482 Erie Blvd.
P.O. Box 1058
Schenectady, NY 12301
Attn: P. Prabhakara

Power Technologies, Inc.
775 Sunrise Ave.
Suite 210
Roseville, CA 95661
Attn: H. Clark

Puerto Rico Power Authority
G.P.O. Box 4267
San Juan, Puerto Rico 00936-426
Attn: W. Torres

R&D Associates
2100 Washington Blvd.
Arlington, VA 22204-5706
Attn: J. Thompson

Robicon Corporation
100 Sagomore Hill Road
Pittsburgh, PA 15239
Attn: A. Maruschak

Sacramento Municipal Utility District
6201 S. Street
Sacramento, CA 95817
Attn: L. Wittrup

Salt River Project
MS PAB 357, Box 52025
Phoenix, AZ 85072-2025
Attn: H. Lundstrom

San Diego Gas & Electric Company (2)
P.O. Box 1831
San Diego, CA 92112
Attn: T. Nelson
J. Wight

W. J. Schafer Associates
303 Lindbergh Avenue
Livermore, CA 94550-9551
Attn: S. Schoenung

R. K. Sen & Associates
3808 Veazey Street NW
Washington, DC 20016
Attn: R. Sen

Silent Power, Inc.
163 West 1700 South
Salt Lake City, UT 84115
Attn: J. Rassmussen

Silent Power, Inc.
489 Devon Park Drive
Suite 315
Wayne, PA 19087
Attn: W. Auxer

Silent Power, Ltd.
Davy Road, Astmoor
Runcorn, Cheshire
UNITED KINGDOM WA7 1PZ
Attn: M. McNamee

Southern California Edison (2)
2244 Walnut Grove Avenue
P.O. Box 800
Rosemeade, CA 91770
Attn: A. Rodriguez
R. Scheffler

SRI International
333 Ravenswood Ave.
Menlo Park, CA 94025
Attn: C. Seitz

Stuart Kuritzky
347 Madison Avenue
New York, NY 10017

Superconductivity, Inc.
2114 Eagle Drive
Middleton, WI 53562
Attn: J. Emerick

United Engineers and Contractors
700 South Ash St.
P.O. Box 5888
Denver, CO 80217
Attn: A. Randall

University of Missouri - Rolla
112 Electrical Engineering Building
Rolla, MO 65401-0249
Attn: M. Anderson

University of Wisconsin - Madison
Dept. of Electrical & Computer Eng.
1415 Johnson Drive
Madison, WI 53706
Attn: D. Divan

U.S. Department of Energy
Energy Information Administration
EI-531 FORSTL
Washington, DC 20585
Attn: T. Petersik

U.S. Department of Energy
Office of Energy Management
EE-14 FORSTL
Washington, DC 20585
Attn: M. Gunn

U.S. Department of Energy (21)
Office of Energy Management
EE-142 FORSTL
Washington, DC 20585
Attn: R. Eaton (20)
N. Rossmeissl

U.S. Department of Energy
Office of Propulsion Systems
EE-321 FORSTL
Washington, DC 20585
Attn: A. Landgrebe

U.S. Department of Energy
Albuquerque Operations Office
Energy Technologies Division
Albuquerque, NM 87115
Attn: G. Buckingham

U.S. Windpower, Inc.
6952 Preston Avenue
Livermore, CA 94550
Attn: B. Erdman

Westinghouse STC
1310 Beulah Road
Pittsburgh, PA 15235
Attn: H. Saunders

W. R. Grace & Company
62 Whittemore Avenue
Cambridge, MA 02140
Attn: S. Strzempko

Yuasa-Exide
P.O. Box 14205
Reading, PA 19612-4205
Attn: F. Tarantino

Zaininger Engineering Co., Inc.
1590 Oakland Road, Suite B211
San Jose, CA 95131
Attn: H. Zaininger

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