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A Summary of the State of the Art of Superconducting Magnetic Energy Storage Systems, Flywheel Energy Storage Systems, and Compressed Air Energy Storage Systems

Paula Taylor, Laura Johnson, Kim Reichart, Phil DiPietro, Joseph Philip, and Paul Butler

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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A Summary of the State of the Art of Superconducting Magnetic Energy Storage Systems, Flywheel Energy Storage Systems, and Compressed Air Energy Storage Systems

Paula Taylor
Laura Johnson
Kim Reichart
Phil DiPietro
Joseph Philip
Energetics, Inc.
7164 Columbia Gateway Dr.
Columbia, Maryland 21046

Paul Butler
Energetics Storage Systems Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-0613

Abstract

This report details the results of an assessment of the state-of-the art of three energy storage technologies for stationary applications: superconducting magnetic energy storage (SMES), flywheel energy storage (FES), and compressed air energy storage (CAES). The assessment analyzed performance and economic attributes of SMES and FES systems for utility applications and carried out sensitivity studies of the analytic results to identify critical cost issues and technical needs that must be addressed to attain widespread market acceptance. Through the analysis, the study identified areas of research and development that represent potential priorities for future development activities.

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Acknowledgments

Sandia National Laboratories and Energetics, Inc., would like to acknowledge and thank Dr. Russell Eaton, Dr. Christine Platt, and Dr. Imre Gyuk of the U.S. Department of Energy's Office of Power Technologies for the support and funding of this work. We would also like to thank numerous manufacturers and vendors who assisted in compiling the data for this study. Many companies and individuals listed in the appendices (Contacts and Bibliography) contributed to this work but are not mentioned explicitly on this page. However, the sponsors and analysts of this study would like to specifically thank all of them and the companies listed below for their contributions. All have contributed to the advancement of energy storage technologies for utility applications by entrusting sensitive information to the database that supports this project and by devoting many hours of their own time to helping the project team gather information.

Active Power Incorporated
American Superconductor Corporation (Superconductivity, Inc.)
Beacon Power
Boeing Corporation
Intermagnetics General Corporation
Lawrence Livermore National Laboratory
Penn State University, Engineering Science & Mechanics, Applied Research Laboratory
Trinity Flywheel Corporation
University of Texas, Center for Electromagnetic Materials
Urenco (Capenhurst) Ltd.
U.S. Flywheel Systems

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Acronyms

ABB	Asea Brown-Boveri
ACESE	Attitude Control and Energy Storage Experiment
AEC	Alabama Energy Cooperative
ANSI	American National Standards Institute
ASC	American Superconductor Corporation
BES	battery energy storage
BOP	balance of plant
CAES	compressed air energy storage
CASH	compressed air storage with humidification
CEM	Center for Electromechanics
DARPA	Defense Advanced Research Projects Agency
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
ESS	Energy Storage Systems (Program)
FES	flywheel energy storage
FESS	flywheel energy storage systems
GE	General Electric
GNB	GNB Technologies, Inc.
GTO	gate turn-off
HTS	high-temperature superconductivity
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated gate bipolar transistors
IGC	Intermagnetics General Corporation
IRR	internal rate of return
LLNL	Lawrence Livermore National Laboratory
LTS	low-temperature superconductivity
MCT	MOS-controlled thyristor
MCU	magnet control unit
MIU	magnet interface unit
MJ	megajoule
MLC	magnetic power loaded composite
MOSFET	metal oxide semiconductor field effect transistors
MRI	magnetic resonance imaging
NASA	National Aeronautics and Space Administration
NbSn	niobium tin
NbTi	niobium titanium
NO_x	nitrogen oxide
O&M	operating and maintenance
OPEC	Oil Producing and Export Countries
PCS	power conditioning system

PCS	power conversion systems
PID	proportional integral derivative
PQ	power quality
PWM	pulse-width modulation
R&D	research and development
rpm	revolutions per minute
RTM	resin-transfer molding
SCR	silicon-controlled rectifier
SI	Superconductivity Inc.
SMES	superconducting magnetic energy storage
SNL	Sandia National Laboratories
T_c	critical temperature
TPC	Tejas Power Corporation
UPM	uninterruptible power module
UPS	uninterruptible power system
USFS	U.S. Flywheel Systems
UT-CEM	University of Texas Center for Electromechanics
VAR	volt ampere reactive

1. Executive Summary

The U.S. Department of Energy's (DOE's) Energy Storage Systems (ESS) Program at Sandia National Laboratories (SNL) is pursuing research and development (R&D) on a portfolio of energy storage technologies and, as part of its activities, initiated a study to analyze performance and economic attributes of superconducting magnetic energy storage (SMES), flywheel energy storage (FES), and compressed air energy storage (CAES) for utility applications. In execution of the study, analysts conducted a library and internet literature search, interviewed industry and research leaders, built spreadsheet models that calculate a measure of performance for SMES and FES systems, and carried out sensitivity analyses of the analytic results to identify critical cost and technical needs that must be met to achieve widespread application of the technologies. Through the analysis, this study identified needed R&D tasks that represent potential priorities for future ESS Program activities. This document reports the rationale, scope, approach, results, conclusions, and recommendations stemming from the study.

1.1 Project Rationale

Over the past several years, many organizations have conducted R&D on energy storage systems and components and have gathered a vast amount of information. However, much of the information is proprietary and not available to the public. Information in the public domain is often scattered in discrete reports. Therefore, literature searches that precede new research projects may miss information, and new projects can duplicate work that other researchers have done. In addition, research projects that do not have the benefit of reports from previous work are likely to pursue avenues that have already been shown to be less fruitful than others. To address these issues, the ESS Program compiled a comprehensive library of information on the status of advanced storage technologies and developed an analytic tool to assess their economic and technical viability for electric power applications.

1.2 Scope and Goals

The ESS Program limited the scope of the study to three technologies: SMES, FES, and CAES systems.[1] A comprehensive data source on cost, performance, potential markets, and availability of information for all three technologies was compiled. The data include a bibliography of relevant literature, a contact database of manufacturers and researchers, and primers on the three storage system technologies and related issues. For SMES and FES systems, a spreadsheet analytic model was developed. This model details cost and performance of system components and calculates a measure of performance for SMES and FES systems using an internal rate of return (IRR). Sensitivity analysis of the measure of performance was also used to identify R&D that has potentially high value to the development of technically and economically viable SMES and FES systems.

1.3 Approach

The project consisted of four activities: (1) identify and survey manufacturers and researchers; (2) characterize subsystems and components; (3) develop spreadsheet analytic models; and (4) conduct technical and economic analyses. Literature and Internet searches identified manufacturers and researchers with whom the ESS Program was not already affiliated. It also identified literature concerning SMES, FES, and CAES technologies. Interviews with selected manufacturers and researchers provided information about the current state of the technologies, and it provided a basis for projections of cost and performance for the next decade. From this information, the project team characterized subsystems and components in terms of key performance parameters and correlated technology characteristics with applications requirements.

[1] Existing programmatic expertise in battery energy storage systems precluded the need for detailed investigation. Budget and time constraints precluded the inclusion of other storage technologies in this phase of the project.

Analysts developed spreadsheet models that use component, system, and application characteristics to calculate a measure of performance for SMES and FES systems. Sensitivity analyses of the calculated parameter indicated whether specific characteristics strongly affected system cost and performance. The models included component technology characteristics and the "value" of electric power applications for storage systems. The project team selected the IRR that would result from the purchase and operation of a SMES or FES system in a specific electric power application as the calculated measure of performance for the technologies. Sensitivity analysis of the IRR to specific inputs identified areas in which targeted R&D could accelerate development of technically and economically viable SMES and FES systems. From the identified areas, this report suggests priorities and recommends potentially high-impact R&D for the ESS Program.

1.4 Results

Literature searches and interviews allowed analysts to compile a comprehensive data source on cost, performance, markets, and availability for SMES, FES, and CAES systems. Spreadsheet analytic models for SMES and FES systems (which the ESS Program sought) were developed as a tool to identify high-impact R&D. The models are structured such that analysts can input new economic and technical information as it becomes available and continuously update the analytic results. The models use cost and technical attributes of system components to calculate IRR as a measure of performance for the systems. Sensitivity analysis of the IRR to specific model inputs identifies areas in which R&D has significant potential to accelerate development of technically and economically viable SMES and FES systems. Results of the sensitivity studies support recommendations for R&D.

1.4.1 Comprehensive Data Source for SMES, FES, and CAES Components and Systems

Literature searches in libraries and on the Internet and interviews with industry and academia produced a bibliography of technical papers, textbooks, and product literature on SMES, FES, and CAES components and systems. The bibliography appears in Section 10.4.

The literature searches (Section 10.4) and interviews (Section 10.3) also contributed to a set of primers that appear in Section 10.1 of this report. The primers address the physics of storage media; components of the system; and cost, performance, and availability of specific components of SMES, FES, and CAES systems. The primers also present summary overviews on supporting technologies and engineering concepts including cryogenics (for the superconductors in SMES coils and FES bearings and motor/generators), power conditioning systems, high-temperature and low-temperature superconductivity (HTS and LTS), and strength of materials/ engineering mechanics.

Summaries of interviews with industry and academia are included in Section 6 and full reports of the meetings appear in Section 10.3. The summaries reflect researchers' and manufacturers' perspectives on SMES, FES, and CAES systems, and on the research needs for them. The organizations shown in Table 1-1 were interviewed and had the opportunity to review the summaries.

The project team constructed and maintained an electronic database of contacts made during the project and of other energy storage stakeholders. The database can be searched for information about corporate interest areas, company names, addresses, names of individuals, telephone/fax numbers, e-mail addresses, and notes of interest. A hard copy of the database appears in Section 10.5 of this report.

1.4.2 Spreadsheet Models of SMES and FES Systems

The project team produced spreadsheet analytic models of SMES and FES systems. The SMES system model allows the user to define the power and energy of the storage system, the type of superconducting material in the SMES coil, and a number of other inputs defined in more detail in Section 7.2.1.1 of this report. Based on these inputs, the model selects the appropriate cryogen and calculates the size of the cryostat and the size of the area around the coil from which personnel must be excluded. Users can select the type of current leads to the coil and the cryogenic and electrical losses associated with system operation. Users can also define characteristics of equipment for connection to the electric utility grid. With a complete set of user inputs, the model calculates an IRR for a specific SMES system that is suited to and used in a specific electric power

Table 1-1. Participating Organizations

Company/Institution	Location	Date Visited	Technology
University of Texas, Center for Electromechanics	Austin, Texas	1/6/98	FES
Active Power	Austin, Texas	1/7/98	FES
American Superconductor	Middleton, Wisconsin	1/8/98	SMES
Penn State University, Applied Research Laboratory	University Park, Pennsylvania	2/18/98	FES
Beacon Power	Woburn, Massachusetts	2/19/98	FES
U.S. Flywheel Systems	Los Angeles, California	4/1/98	FES
Boeing Corporation	Seattle, Washington	9/2/98	FES
Lawrence Livermore National Laboratory	Livermore, California	9/3/98	FES, SMES
Trinity Flywheel Corporation	Livermore, California	9/3/98	FES

application. To enable sensitivity studies of the IRR, the model accepts user-selected modifications to the unit-cost of materials and components, terms and interest rates for financing options, and the dollar value of several applications. Analysis determined the following applications to be most appropriate for SMES systems:

- Current use
  - Power quality
- Future use
  - Power quality

The FES system model allows the user to define the power and energy of the storage system via the speed, size, configuration and material (steel- or fiber-reinforced epoxy options), and manufacturing process used for the rotor. From these inputs, the model determines the most appropriate containment system and vacuum system, and it determines the need for cryogenics. Users can also select the type of bearing and motor/generator. As in the SMES model, user selections define the parameters by which the model calculates an IRR for a specific FES system. To enable sensitivity studies, the model permits the user to modify the unit cost of materials and components, terms and interest rates for financing options, and the dollar-value for the system selected. Analysis determined the following applications to be most appropriate for FES:

- Current use
  - Power quality
- Future use
  - Power quality
  - Telecommunications
  - Storage for renewable generation and hybrids

Figure 1-1 is a flow chart that illustrates the input and output functions of both models. The model identifies areas in which technical and economic information is sparse and areas in which the state of the technology must advance before systems for electric power applications will gain widespread acceptance and adoption. Therefore, the models identify R&D needs that could help advance the technologies.

1.5 Conclusions

Sensitivity studies using the models identified cost goals that SMES and FES technologies must achieve in order to compete with other technologies and gain widespread acceptance. As shown in Figure 1-2, each application has a range of costs over which SMES and FES systems begin to compete.

System costs that are below the costs shown in the solid horizontal bars are very likely to promote acceptance and adoption of SMES and FES systems in specific electric power applications. Costs within the range indicated by the bars span the range of acceptable costs for commercial applications that are not critical (and for which alternative technologies do not already compete). Systems with costs at the high end of the bars will only compete successfully in critical applications involving either tremendous cost or physical risk (for example, defense applications, semiconductor manufacture). Further exercise of the models determined the current cost of SMES and FES systems and the cost breakdown of the systems at present, in the near term and in the long term. Given the cost thresholds and technical capabilities of SMES and FES systems, both technologies have

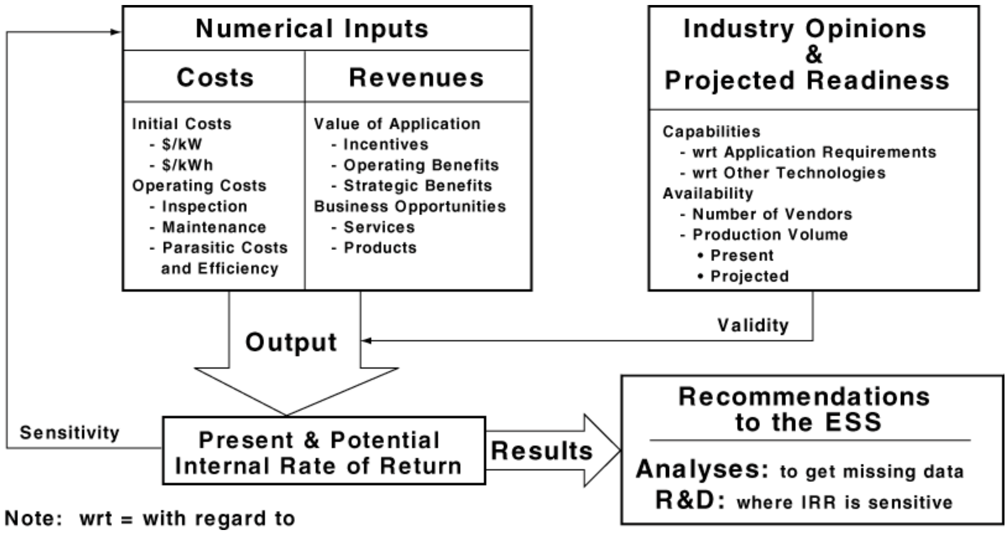

Figure 1-1. Flow Chart of SMES and FES System Models.

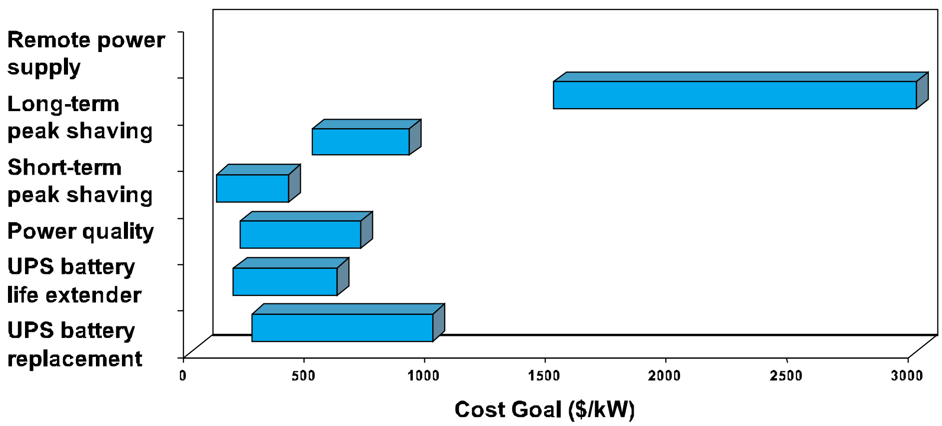

Figure 1-2. Cost Thresholds for Adoption of SMES and FES Systems in Electric Power.

promise to eventually compete in such applications as short-duration peak shaving and power quality, and as a means to extend the life of batteries in uninterruptible power supply (UPS). FES and SMES systems will compete for long-duration peak shaving and remote power supply applications only when they can supply several hours of energy in a cost-competitive manner.

For SMES systems, as shown in Figure 1-3, the greatest cost improvements are most likely in the area of cryostats. Projected improvements for the next generation include further technical advances in cryogenics and reduced cryogenic demands from the use of more high-temperature superconducting materials and improvements in magnets.

For FES systems, although power electronics represent the largest portion of the system cost as shown in Figure 1-4, researchers emphasize the need for R&D on advanced bearings. This emphasis is based on achieving the reduced operating and maintenance costs that are possible with advanced bearings (less friction, greater efficiency, long bearing life, fewer replacements) and rotors.

As shown in Figure 1-5, the cost of the power conditioning system (PCS) becomes a smaller fraction of the entire system cost as discharge duration increases. Conversely, the cost of the rotor increases with the amount of energy that the system stores. This increase is the result of the of the need to use composite rotors to achieve high energy capacity and the need to use more expensive carbon fibers in rotors for mechanical survival at high rotation speeds. As a

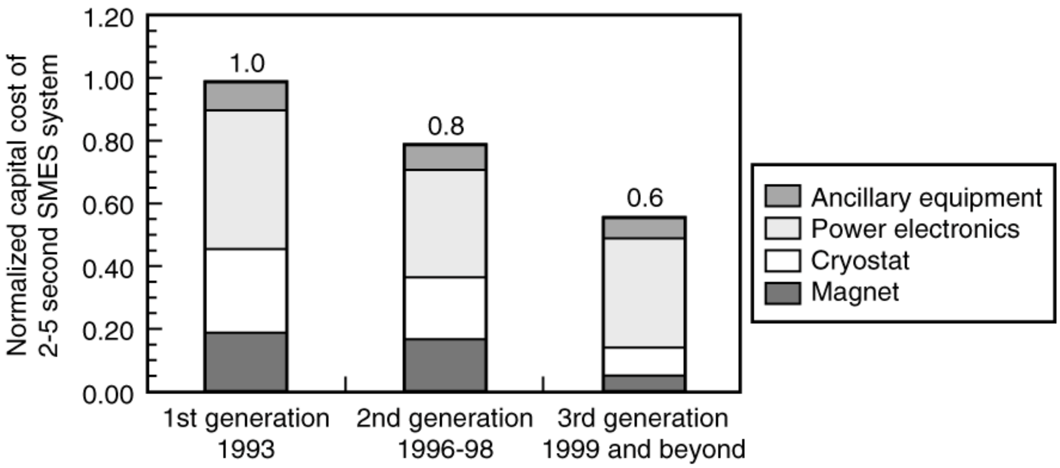

Figure 1-3. Costs of Components as a Percentage of Total Cost of Several Generations of SMES Systems.

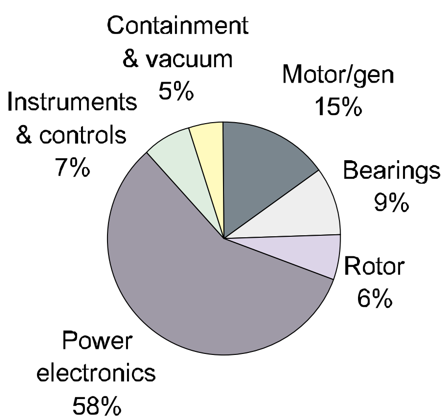

Figure 1-4. Percentage of Total Cost of FES Components in Present Systems.

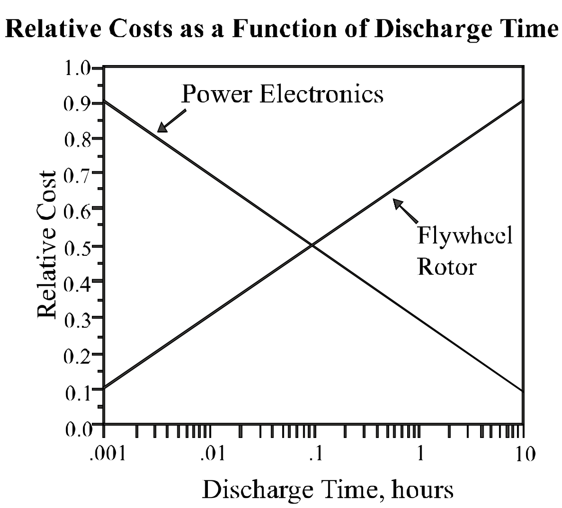

Figure 1-5. Relative Costs of FES System Components as a Function of Discharge Time.

result, R&D to advance rotor technology has high potential for advancing FES systems in electric power applications that require long storage times.

With the information from interviews within industry and academia and with results from the models, analysts determined a number of R&D areas that have the potential to advance SMES and FES systems in electric power applications. R&D for SMES systems, shown in Figure 1-6, spans a range of difficulty and potential impact. The R&D goals plotted at the left side of the graph are expected to be relatively easy to achieve with respect to those on the right. The objectives plotted at the top of the graph have the potential for high impact on SMES cost and performance relative to those at the bottom. Therefore, SMES would benefit most from activities such as improving coil materials and winding processes in which the difficulty is moderate and the potential impact is high.

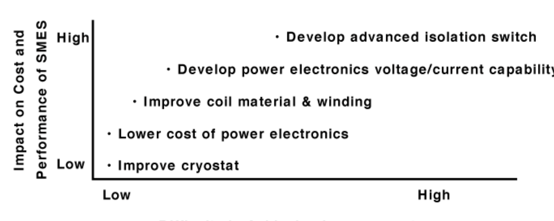

Figure 1-6. Areas of R&D for SMES Systems Based on Impact Versus Difficulty.

While flywheel developers are conducting R&D on fiber-winding processes, optimized use of low-cost and high-strength fibers in composite rotors, and advanced bearings to reduce operating and maintenance costs of the systems, much of the R&D is expensive and represents a relatively high-risk investment for private companies. Continued study of rotor failure, codification of the rotor manufacturing process, further advancement of the fiber winding process, and continued research into motors are areas of FES system development that could be advanced by federal assistance. Figure 1-7 presents R&D goals in terms of likely impact on FES advancement and the difficulty in achieving those goals. The activities in the upper left quadrant of the graph have the highest likelihood of improving cost and performance of FES and are relatively easy to achieve.

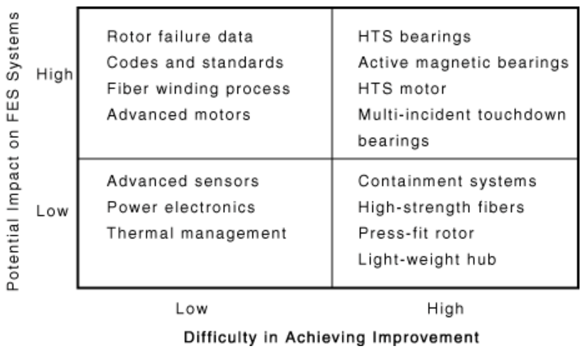

Figure 1-7. Areas of R&D for FES Systems Based on Impact Versus Difficulty.

1.6 Recommendations

Given the cost thresholds shown in Figure 1-2 and the impact versus the difficulty of specific R&D activities shown in Figures 1-6 and 1-7, several specific areas of R&D have the most promise to advance SMES and FES systems in electric power applications. These applications are summarized in Table 1-2. For SMES systems, the most significant advances would result from (1) improvements to the coil material and winding process to reduce the demands on the power electronics, (2) development of power electronics that are specifically suited to SMES devices, and (3) development of an advanced isolation switch or "cold switch" that operates inside of the cryogenic area and improves system efficiency and performance in power quality applications. The risks of investing in these relatively difficult R&D tasks are high for private industry, but the results could tremendously advance SMES systems in electric power applications.

For FES, the high-risk, high-impact R&D areas include development of advanced bearings and HTS motor/generators. There is a pressing need for rotor failure data as well as for codes and standards for manufacturing and operating composite-rotor FES. R&D of bearings, HTS motors, and a uniform set of codes and standards are outside of the near-term reach of the private sector, but are necessary for FES systems if they are to perform in a cost-effective manner in any application that requires more than a few minutes of discharge.

Table 1-2. High-Priority R&D for SMES and FES Systems

SMES R&D	FES R&D
• Improve coil material and winding process – to increase power and energy – to reduce demands on power electronics – to increase efficiency • Improve power electronics • Develop advanced isolation switch – to reduce system thermal losses – to eliminate transients caused by ambient/cryogenic interface	• Develop components to improve system efficiency and reduce O&M costs – advanced bearings – HTS materials – active and passive magnetic types – multi-incident touchdown types • Assist in development of codes and standards (and failure data) for composite rotors for – manufacture – operation

2. Introduction

Over the past several years, many organizations have conducted R&D on energy storage systems and components, and they have generated a vast amount of information. However, much of the information is proprietary and not available to the public. Information in the public domain is often scattered in discrete reports. Therefore, literature searches that precede new research projects easily miss information, and new projects can duplicate work that other researchers have done. In addition, research projects that do not have the benefit of reports from previous work are likely to pursue avenues that have already been shown less fruitful than others.

The ESS Program is pursuing R&D of a portfolio of energy storage technologies including a variety of storage media, power electronics, and peripheral devices that are essential for system function. To reduce the risk of duplicating effort in its own R&D, the ESS Program contracted with Energetics, Incorporated, to develop a comprehensive, verifiable source of information on the state of storage-system technologies and an analytic tool to assess their economic and technical viability in electric power applications.

The ESS Program limited the scope of the study to three technologies: SMES, FES, and CAES systems.[1] The project produced a comprehensive data source on cost, performance, potential markets, and availability of information for all three technologies. The data include a bibliography of relevant literature, a contact database of manufacturers and researchers, and a primer on the three storage-system technologies.

For SMES and FES systems, a spreadsheet-based analytic model was developed. This model details the cost and performance of system components and calculates a measure of performance for SMES and FES systems. Sensitivity analysis of the measure of performance was also used to identify R&D that has the potential for bringing high value to the development of technically and economically viable SMES and FES systems.

Finally, the project produced this final report, which includes the project rationale; project goals; the approach for data collection and model development; and the results, conclusions, and recommendations for future R&D.

The recommendations are based on the following parameters:

- compatibility with specific applications
- requirements for power electronics
- requirements for peripheral devices
- requirements for system integration
- technical maturity now and projected maturity in the future
- availability of components now and in the future
- costs of components and system integration
- availability of markets for specific applications now and in the future.

Through development of a catalogue of private-sector contacts, technical publications, product literature, a bibliography of relevant publications, and a spreadsheet-based set of models of SMES and FES systems, the project team put together a single verifiable data source from which the ESS Program and others can determine how to best focus R&D efforts.

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[1] Existing programmatic expertise in battery energy storage systems precluded the need for detailed investigation. Budget and time constraints precluded the inclusion of other storage technologies in this phase of the project.

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3. Approach

The project consisted of four parts: (1) identify and survey manufacturers and researchers, (2) characterize subsystems and components, (3) develop spreadsheet-based analytic models, and (4) conduct technical and economic analyses. Literature and internet searches identified manufacturers and researchers with whom the ESS Program was not already affiliated. Searches also helped locate literature concerning SMES, FES, and CAES technologies. Interviews with selected manufacturers and researchers provided information about the current state of the technologies and helped establish a basis for cost and performance projections for the next decade. From this information, the project team characterized subsystems and components in terms of key performance parameters and correlated technology characteristics with applications' requirements.

Analysts developed spreadsheet-based models that use system, component, and application characteristics to calculate a measure of performance for SMES and FES systems. A sensitivity analysis of the calculated parameter indicates whether specific characteristics strongly affect system cost and storage performance. The models include component technology characteristics and the estimated value of electric power applications for storage systems.[1] The project team selected the IRR that would result from the purchase and operation of a SMES or FES system in a specific electric power application as the calculated measure of performance for the technologies. Sensitivity analysis of the IRR to specific inputs identified areas in which targeted R&D could be beneficial or necessary for the development of technically and economically viable SMES and FES systems. From the identified areas, this report suggests priorities and recommends potentially high-impact R&D for the ESS Program.

The following sections discuss the details of the assumptions made, methods of gathering data and developing the models, and the iterative process by which sensitivity analysis was conducted.

[1] Another ESS activity, the Phase II Opportunities Analysis, will refine the 'value' of specific applications. The new values, inserted into the SMES and FES system models, will focus the analytic results even more tightly.

3.1 Data Gathering Technology, Characterization, and Modeling

Data gathered for the study included the names of manufacturers and researchers with whom the ESS Program was not already interacting. Literature concerning SMES, FES, and CAES technologies was also obtained. Interviews with selected manufacturers and researchers provided information about the current state of the technologies in terms of key performance parameters.

Project analysts used the data to characterize subsystems and components and to identify areas where more information could be collected through follow-up calls to industry and academic experts. System developers and component vendors verified that cost and performance data were reasonable and that technology characteristics correlated with the requirements of the applications selected for analysis. From the information resources, analysts constructed spreadsheet models of SMES and FES systems. Both models use present and projected technology capabilities and costs to calculate the IRR that would result from the purchase and operation of a system in a specific application. The IRR provides a reference for sensitivity analysis of technical and cost characteristics of the systems. Through iterative modifications of selected inputs, analysts identified R&D priorities that are detailed in Section 8 for the ESS Program to consider (reported in Section 10).

3.2 Literature Review

The literature review included searches at the U.S. Library of Congress and the libraries of the University of Maryland, George Washington University, Pennsylvania State University (Penn State), and Johns Hopkins University. It also consisted of extensive searches of the Internet using databases such as Electric Library and search engines including Hot Bot, Yahoo!, Alta Vista, Excite, Dogpile, and WebCrawler. In addition, the literature survey included product marketing materials and specifications from system developers (some of these materials address existing commercially available products; some address products envisioned by the developers). Analysts reviewed the information from the libraries, the Internet, and vendor publications; compiled a bibliography of the materials; developed the analytic models; and constructed an archive (of available materials) that resides at Energetics' headquarters in Columbia, Maryland. This archive is a comprehensive, verifiable source of information that the ESS Program plans to further develop for energy storage technologies. The materials include all of the documents listed in the Section 10.4 (contact list), 12 additional documents that were either dated or insufficiently relevant for citation, nine internet pages, six vendor marketing pieces, and all of the patents listed in Section 11. Of the 98 documents in the bibliography, 62 are SMES related, 21 are FES related, and 12 are CAES related. The remaining 3 are general discussions of new electricity technology.

4. Electric Power Applications Considered for This Study

For all energy storage technologies, load leveling (diurnal storage of inexpensive off-peak energy and dispatch during peak-demand times) was the first electric power application considered by the power industry. Unfortunately, the energy capacity required for load leveling was not economical for most storage technologies (except pumped hydro and CAES – discussed later). Instead, applications that use a few hours, minutes, seconds, or even milliseconds of storage emerged as analysts considered the cost benefit of storage technologies. In many cases, the applications identified as most viable for battery energy storage systems[1] were also potentially viable uses of SMES and FES as well.

4.1 Power Quality

Power quality is the term that electric power providers and their customers use to describe how closely service voltage and current adhere to their nominal values. Power quality encompasses both the magnitude and the duration of voltage and current fluctuations. Because fluctuations of only a few percent that last for milliseconds can shut down critical and expensive processes, power quality is a pressing concern for electric power providers and their customers. The following list identifies some of the causes of power quality issues:

- Temporary power disturbances: Most large industrial and commercial sites are served by overhead lines whose feeders are subject to many types of temporary power disruptions, including those caused by lightning and high wind.
- Higher distribution voltages: Many electric utilities have increased the voltage at which they distribute power. This allows a single circuit to serve more customers or deliver higher loads and reduces energy losses in the system. However, the overhead distribution circuit is generally longer and has more exposure to causes of potential disturbance.
- Increased sensitivity to momentary voltage sags: The increased use of computers and electronic equipment in industrial plants is providing vastly increased efficiency and control in critical processes. But with sensitivity to brief variations in electric power quality, computer-driven devices can shut down when power is disturbed for even a few milliseconds.
- High costs of downtime: Poor electric power quality costs U.S. industries billions of dollars each year in downtime, product loss, and equipment damage.[2] Bell Laboratories found that 87% of downtime is caused by interruptions lasting no more than 0.5 seconds. Typical outages, surges, sags, and swells of even .03 seconds can cost a company hundreds of thousands of dollars.

For decades, backup battery systems have protected against these disturbances. In the past five years, more modular, faster-responding, commercial battery[3] and superconducting-magnet-based[4] systems that are specifically designed to address power quality have emerged. Utilities that must compete for business and electricity customers with sensitive loads are beginning to install these systems to solve power quality issues.

Resolving power quality problems requires relatively small amounts of energy storage. Therefore, small SMES devices that are technically and economically feasible are emerging to compete with battery-based

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[1] *Battery Energy Storage for Utility Applications: Phase 1 – Opportunities Analysis* by Paul C. Butler, Sandia National Laboratories, SAND94-2605 (reprinted March 1995).

[2] Section 5 discusses other commercial ESS technologies for power quality.

[3] For additional information on SMES, see Section 10.1.

[4] American Superconductivity Corporation offers a 1-MW, 1-second, power-quality micro-SMES. IGC offers a 6 MJ micro-SMES unit. For more information on SMES for power quality applications, refer to the primer on SMES technology in this report.

systems that have been the power quality mainstay for decades. Micro-SMES units are designed to store approximately 1 MJ and are able to dispatch power very quickly; response time is generally less than 10 ms. Figure 4-1 presents the utility supply voltage and the voltage that a load manufacturing site sees when it is connected to a micro-SMB.

FES systems have promise to provide high quality power, but R&D will be necessary to advance the technology sufficiently. Flywheel systems will have to provide megawatts of power in just a few milliseconds for a duration of several seconds, or possibly a minute. These requirements suggest necessary R&D in rotor materials and design (to withstand rapid kinetic changes) and in integrating the flywheel system with power electronics that deliver high quality AC power.

4.2 Support for Intermittent Renewables

Solar and wind generation resources are intrinsically intermittent. Clouds obscure sunlight, and wind is not constant. Because electric power providers must be able to guarantee the level of power that they contract to provide, they derate the capacity of renewables according to their intermittency. To increase the capacity credit for renewable resources, owners of solar and wind generators can use storage to “firm” the power at a consistent level. Power “firming” requires storage systems that can deliver 1 to 5 MW of power for a minimum of several seconds. In areas with greater intermittency, minutes, hours, or even days of storage may be required. If SMES achieves the goals that its developers have set for it by the year 2010, SMES may be able to address “power-firming” applications that require less than ten seconds of storage. Flywheels could also provide reliable support for renewables.

4.3 Uninterruptible Power Supply

Several commercial flywheel developers are working independently and in teams with academia, electric power providers, and potential customers to market flywheel systems that supplement or replace electrochemical batteries in UPS devices. These UPS devices provide power to critical electrical loads, such

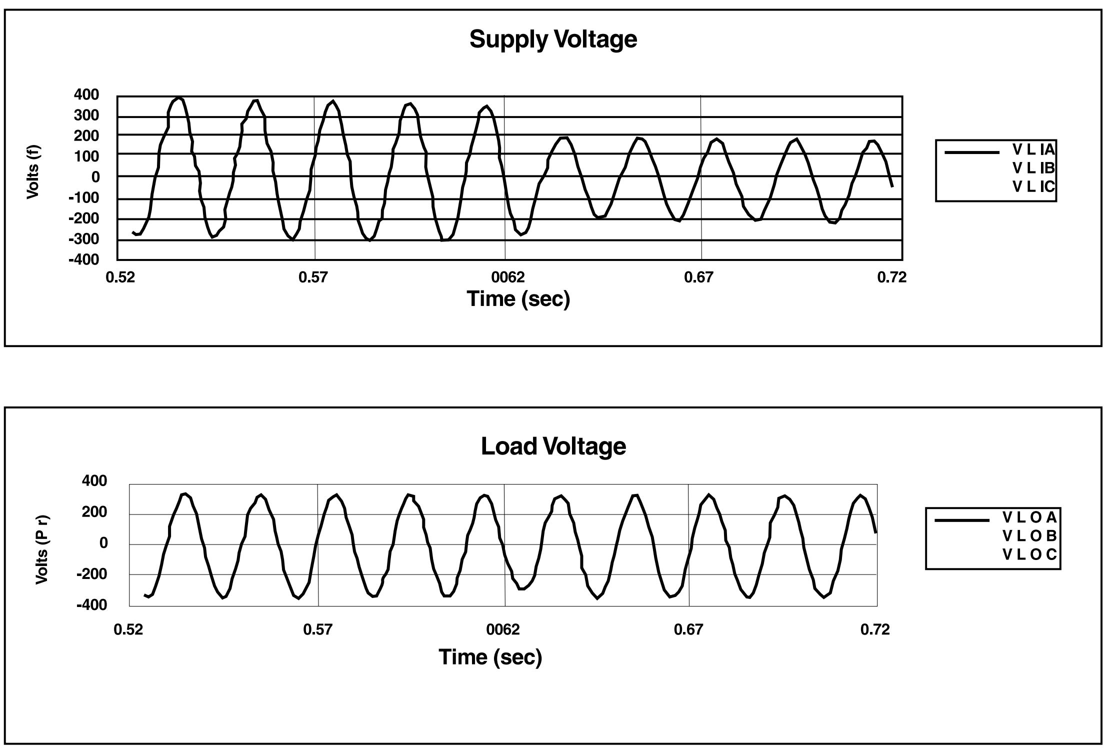

Figure 4-1. Voltage Sag from Utility and Subsequent Ride-Through Protection of SMES Unit.

as computer-controlled manufacturing processes, telecommunications, cable television, and health care services that must continue operating even during power outages. Several companies are distributing literature about integrated flywheel products for UPS applications. The system integration in these products, however, is limited to the flywheel, bearings, motor/generator, and vacuum, and does not include the sophisticated power electronics that would be essential to the other electric power applications in which flywheels might serve.

Because UPS devices can serve either a single critical load or a whole facility, and because the duration of the service can vary widely, the power and energy capacities for the UPS system also vary widely. Power ratings can vary from kilowatts to megawatts, and the energy capacity could be adequate for maximum discharge durations from 10 or 15 minutes up to several hours.

4.4 Customer-Demand Peak Shaving

During times of peak electricity demand, electric power producers often must use expensive diesel generation to supplement the generation capacity of less expensive coal and nuclear power plants that provide enough power during the rest of the day. Power producers recover the cost of providing this expensive power by charging customers more for the electricity that they use during peak-demand times. Equations 4-1, 4-2, and 4-3 illustrate a simplified[5] version of the formulas that utilities use to calculate customers' monthly charges:

Total Monthly Charge = Demand (Power) Charge + Energy Charge [4-1]

Demand Charge = (Peak Demand,[6] kW) × (Peak Rate, \$/kW) + (Off-Peak Demand, kW) × (Off-Peak Rate, \$/kW) [4-2]

Energy Charge = (Peak Energy Use) × (Peak Rate, \$/kWh) + (Off-Peak Energy, kWh) × (Off-Peak Rate, \$/kWh) [4-3]

Typical on-peak demand rates range from between \$8 to \$30/kW. Off-peak demand rates are often zero. On-peak energy rates are in the range of \$.03 to \$.10/kWh. Off-peak energy rates are typically \$.02 to \$.05/kWh. Peak rates often apply between 8 a.m. and 6 p.m. on weekdays. Under these conditions, an industrial customer who continuously uses 10 MW of electricity could pay more than \$300,000 per month, most of which comes from the peak demand charge.[7] Therefore, such a customer could significantly reduce electricity costs by reducing electricity use during peak demand times. If the peak demand charge is \$30/kW, even a one-megawatt decrease in demand would be worth \$36,000 annually.[8] Battery energy storage (BES) systems designed to reduce customers' demand during peak times[9] are emerging on the commercial market, and FES systems show promise as future peak-shaving products. The power requirements for a peak-shaving device are between several-hundred kilowatts and several megawatts. The energy capacity for a peak-shaving device depends on the duration of individual electricity customers' peak demand. If the customer's demand is high for only 15 minutes, the energy capacity of a peak-shaving device would be very modest. In general, peak-shaving tends to have economic benefit when the duration of dispatch for the system is two hours or less. Research into rotor materials and design, bearings, and motor/generators could help flywheel systems achieve the energy capacity and efficiency that they will need to serve the full range of peak-shaving applications.

4.5 Load Leveling

Load leveling refers to the first identified electric power application of energy storage. In this application, electric power providers charge their energy storage systems during low-demand times, using the energy from inexpensive generation sources (such as

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5 This equation neglects charges for poor power factor, knee rates, seasonal rates, billing ratchets, curtailable service credits, and other complex variants that can appear in billing formulae.

6 The highest demand by the customer in any 15-minute interval during the utility s peak-demand period (typically 9 a.m. to 6 p.m.).

7 $[(10\times30)+(10\times0)]+[(100\times0.10)+(140\times0.05)]\times10^3= [(300+0)+(10+7)]\times10^3=317\times10^3$ dollars

8 $(1\times30)\times10^3$ dollars × 12 months

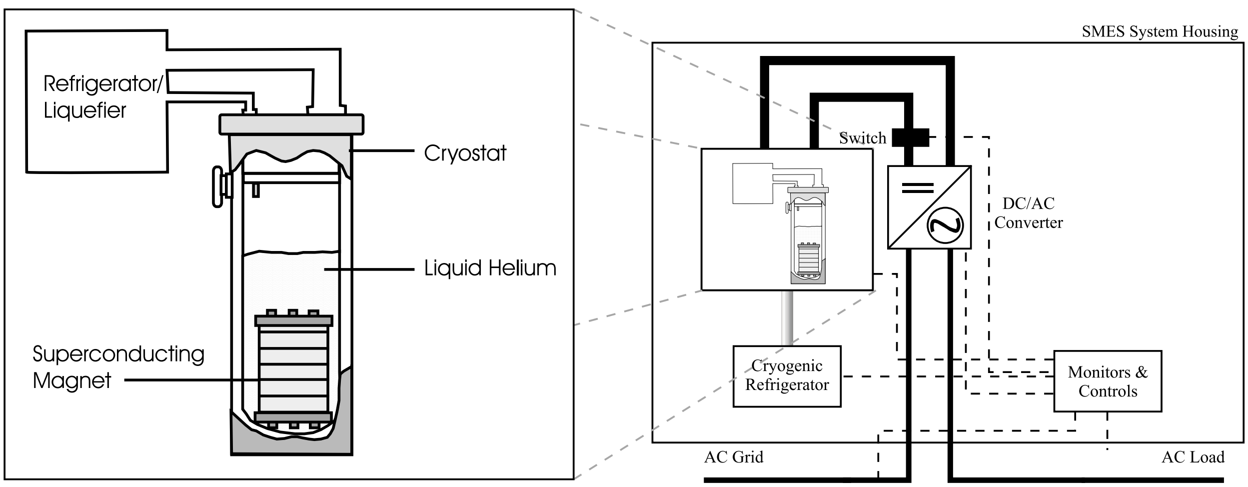
9 GNB Technologies (GNB) and General Electric (GE) have teamed to develop and install battery-based energy storage systems to shave electricity customers' peak demand.

base-load fossil and nuclear plants) that would otherwise be underutilized. The power providers then dispatch the stored energy during peak times that would otherwise require the use of expensive generation (like diesel). This application achieves economic benefits through the avoided marginal costs of the generation sources. CAES is the only technology examined in this study that is at present capable of storing and delivering the many hours of hundreds of megawatts that are necessary to serve this application.

5. Technology Status

5.1 SMES Status

SMES systems for power quality applications are available from two vendors in the United States: American Superconductor Corporation (ASC) and Intermagnetics General Corporation (IGC). Both systems, as shown in Figure 5-1(a), consist of LTS coils that operate in liquid helium at a temperature of 4 K (–269°C). The devices use HTS leads as an interface to copper conductors that are used outside of the cryogenic area of the SMES. Because the HTS leads operate at higher temperature than LTS materials, they improve system thermal efficiency and electrical performance at the cryogenic/ambient interface. Figure 5-1(b) illustrates a SMES unit connected in series with the electric grid and an AC load. Table 5-1 summarizes the characteristics of existing SMES systems. Section 10.1.1 presents more detailed information regarding SMES.



a) Cutaway of Cryostat & Coil **b) SMES System**

Figure 5-1. Blowup of SMES Cryostat and Coil and SMES System in Series Grid-Connected Configuration.

Table 5-1. Characteristics of Existing SMES Systems

Coil shape	Solenoidal
Coil material	Low-temperature superconductor
Lead material	High-temperature superconductor
Cryogen	Liquid helium
Power electronics	Insulated-gate bipolar transistors (IGBT)-based
Response time	Milliseconds
Discharge duration	1–2 seconds
Power capacity	Megawatts
Applications	Power quality (transportable or fixed)

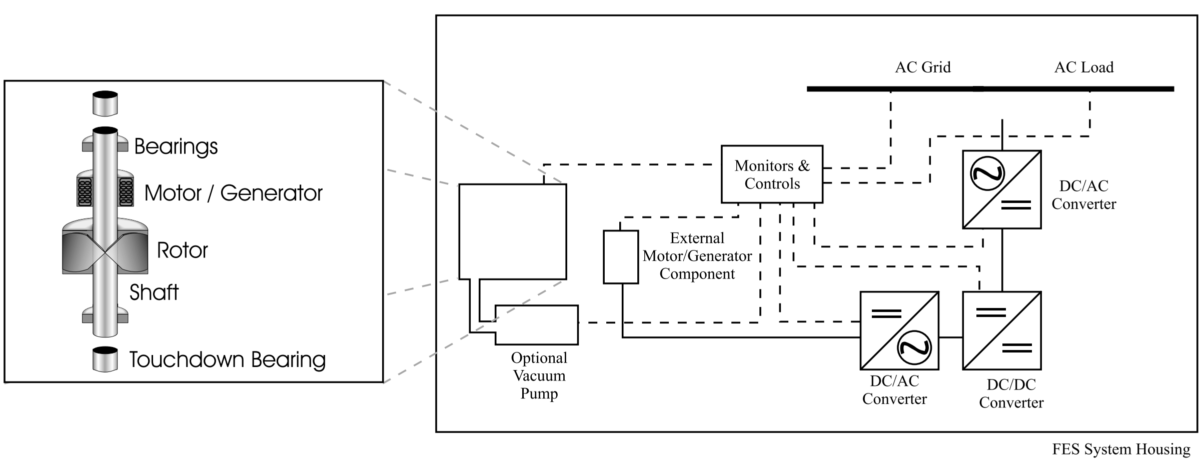
5.2 FES Status

At present, no fully integrated FES systems (as defined by the ESS Program) are commercially available. However, a number of developers have advanced components and are initiating the integration of several of the necessary components for FES systems. Some developers have full integration as a goal while others are targeting the integration of select components as their market niche. Information about FES system developers who directly participated in this study appears in Sections 6 and 10.3. Information about these companies (names, addresses, etc.) and companies that did not directly participate appears in Section 10.5.

Two types of flywheel systems are under development: an FES system with steel rotors and an FES system with composite rotors. The energy capacity of flywheels with steel rotors is limited primarily by the mass of the rotor and associated frictional losses that inhibit long-term (more than a few minutes) energy storage. However, developers such as Active Power view the steel-rotor device as a technology to support or replace batteries in UPSs.

The second type of flywheel, based on composite rotors, is designed to overcome the mass-related energy limit. Composite rotor developers include Beacon Power, Boeing Corporation, Intermagnetics General Corporation, Lawrence Livermore National Laboratory (LLNL), Pennsylvania State University, Trinity Corporation, University of Texas, Urenco, and U.S. Flywheel Systems (USFS). The composite rotors that dominate the field consist of fine glass and carbon fibers that are impregnated with epoxy and wound into a disk or cylinder. The composite rotor, which is lighter than steel, can spin faster and longer because it has less frictional loss. The high rotational speed creates stress in the rotor that can make it pull apart. To prevent such failure, rotor developers use stronger (and more expensive) carbon fibers in a ring on the outside edge of the rotor to reinforce weaker (less expensive) glass fibers that make up the inside of the rotor. Developers believe that long-duration-discharge FES devices are technically achievable, but they cite the cost of the carbon fibers as being prohibitive for systems with discharge times in excess of three to five minutes. Because composite materials have more variable properties than steel, composite rotor developers also cite a need for extensive failure data and codes and standards for manufacture and operation before composite-rotor FES systems can achieve widespread adoption. Figure 5-2(a) is a basic diagram of a FES unit's components regardless of rotor material. Figure 5-2(b) shows an FES unit connected in parallel with the electric grid to an AC load.

Bearings in FES systems also affect their performance and cost effectiveness. The friction associated with mechanical bearings not only limits the discharge duration of a FES, but it also causes wear in the bearing. This wear results in periodic replacement, which increases system operation and maintenance costs significantly. To reduce wear, some developers use electromagnetic levitation to "off-load" mechanical bearings. Others use "magnetic bearings" in which magnetic repulsive forces levitate the rotor so that no mechanical contact occurs between the rotor shaft and its surroundings. Magnetic bearings include permanent magnets, electromagnets, and superconducting magnets.



a) Flywheel Rotor Assembly **b) FES System**

Figure 5-2. Blowup of a Rotor Assembly and FES System in Parallel Grid-Connected Configuration.

Developers cite bearing development as a key to the kind of service life and life-cycle costs necessary for adoption of FES systems in electric power applications.

While some diversity exists in FES characteristics, sufficient similarity in the devices exists to summarize FES systems in Table 5-2. Section 10.1.2 presents more detailed information on the FES systems.

5.3 CAES Status

CAES is a large-scale, technically mature storage technology for high-power, long-term, load-leveling applications. Further research on CAES may result in incremental improvements to efficiency from better turbines and heat transfer equipment used to pump and retrieve compressed air. At present, application of CAES is limited by the need for a large subterranean cavern to store air. The salt-dome caverns that are most economical for CAES are not available everywhere in the United States, and, while advances in cavern-preparation techniques may improve the economics for hard-rock and aquifer formations that exist in many places in the United States, all CAES installations require a large capital investment similar to that of a pumped hydro unit or a central coal-fired generating station. This economic hurdle is significant in the newly competitive electric power industry. Figure 5-3 is a schematic of a CAES system.

Although rumors that industry was interested in a micro-CAES plant surfaced several times while this study was underway, no verifiable evidence of the development of smaller-scale CAES was obtained, even with considerable investigation. However, several large-scale CAES developers are watching the electricity industry with interest to see if opportunities emerge for that technology under deregulation and industry competition.

Table 5-2. Characteristics of FES Systems

Characteristic	Steel Rotor	Composite Rotor
Rotor material	Stainless steel	Epoxy, glass fiber, carbon fiber
Rotor speed	1,000s of RPM	100,000s of RPM
Bearing type	Unloaded mechanical and magnetic	Unloaded mechanical and magnetic
Power electronics	---	IGBT-based
Response time	Millisecond	Milliseconds
Present discharge duration	Minutes	Minutes (depends on power)
Future discharge duration	Minutes	Hours (if fiber cost reduction is possible)
Power capacity	100s of kWs	100s of kWs
Present applications	UPS support, power quality	UPS support, power quality
Future applications	UPS support, power quality	UPS support, power quality, renewable support, telecom

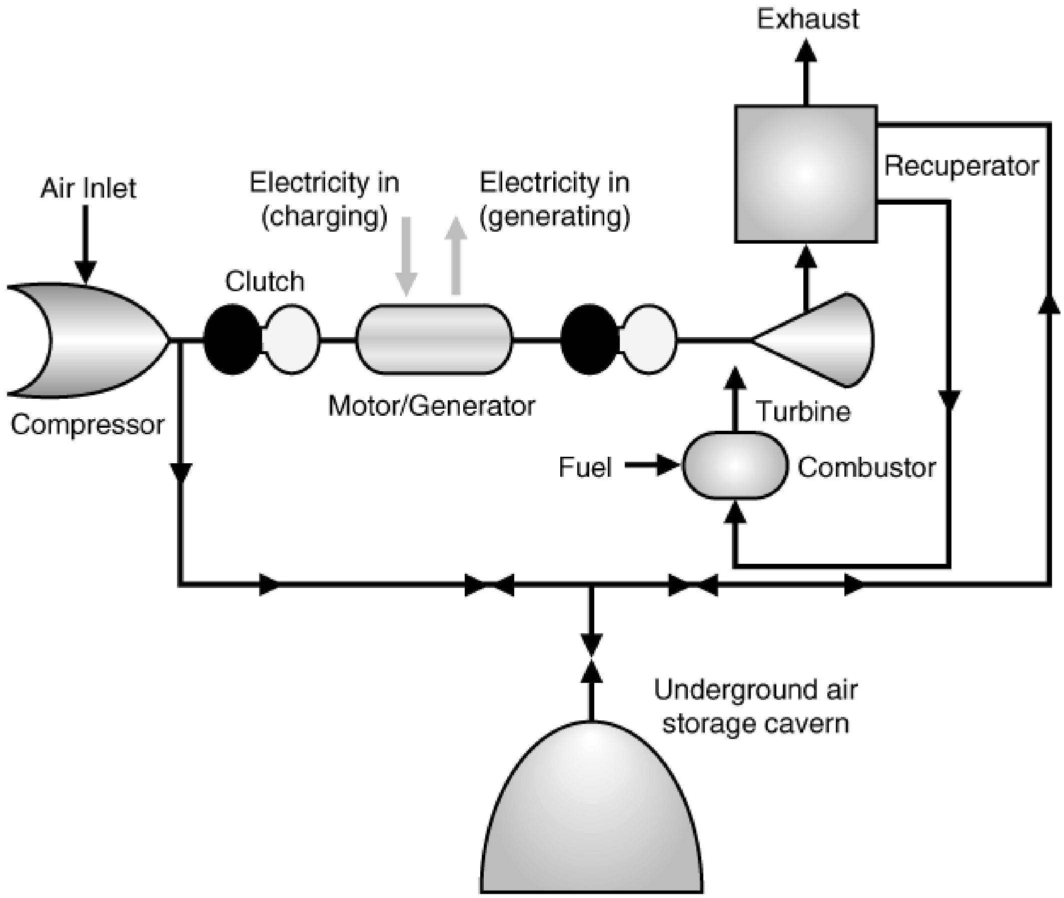


Figure 5-3. Schematic of a CAES Plant.

6. Manufacturer Interview Summaries

This analysis required extensive information from system developers. Interviews with these developers are summarized below. More detailed discussions with each developer appear in Section 10.3.

6.1 Active Power, Inc.

Active Power, Inc. manufactures a steel flywheel, which spins at about 7000 rpm. Active Power has pursued a steel flywheel as opposed to a composite fiber flywheel for several reasons: low cost, safety, and high power density. Their baseline product, the CleanSource flywheel (shown in Figure 6-1) provides 400 kW of DC power for five seconds, but varied combinations of power and discharge duration are possible with the same rotor. Also, two or more rotors can be combined to serve loads up to 800 kW or more. The Active Power design has several innovations:

- a single piece of forged steel serves as the flywheel, charging motor, and generator,
- a magnetic coil design reduces eddy current losses, and
- an electromagnetic upward force on the steel rotor reduces the load on the bearings.

Active Power has chosen not to integrate a power conversion system into its flywheel, instead making its technology more readily incorporated into existing UPS products. Active Power plans to market its products in power quality and battery extension applications.

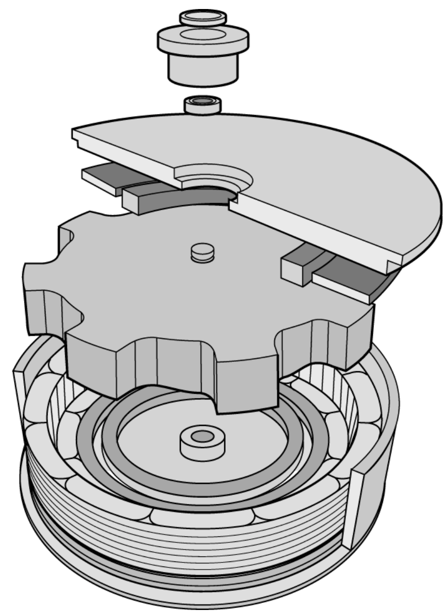


Figure 6-1. Diagram of Active Power, Inc.'s, Flywheel System.

6.2 American Superconductor Corporation (formerly Superconductivity Inc.)

Superconductivity Inc., now part of American Superconductor Corporation (ASC), installed the first SMES unit in 1993, and now has nine installations worldwide. ASC configured their turnkey system in a transportable semitrailer. ASC is currently developing and marketing SMES devices for utility power quality applications. Their standard product can deliver 1 MW for 1 second within 5 ms of a disruption in the primary energy source. The magnet is made of an LTS coil requiring a liquid helium-based cryogenic system. ASC manufactures the magnet from niobium tin wire with a copper buffer.

In late 1997, ASC introduced a new SMES product with high-temperature superconducting current leads and two "high temperature" shields that reduce the cooling loss at 4 k to 1 W. The new SMES system can sustain normal operation for about 200 hours after an unplanned shutdown of the refrigeration system. This is a significant improvement over the older system and lowers maintenance costs of deployed units.

6.3 Beacon Power

Beacon Power, a newly formed subsidiary of SatCon, has developed a composite rotor flywheel that can deliver 1 kW of DC electricity for two hours. Beacon's general approach in designing their flywheel was to trade energy density against flywheel cost. Their flywheel rotor weighs 150 pounds and is made of a carbon fiber outer rim with a glass fiber interior.

A proprietary steel hub connects the flywheel to the shaft, expanding and contracting with the flywheel. The rotor is oriented vertically and is suspended by a large magnet using attractive force. The system contains a touchdown bearing in the event that the primary magnet fails. The flywheel rotates within a vacuum chamber, and an ion pump maintains the vacuum while the unit is in operation.

Beacon is focused on safety. The nominal rotor speed is 30,000 rpm, well below the estimated burst speed of 46,000 rpm. Beacon has developed a monitoring system that can track the rotational orbit of the flywheel and detect cracks in the rotor before a failure occurs. In addition to monitoring, Beacon plans to bury most of its early installations. After a significant time of operation without incident, Beacon plans to begin offering above-ground units to its customers.

6.4 Boeing Corporation

Boeing develops and manufactures commercial aircraft, military aircraft and missiles, space transportation systems, space systems, and information and communication systems. Phantom Works, the R&D arm of Boeing, develops new products for new markets and components that can improve existing integrated products. Building on existing capabilities in rotating equipment, carbon composite materials, and high-temperature superconducting materials, Boeing is developing FES systems based on a design shown in Figure 6-2. Their flywheel design and development efforts are focused on taking advantage of projected high-volume manufacturing cost reductions for integrated systems.

Boeing is primarily interested in two target markets for flywheel products: terrestrial power supplies and space systems. Power supply applications include power quality, UPS, and load leveling. Backup power systems for the telecommunications industry are a significant application need. As a part of their primary business area, Boeing is familiar with power quality issues and lead-acid battery UPS systems. Conversations that Boeing representatives have had with industry indicate that the market entry price for flywheel systems providing several minutes to an hour of power range from $500 to $1,500/kW. Boeing's approach is to build a standard rotor/bearing platform and match the motor/generator size to the discharge duration requirements of the various applications.

Boeing plans to employ relatively thin-walled rotors, with an inner-to-outer radius ratio of 0.7 that holds 75% of the energy stored in a solid disk and uses much less material. Boeing is also developing a rotor winding machine. The Boeing machine uses fiber "tape" made of carbon fiber and thermoplastic resin. Boeing's passive bearing system uses a combination of ball bearings, conventional magnets, and HTS magnets. The rotor is fully levitated during its spinning operation, and Boeing expects system losses of 0.1% of the total energy stored per hour. Conventional magnets provide 95% of the vertical lift. The HTS magnets provide some incremental lift, but give mostly lateral support because of flux pinning.

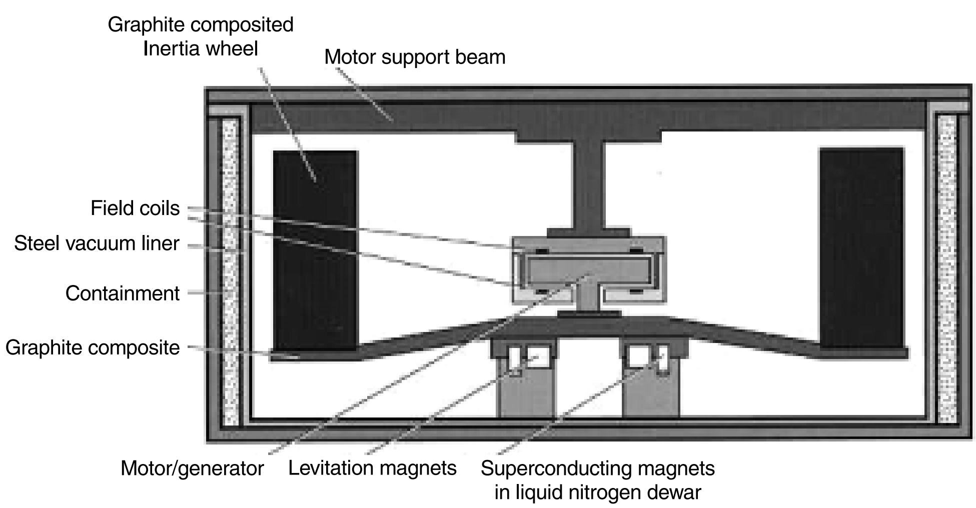


Figure 6-2. Diagram of Boeing's Flywheel System.

6.5 Intermagnetics General Corporation

Intermagnetics General Corporation (IGC) developed its expertise in superconductivity through involvement with magnetic resonance imaging (MRI) for health care applications. The company now manufactures fully-integrated SMES systems that address sags, spikes, and electrical interruptions. One of their products is installed at Tyndall Air Force Base in Panama City, Florida. The system consists of a 6-MJ superconducting coil, a closed-loop cryocooler, and commercial, off-the-shelf power conditioning and remote monitoring units. Final acceptance testing of the system was completed in February 1998. Housed in a mobile/relocatable shelter, as shown in Figure 6-3, the system is designed to minimize on-site engineering. The system is intended for unmanned operation, similar to commercially available UPS systems.

IGC's magnet has many design features that have been developed as a result of IGC's experience with MRIs. Advanced features of the magnet include HTS current leads and a cryocooler, zero helium boil-off refrigeration system. They have also integrated a magnet control unit (MCU) into the SMES system. The MCU is a microprocessor-based device that performs monitoring and control functions. The power conditioning system consists of a commercially available uninterruptible power module (UPM) and a magnet interface unit (MIU). The MIU extracts energy from the magnet at a set voltage and delivers the energy, under control of a voltage feedback loop, to the 500 Vdc bus of the UPM. The MIU controls the magnet charge rate through an AC/adjustable DC voltage power supply. According to IGC, challenges to installing and operating an SMES system include power integration issues, control optimization, and the integration of ancillary functions.

6.6 Lawrence Livermore National Laboratory

The work on flywheels at LLNL originated with research for transportation applications in which concepts for high-efficiency motor/generators and passive magnetic bearings were investigated. However, because of the lack of small, light containment, LLNL begin to explore electric power applications in which containment is less crucial. The LLNL Halbach motor/generator technology was licensed to Trinity Flywheel for commercialization. LLNL has also developed a passive magnetic bearing concept in which magnets levitate the rotor and act as a passive bearing that does not require active control. This concept provides a room-temperature, low-loss bearing system for composite rotors in higher energy density flywheels.

LLNL has investigated Toray carbon composite materials for rotors. It has conceptualized a flywheel system with the composite rotor, passive magnetic bearings, and a Halbach array motor/generator and has done some preliminary design work. LLNL

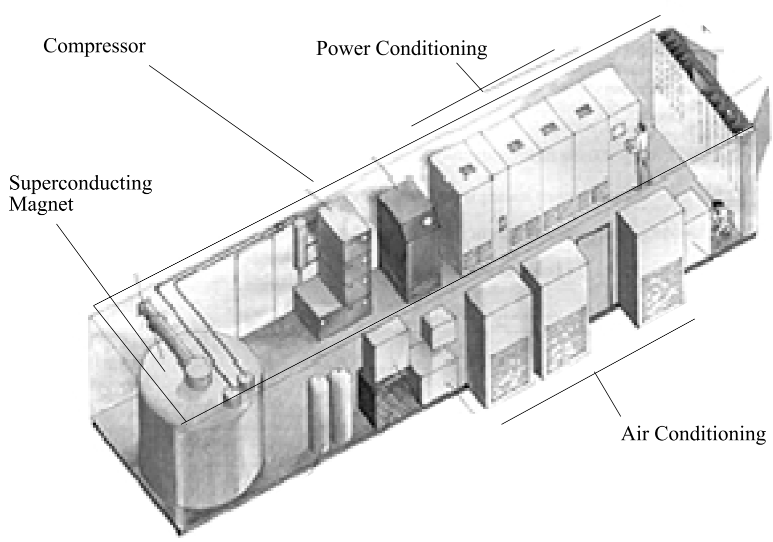


Figure 6-3. Diagram of IGC's SMES System.

envisions applications for such a system in transportation, distributed stationary energy storage, UPS, and pulsed-power systems.

6.7 Penn State University, Applied Research Laboratory

Penn State's flywheel program consists of several activities: designing and manufacturing composite rotors; material characterization with regard to creep, fatigue, and quasi-static behavior; health monitoring for multi-ring rotors; and developing a novel approach to relieving radial stress with elastomeric interlayers and/or matrices.

Penn State researchers believe that the best material for a flywheel would be the strongest and lightest that could be found. There is a potential cost/performance benefit in using "cheaper carbon" fibers in rotors. The flywheel research professor at the Applied Research Laboratory who worked on projects that increased the use of carbon fiber may reduce Applied Research Laboratory's price to about $10/lb between the years 2000 and 2005, but he believes that lower prices would require a huge increase in volume of carbon fiber sales.

Most of Penn State's work with industry involves circumferential filament winding as shown in Figure 6-4. Because the waste in filament winding is very low, it can support a very high manufacturing yield, especially if the speed of filament winding is increased to achieve production scale. Penn State has focused most of its R&D on the rotors. University researchers perceive that the greatest need for work is

Figure 6-4. Penn State 3-Axis Filament Winding Machine.

in the areas of development of improved manufacturing processes, development of codes and standards for manufacturing processes, determination of rotor performance and life via spin and burst testing, and development of codes and standards for rotor performance and life.

6.8 Trinity Flywheel Corporation

Trinity Flywheel Corporation produces products with two flywheel rotor sizes that have the following common attributes: the rotors are made from glass and carbon fibers and epoxy; the hub and rotor have a mechanical interface; the rotor shaft spins on ceramic ball bearings (future products may include passive magnetic bearings); and the rotors have a "drum-like" architecture with permanent magnets mounted on the inner diameter.

Trinity products can provide 300 to 800 Vdc or three-phase service by using an adjustable speed drive. Mobile and custom configurations are also possible. At present, one DC product delivers 50 kW for 20 seconds at 300 Vdc (nominal range between 240 and 400 Vdc). A second product delivers 700 kW for 5 seconds at 800 Vdc. Trinity has held discussions with other developers including U.S. Flywheel, SatCon, Beacon, the University of Texas' Center for Electromechanics (CEM), and Penn State's Applied Research Laboratory, and is developing a relationship with the National Aeronautics and Space Administration (NASA) Lewis. Trinity is also working closely with LLNL on passive magnetic levitation products to reduce operating and management requirements.

Trinity views the barriers to FES products as being equally divided among technical obstacles, market development, and capitalization issues. Trinity believes that private companies are facing some high-risk R&D on bearings and development of a coordinated life program and criteria for safe operating standards.

6.9 University of Texas Center for Electromechanics

The University of Texas' CEM flywheel program grew out of a Department of Defense (DoD) contract to develop rotating power supplies for high-power pulses. Today, CEM is focusing on the design for a 600-MJ, 3-MW prototype composite flywheel for a locomotive. The first integrated flywheel system is expected in the year 2000. CEM's rotor is two feet in diameter and two feet high and is made of composite material separated by thin layers of glass. The rotor, illustrated in Figure 6-5, spins at 45,000 rpm with a rim speed of over 950 meters per second. The flywheel system can discharge at a rate of 3 MW for 2.5 minutes.

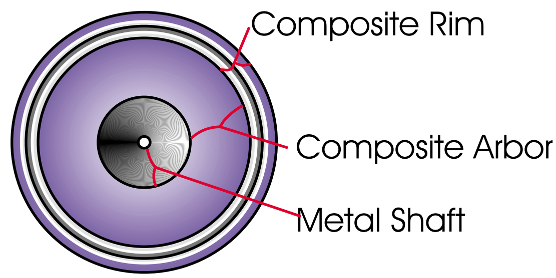


Figure 6-5. Illustration of CEM's Rotor Design.

To get the most energy per unit of composite material, the inner diameter of the composite rim is relatively large. The arbor that connects the rotor to its shaft has a proprietary structure that can expand and contract with the rotor as it spins.

CEM has designed its rotors to enhance safety. The inner windings do not rely wholly on the outer windings for strength. If an outer winding fails, the circumferential force on the winding below it will increase, but not above its design strength. In this way, individual winding failures will not cause a catastrophic rotor burst.

6.10 Urenco (Capenhurst)

Urenco has been known as a uranium enrichment company in Great Britain for more than 25 years and has built centrifuges that can operate for 10 years without interruption. Power disruptions have become the primary cause of lost production. In response, Urenco began exploring options for protecting the facility from power disruptions, and used their expertise in centrifuge manufacture to design a FES system.

This project began four years ago, and is now close to launching a commercial flywheel product for power quality applications. Urenco's PIROUETTE, as shown in Figure 6-6, is designed to provide 120 kW of power for 28 seconds. The rotor is made of carbon and glass fibers, its outer diameter is 300 mm while the inner diameter is 170 mm, and its unique design includes a tall, thin rotor profile. Another unique design advancement includes a layer of magnetic powder-loaded composite material, essentially glass fibers embedded with powdered permanent magnetic material. Two sectors on the rotor are magnetized, one to serve as the stators of the permanent magnet motor/generator and the other to serve as the magnet portion of the magnetic levitation assembly.

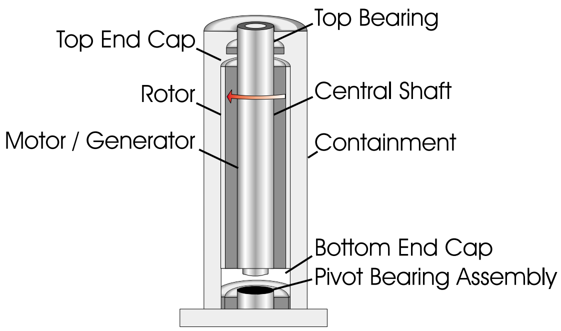


Figure 6-6. Schematic of a Urenco PIROUETTE Flywheel.

Urenco indicated that their rotor will fail by bending along its long axis before it breaks, skid along the inner containment wall, and safely dissipate its kinetic energy. The shaft is designed to absorb energy during a failure as well. Urenco has not had a rotor escape the containment vessel during any of the various failure tests.

6.11 U.S. Flywheel Systems

USFS has developed a flywheel system with a composite-fiber rotor, conventional bearings (although magnetic bearings are under development), a control subsystem with more than 100 sensors, and a unique approach to containment. USFS also designed and built its own winding machine that achieves unprecedented control over the composite rotor fabrication process. Rotors made on the machine have nearly as much fiber content as is theoretically possible, and require little balancing because their centers of gravity are nearly perfect.

USFS's design team is developing control mechanisms for levitated magnetic bearings. USFS hopes to be able to demonstrate safe operation in the supercritical regime with their advanced bearings. USFS prototype flywheel systems contain more than 100 sensors, providing both control and safety monitoring. The development of fiber-optic connectors will greatly reduce the bulk of wires in the system.

USFS is currently focusing on R&D and is not trying to commercialize a product. They are interested in becoming partners with a manufacturer but have found no matches yet. An important first step in commercializing flywheels is to identify a standard system size that balances economy of scale against footprint limitations of specific applications.

6.12 Relevant ESS Program Experience

Although the scope of this study was limited to three technologies, SMES, FES, and CAES systems, the ESS Program has significant experience in R&D of BES systems and has working relationships with their manufacturers. Both the experience and the relationships have provided the program with a wealth of information about commercial energy storage systems. This information is relevant to developers and potential customers of SMES, FES, and CAES systems. Of particular interest are the commercial BES products that serve applications defined in Section 4.0 that SMES, FES, and CAES can serve.

A number of commercial BES products have evolved from R&D projects with the ESS Program and with other organizations such as the Electric Power Research Institute (EPRI) and state energy offices. Omnion Power Engineering is a company that has worked closely with the ESS Program, and offers three BES products that have their roots in R&D collaborations. The first is the PM250, a 250-kW/167-kWh BES system that can deliver 250 kW from a load peak for approximately 40 minutes. The second, the PQ2000, is a 2-MW/10-second BES system that can deliver 2 MW to improve power quality by preventing momentary fluctuations and interruptions in voltage from affecting sensitive manufacturing and information equipment. The third product, a transportable version of the PQ2000, similarly improves power quality. These products contain deep-cycle, low-maintenance, flooded lead-acid batteries and Omnion IGBT power electronics.[1]

GNB and GE are also companies that have worked closely with the ESS Program in R&D collaborations.

[1] For a complete discussion of power electronics, refer to Section 10.1.4.

The GNB/GE team has developed and installed two BES systems that each serve multiple applications. A 5-MW BES system at a lead smelter in Vernon, California, provides backup power for the facility's emissions control system, allows peak shaving to reduce monthly demand charges, and improves power quality for the facility and the entire bus that serves it. A 1-MW BES system in Metlakatla, Alaska, provides rapid spinning reserve,[2] frequency regulation control,[3] power quality, and support for Metlakatla's renewable hybrid generation (4.9-MW of hydro power and 3.3-MW of diesel). Both of these systems contain GNB valve-regulated lead-acid batteries and GE's gate turn-off (GTO) power electronics.

Another BES system that is now in commercial operation and that came from an R&D project is the 500-kW/500-kWh BES, which is in operation at Energy United in Statesville, North Carolina. The system, originally developed as a battery test facility, has been in operation at the electric cooperative since 1986 and shaves peak load and reduces Energy United's monthly demand charges. The system contains GNB flooded lead-acid batteries and Firing Circuits silicon-controlled rectifier (SCR) thyristor power electronics.

A 20-MW/14-MWh BES in commercial operation at a substation in Sabana Llana, Puerto Rico, provides rapid spinning reserve and frequency control that the Puerto Rico Electric Power Authority would have otherwise obtained with diesel generation. The system contains C&D Technologies' deep-cycle, flooded-lead-acid batteries and GE GTO power electronics.

[2] Rapid spinning reserve is an application in which energy storage displaces generation capacity (typically provided by backed-off thermal fossil power plants or diesel generators) that a utility holds in reserve to prevent interruption of service to customers in the event of a failure of an operating generating station.

[3] Frequency regulation is an application in which storage alternately dispatches and absorbs power to isolated utilities to ensure that the frequency of the electricity in the system remains within a few percent of nominal (60 Hz in the United States) regardless of fluctuations in load or outages at generating stations.

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7. Project Results

The project met all of its objectives. It produced a comprehensive data source on cost, performance, markets, and availability for SMES, FES, and CAES systems. The project also produced spreadsheet analytic models for SMES and FES systems that the ESS Program sought as a tool to identify high-impact R&D. The models are structured in a way that allows analysts to input new economic and technical information as it becomes available and continuously update the analytic results. The model uses cost and technical attributes of system components to calculate an IRR as a measure of performance for the systems. Sensitivity analysis of the IRR to specific model inputs identifies areas in which R&D has significant potential to accelerate developing technically and economically viable SMES and FES systems. Results of the sensitivity studies support recommendations for ESS Program R&D. The following sections identify the specific results of the project on the comprehensive data source, spreadsheet models, exercise of the FES and SMES system models, and sensitivity analyses.

7.1 Comprehensive Data Source for SMES, FES, and CAES Components and Systems

Literature searches in the library, on the internet, and interviews with industry and academia produced a bibliography of technical papers, textbooks, and product literature on SMES, FES, and CAES components and systems that appear in Section 10.4 of this report. A library at Energetics' headquarters in Columbia, Maryland, houses documents the analysts had access to.

The interviews (Section 10.3) and literature searches (Section 10.4) also contributed to primers that appear in Section 10.1. The primers address the physics of storage media; components of the system; and cost, performance, and availability of specific components of SMES, FES, and CAES systems. The primers also present summary overviews on supporting technologies and engineering concepts including cryogenics (for the superconductors in SMES coils and FES bearings and motor/generators), power conditioning systems, HTS and LTS, and strength of materials/ engineering mechanics.

Summaries of interviews with industry and academia are included in Section 6, and full reports of the meetings appear in Section 10.3. The summaries reflect researchers' and manufacturers' perspectives on SMES, FES, and CAES systems, and on research needs for these systems. The organizations shown in Table 7-1 have reviewed the summaries.

The project team constructed and maintained an electronic database of contacts made during the project and of other energy storage stakeholders. The database can be searched for corporate interest areas, company names, addresses, names of individuals, telephone/fax numbers, e-mail addresses, and notes of interest. Contacts gleaned from the database are listed in Section 10.5. Electronic copies of the database are at Energetics' headquarters in Columbia, Maryland, and at SNL in Albuquerque, New Mexico.

7.2 Spreadsheet Models of SMES and FES Systems

The project team produced spreadsheet analytic models of specific SMES and FES systems. The SMES system model allows the user to define the power and energy of the device, the type of superconducting material in the SMES coil, and a number of other inputs defined in more detail in Section 7.2.1.1. From these inputs, the model selects the appropriate cryogen and calculates the size of the cryostat and the size of the area around the coil from which personnel must be excluded. Users can also select the type of current leads to the coil and the cryogenic and electrical losses associated with system operation. Users can also define characteristics of equipment for connection to the electric utility grid. With a complete set of user inputs, the model calculates an IRR for a specific SMES system that is suited to and used in a specific electric power application. To enable sensitivity studies of the IRR, the model accepts user-selected modifications to the unit cost of materials and components, terms and interest

Table 7-1. Participating Organizations

Company/Institution	Location	Date Visited	Technology
University of Texas, Center for Electromechanics	Austin, Texas	1/6/98	FES
Active Power	Austin, Texas	1/7/98	FES
American Superconductor	Middleton, Wisconsin	1/8/98	SMES
Penn State, Applied Research Laboratory	State College, Pennsylvania	2/18/98	FES
Beacon Power	Woburn, Massachusetts	2/19/98	FES
U.S. Flywheel Systems	Los Angeles, California	4/1/98	FES
Boeing Corporation	Seattle, Washington	9/2/98	FES
Lawrence Livermore National Laboratory	Livermore, California	9/3/98	FES, SMES
Trinity Flywheel Corporation	San Francisco, California	9/3/98	FES

rates for financing options, and the dollar value of several applications.

Analysis determined the following applications to be most appropriate for SMES systems.

- Current use
  - Power quality
- Future use
  - Power quality

The FES system model allows the user to define the power and energy of the device by the speed, size, configuration, material (steel- or fiber-reinforced epoxy options), and manufacturing process for the rotor. From these inputs and others defined in more detail in Section 7.2.1.2, the model determines the most appropriate containment system, vacuum system, and the need for cryogenics. Users can also select the type of bearing and motor/generator. As in the SMES system model, user selections define the parameters by which the model calculates an IRR for a specific FES system. To enable the sensitivity studies discussed in Section 7.3.3, the model permits the user to modify the unit cost of materials and components, terms and interest rates for financing options, and the dollar value for the system selected. Analysis determined the following applications to be most appropriate for FES systems.

- Current use
  - Power quality
- Future use
  - Power quality
  - Telecommunications
  - Storage for renewable generation and hybrids

Figure 7-1 is a flow chart that schematically illustrates the input and output of both models. The model identifies areas where technical and economic information is sparse and areas where the state of the technology must advance before systems for electric power applications will gain widespread acceptance and adoption. Therefore, the models identify R&D that could help advance the technologies.

7.2.1 Model Structure

Both the SMES and FES system models accept user input regarding the technical and financial attributes of the technologies. The models also have "hard-wired" calculations that are both unique to the technologies they address and alike in their treatment of economics. The following sections detail the structure of the models and the assumptions that were made in their design.

7.2.1.1 SMES System Model

The model characterizes the following components that are contained in a fully integrated SMES system: magnetic coil, current leads, isolation switch, the inner and outer containment vessels (including insulation), the cryogenic refrigeration system, the power electronics (snubber, capacitor, inverter), resistive dump load, enclosure and perimeter fencing. The algorithms that characterize each component receive information from system performance specifications,

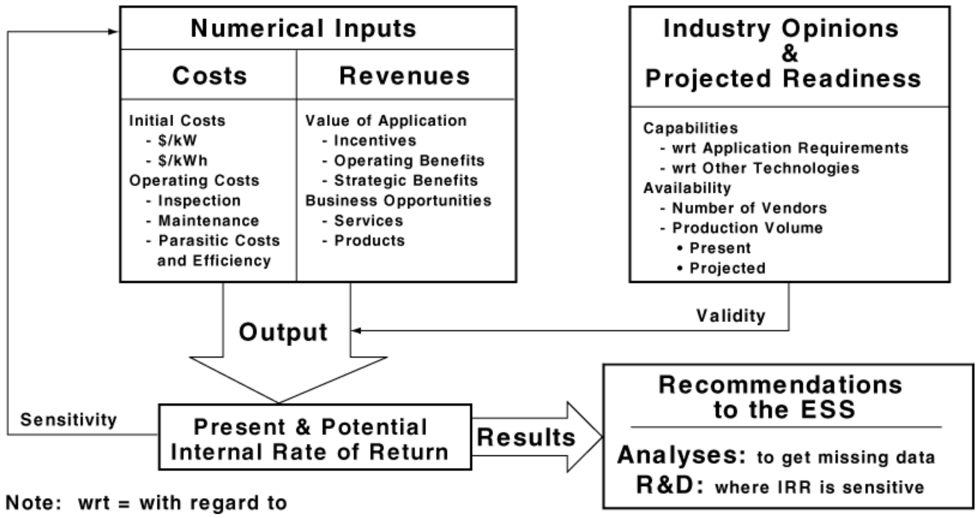

Figure 7-1. Flow Chart of SMES and FES System Models.

component cost and performance data (both from user inputs and data contained in the model), and results from other component modeling algorithms. A system capital cost estimate is made by summing the cost estimates for all the components. The model also estimates the annual electricity consumed by the SMES system based on the component efficiencies and the user-specified duty cycle. The capital cost and energy efficiency estimates feed into an economic comparison between a SMES system and a lead-acid battery system designed for the same application.

As shown in Figure 7-2, the user enters the dimensions of the magnetic coil, wire characteristics, operating current, discharge power, and duration. The model estimates the energy contained in the magnetic field and evaluates the voltage and dI/dt during a constant power discharge cycle.

The model estimates the cryogenic load based on conductive losses through the leads, the containment system, and cooling required to offset AC losses within the magnetic coil. Conductive losses are reduced by two thermal shields (base case: 30 K and 70 K). Losses of 4 K are modeled as a cold head recondenser, which is consistent with the most recent product designs.

The cost of the isolation switch is correlated to the current. The switch requires a water chiller. The user defines the resistive losses across the switch, which are the bases for the chiller sizing.

The user can specify three different power electronics configurations: DC, shunt AC, and injection transformer. The costs of the power electronics components are correlated to the discharge power. The injection transformer is less expensive than the shunt AC, but it has a constant parasitic load associated with it.

The containment vessel cost is correlated to the volume of the magnetic coil. The perimeter fencing cost is correlated to the dimensions of the magnetic field (that is, the 5-gauss line).

7.2.1.2 Flywheel Model

The flywheel model characterizes the following major components contained in a fully integrated energy storage system: rotor, bearing system, motor/generator, containment vessel, vacuum system, power rectifier, power inverter, electronics, sensors, enclosure, and controller. The algorithms that characterize each component receive information from system performance specifications, component cost and performance data (both from user inputs and data contained in the model), and results from other system component modeling algorithms. A system capital cost estimate is made by summing the cost estimates for all the components. The model also estimates the annual electricity consumed by the flywheel system based on the component efficiencies and the user-specified duty cycle. The capital cost and energy efficiency estimates feed into an economic comparison between an FES system and a lead-acid battery system designed for the same application.

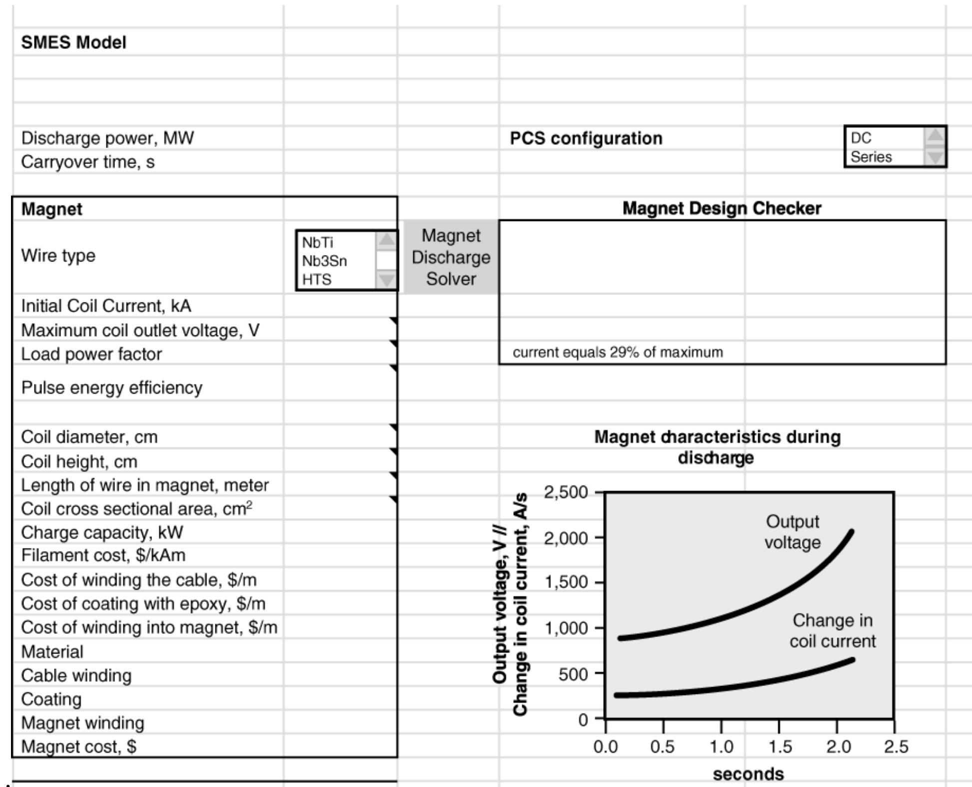

Figure 7-2. Input Screen from SMES Model.

Figure 7-3 shows an input screen from the flywheel model. The user defines the rotor materials of construction, dimensions, and operating speed. The model estimates the maximum radial and circumferential stresses within the rotor and compares them to the maximum allowable based on the strength of the fiber and epoxy materials selected. The model alerts the user if the operating speed is too high. The model enables the user to specify two layers of different fiber material, consistent with common industrial rotor design containing a thin layer of high-strength material at the outer edge of the rotor and a lesser strength, less expensive material in the middle. The model considers continuous-wound mandrel manufacturing only. Other interesting manufacturing procedures (for example, press-fit annular sections and resin transfer molding) exist, but they are less prevalent than filament winding and were not included in the scope of the modeling. The model estimates the cost of a stainless steel hub based on the rotor height and inner diameter.

The user can specify several different bearing configurations: simple ball bearing, ball bearing with z-directional unloading, levitation using conventional magnets, and levitation with a hybrid HTS and conventional magnetic system. In each case, the cost of the bearing system is positively correlated to the weight of the rotor assembly. For the levitated systems, the model estimates the amount of magnetic material required and multiplies that by the unit cost of material. The useful life of the ball bearing systems is estimated based on their loading. Replacement costs over a 20-year system life are discounted to year zero and included in the capital cost estimate.

The containment system cost is not based on a vessel designed to withstand catastrophic failure of the rotor. It is assumed that the rotor is either steel and conforms to existing codes and standards or is a proven fail-safe composite rotor. The containment vessel cost is correlated to the rotor size. Similarly, the vacuum system cost is correlated to the containment vessel surface area. The user can set the vacuum system cost to zero to represent factory-sealed designs.

The cost of the motor/generator and power electronics is based on the user-specified system discharge capacity. The model contains a library of unit costs for stand-alone permanent magnet generators. Some developers have achieved greater stability and other

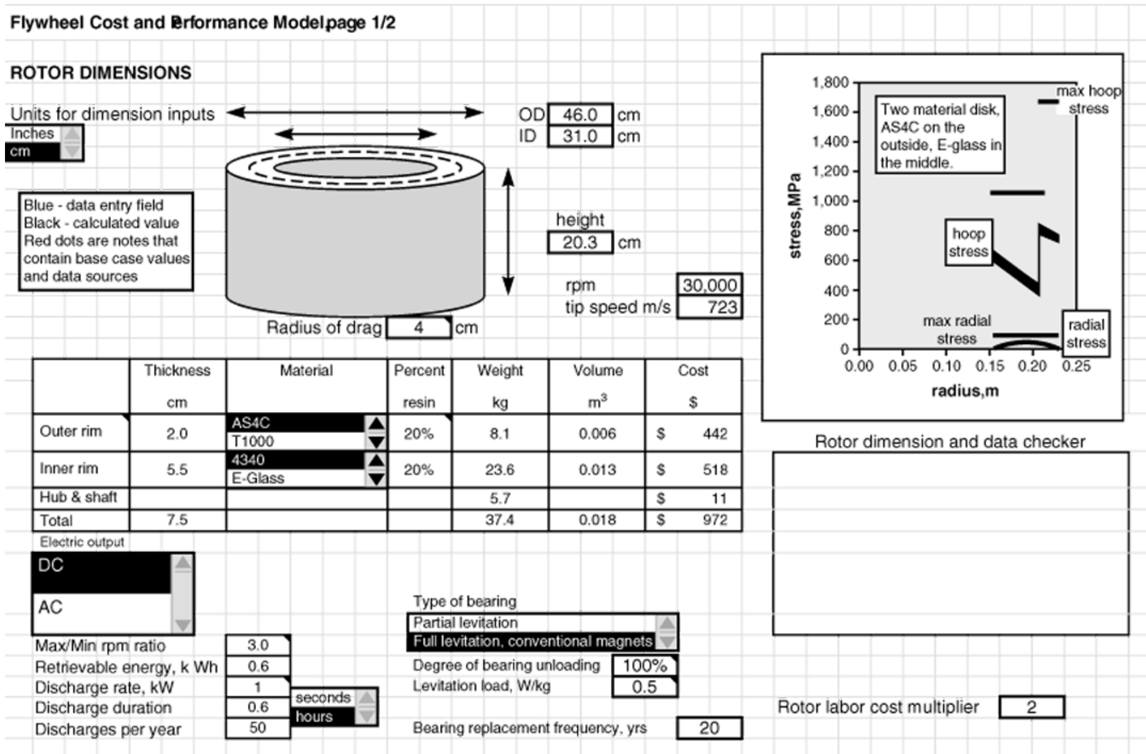

Figure 7-3. Input Screen from FES System Model.

system integration benefits by integrating the generator into the rotor. However, they do realize a higher winding cost because of needed customization, which can be represented by adjusting the unit cost of the motor above the base case value.

The model estimates the standby load. The inputs into this calculation are the frictional losses of the bearing system, the energy required by the levitation system, vacuum pump load, hysteresis associated with the motor/generator, and cryogenic refrigerator load (if needed). For short-duration systems, the motor/generator losses can be significant. The motor/generator losses are highly dependent on a particular component design.

The degree of uncertainty associated with the flywheel system capital cost estimate is on the order of ±50%. A large portion of the manufacturing cost is assembly labor and recovery of investment in facilities and engineering. The cost estimates should be used to show system cost drivers across various market applications and to assess the potential impact of R&D activities. It is not intended to be used to justify an investment in flywheel technology.

7.2.1.3 Economic Model

The FES and SMES system models share the same economic analysis tool. The tool calculates the IRR generated by an investment in a FES or SMES system. The revenue stream is compared to the avoided cost of purchasing and maintaining a mature technology that can provide the same service. At present, the established technologies for the applications identified in Section 4 are diesel and gas generation, fast switches, capacitors, or storage systems that use either flooded lead-acid or valve-regulated lead-acid batteries as the storage medium.

In remote power supplies and short- and long-term peak shaving, diesel and gas generation and BES are the competing technologies. For power quality (and power factor correction), fast switches, capacitors and BES are the competing technologies. For UPSs, BES is the competing technology. BES, a competing technology for each of the applications considered in this study, provided analysts with a common element by which they could assess SMES and FES for all applications considered. With this reference point, analysts considered the capital and maintenance costs for lead-acid BES systems designed for each application as a basis for comparison to SMES and FES systems.

The cost drivers associated with a BES system are the initial capital cost, battery replacement cost, and routine maintenance cost. The model contains a worksheet that allows users to tailor the battery system costs being used as a reference to the following application-specific considerations:

- the duty cycle being considered,
- site-specific maintenance costs,
- capacity de-rating because of ambient conditions, and
- other factors.

The model enables the user to choose two different revenue bases: (1) battery replacement or (2) adding the FES or SMES system to shield the battery from what FES developers refer to as "nuisance discharges" and extend battery life. The first revenue basis involves using SMES or FES in a way that requires users to rely exclusively on technologies they have little or no experience with. But the approach results in higher revenues than the second revenue basis that allows users to "back up" the new technology with batteries (that must still be bought and maintained). For remote power supplies and short- and long-term peak shaving, analysts used revenue basis (1) above. For power quality and UPS, analysts considered revenue bases (1) and (2).

The IRR in both revenue bases is calculated from a pro-forma, after-tax, cash-flow model that is based on the following characteristics:

- a 24% marginal tax rate,
- a 10-year accelerated capital recovery schedule depreciation, and
- a 50% debt-to-equity with a debt-interest expense of 7.5%.

A positive IRR indicates that the SMES or FES system under consideration has a lower life cycle cost than the competing technology. Therefore, the incentive for users to choose the advanced technology for electric power applications increases with increasing positive values for IRR.

7.3 Analysis with Spreadsheet Models

Both models use technical and economic characteristics of existing systems and projected characteristics of future systems to quantify the technical and economic viability of the technologies in electric power applications. Both models are structured so that new inputs can update the analysis and keep it current with advances in technologies.

7.3.1 FES System Analysis

The components of a flywheel system fall into the following three categories:

- components that contribute to the cost of energy capacity,
- those that contribute to the cost of power capacity, and
- ancillary equipment, the cost of which is not readily correlated with power capacity.

The rotor and bearings are the primary energy storage components for a FES system. The model estimates the energy stored in the rotor from the kinetic mechanical energy created by a rotor with user-defined materials, dimensions, and operating speed. The calculations assume that the rotor stops discharging at one third the operating speed. The maximum or burst speed (rpm) for each rotor is determined by evaluating the stresses; the model notifies the user if the operating speed exceeds a safe percentage of the burst speed. For a steel rotor, the operating speed is half the maximum speed. For a composite flywheel, the assumed operating speed is 25% less than maximum. A detailed discussion of the stresses in rotors appears in Section 10.1.2.2.

Calculations of the material costs also use the user inputs for materials, dimensions, and operating speed. For the rotors defined in Table 7-2, the steel rotor weighs more than ten times the composite rotor per unit of energy stored. Weight is not a critical factor in short-duration-discharge stationary applications, and several companies (for example, Active Power, Piller) are developing steel rotor flywheel systems for those applications. However, longer duration applications will require composite rotor designs that include a hub. The cost and weight of the hub are not considered in the analysis shown in Table 7-2.

Importantly, these costs reported in Table 7-2 are only for materials. Therefore, this model is useful in assessing the low-cost potential, but would have to include processing cost to completely quantify the costs of manufacturing a flywheel rotor from steel or carbon stock.

Table 7-2. Comparison of Steel and Composite Rotors

	Steel Rotor	Composite Rotor
Diameter, cm	64	46
Height, cm	23	20
Weight, kg	555	32
rpm	7,000	29,000
Tip speed, m/s	233	698
Retrievable energy storage, kWh	0.8	0.6
Material cost, $/kg	1*	15**
Energy cost, $/kWh	690	960

* Obtained from consultations with steel suppliers.
** Composite fiber costs (S-glass and high-strength carbon fiber).

The bearing cost correlates directly to the weight of the rotor. The most elegant concepts are passive levitated bearings, using either high-temperature superconducting or conventional magnetic materials to "lift" the rotor off of the bearing and reduce the demands on it. Ball bearings are a practical near-term option that is adequate for short-duration discharge systems.

The cost of steel ball bearings is roughly $10/kg of weight supported, while ceramic bearing cost is roughly $30/kg. Despite the increase in cost, ceramic bearings are more amenable to energy storage flywheel duty. The cost of magnets for HTS bearings is roughly $40/kg. Both ball bearings and HTS bearings are often used in hybrid configurations where they are off-loaded with less expensive conventional magnets. Ball bearings can be off-loaded so that they barely touch the rotor; off-loading of up to 95% is possible with HTS bearings, depending on what is needed for lateral support. Levitated systems require significant ancillary systems for start-up, shutdown, and periodic touch-down. The model uses an estimated cost of hybrid bearings between $5/kg and $10/kg of load-bearing capacity (not including the cost of ancillary systems). For a composite rotor system, the bearings represent a cost equal to 30% to 70% of the material cost of the rotor.

With the current state of the technology, the cost of energy storage in a flywheel system is high compared to lead-acid battery storage, the most mature technology competing with the flywheel. But for the power-quality systems being developed for the near term where only 5 to 30 seconds of energy storage capacity is required, the rotor bearing system cost does not drive the overall system cost. Figure 7-4 shows the normalized relative costs of the assembly versus the power electronics and motor of a FES system. The main benefit of developing advanced rotor materials and bearing systems will be more economical, longer duration flywheel systems.

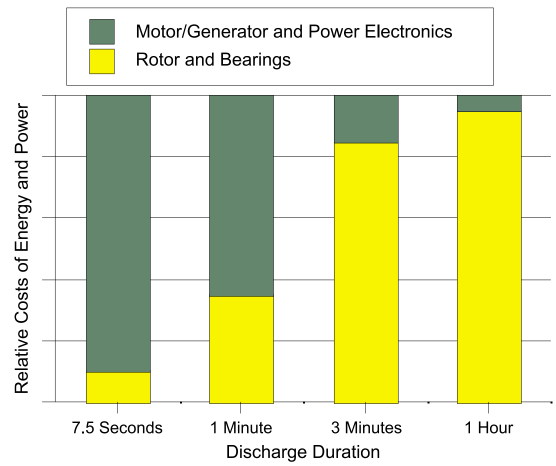

Figure 7-4. Proportions of System Cost for Flywheel Systems of Various Discharge Durations.

The value of levitated systems supporting longer power duration is also evident when one considers the contribution of the friction factor to the parasitic load. Table 7-3 shows the parasitic losses from bearing friction as a percentage of the FES system discharge capacity for various bearing systems and discharge durations. The benefits of HTS become significant in the one-hour discharge system.

The two flywheel components primarily associated with discharge capacity are the motor/generator and the power electronics. The purchase cost for off-the-shelf permanent-magnet generators is from $30/kW to $50/kW of electricity generation capacity. Most flywheel system designers choose to use a custom-designed magnet/winding assembly incorporated into the rotor, because it can use the strength of the rotor to contain the magnets and provide greater system rotational stability.

Special winding designs are also employed to minimize stray fields and resulting standby losses. The near-term cost of the custom windings is high, but it is reasonable to assume that they will approach the cost of standard motors over time.

Table 7-3. Parasitic Load Associated with Friction as a Percentage of Discharge Rate

Bearings	5 sec	1 min	3 min	1 hour
Physical bearings*	.06%	.7%	2.1%	43%
90% levitated bearings**	.009%	.09%	33%	6.6%
HTS bearings***	.002%	.02%	06%	1.2%

* Coefficient of friction for physical bearings is .001.
** Coefficient of friction for levitated bearings is .000195.
*** Coefficient of friction for HTS bearings is .00005.
Note: Does not include load associated with levitation.

The power electronics of a flywheel system must contain a rectifier to produce a stable DC from the generator output and an inverter to build AC from the DC bus. The inverter is a standard piece of equipment similar to what is contained in any lead-acid battery double conversion UPS. The rectifier must generate constant-power DC from an AC signal of varying frequency and amplitude as the rotor spins down. The technology and control system for the rectifier is well understood, but flywheel systems are not mass produced. Therefore, as shown in Figure 7-5, power electronics costs are a relatively high percentage of the total system cost. The technology of the building block for the rectifier, the inverter, and the solid state switch has been developing rapidly in recent years; future cost reductions are anticipated.

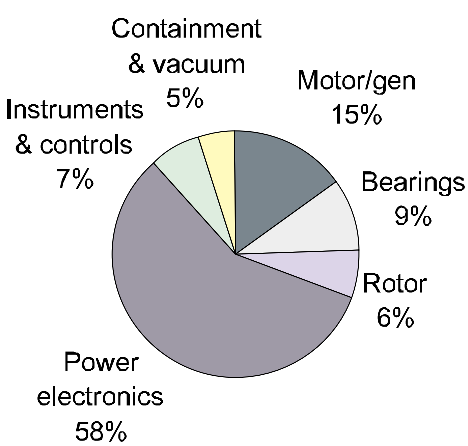

Figure 7-5. Percentage of Total Cost of FES Components in Systems.

Not one piece of required ancillary equipment stands out as a system cost driver, but their combined contributions add up. Ancillary equipment includes the vacuum vessel to house the rotor/bearing assembly; the vacuum pump; temperature, pressure, and motion sensors; electronic controls; a computer chip with system control software; remote monitoring/communications systems; and a cryogenic refrigerator (HTS bearing systems only).

The model predicts the total system cost for a five-second flywheel system to be from $200/kW to $500/kW. The cost of a one-hour flywheel system today is from $1,000/kW to $3,000/kW. These predicted costs represent projected learned-out costs.

While the model can calculate economic returns for a FES system, it cannot predict market-driving questions such as, “What duration of discharge is needed for a customer to consider a flywheel equivalent to a 15-minute battery in a UPS application?” We have defined a maximum allowable cost of a FES system based on a comparison to lead-acid batteries. A UPS battery is sized with 15 minutes of capacity because of the characteristics of a lead-acid cell. Data on power disruptions indicate that a 2–5-second machine can eliminate 80% to 90% of the problems, and that a large portion of the disruptions over 2–5 seconds last several hours. The time over 5 seconds to 15 minutes can be used to start up a generator to supply the load for hours or to shut down the equipment in a controlled manner. It remains to be seen what performance the market will demand. The model can, however, help researchers and developers set goals for the technology.

Using the financial assumptions given in Section 7.2.1.3, a flywheel system with a capital cost of $800/kW (and an O&M cost of 2% of capital per year and an incremental parasitic load of 4%) can compete successfully with a battery-based UPS with an initial capital cost of $450/kW and battery change-out costs of $525/kW.

Most FES system developers are pursuing niche applications where the costs of owning competing technologies are relatively high. For example, applications that require frequent discharges can reduce battery life from the base case of 5 years to 2–3 years. Hot or cold climates can require battery derating. In any remote application, the cost of transporting the battery and travel costs for qualified maintenance staff increases costs over the base case. To gain market acceptance in UPS applications, the initial cost of a FES system can be roughly twice that of a comparable lead-acid battery system.

7.3.2 SMES System Analysis

A SMES system requires a unique power conversion system. The magnet is best characterized as a current source (a lead-acid battery is a voltage source). First, the power from the magnet is run through a capacitor bank to turn it into a voltage source. A fast-acting high-voltage isolation switch is required, as are high-voltage inverters and voltage regulators. Ancillary equipment includes snubbers to handle voltage spikes and a resistive sink to accept the magnet charge if there is a loss of superconductivity. Much of the power conversion equipment was custom designed for early units, but developers are now seeking to use off-the-shelf components wherever necessary. These advances are bringing down the cost of this relatively costly component.

At a low-temperature superconducting coil cost of $2/kA meter, the materials cost for SMES is roughly $28,000/kWh. Several winding and coating processes are needed to produce a magnet from HTS wire; the cost of these processes is not known. Most SMES systems are developed for under five seconds of discharge capacity. In these short-duration applications, the cost of the magnet is not a system cost driver. For example, at two seconds of output, the component cost of the magnet is $28,000/kWh, equivalent to $15/kW (2% to 3% of the system cost).

Developers have also been working to reduce the costs associated with parasitic loads on SMES systems. The parasitic load on a shunt-connected SMES system is roughly 4% of the protected load. Developers have investigated series injection systems for voltage regulation applications. In those systems, the injection transformer roughly doubles the parasitic load. Table 7-4 shows the breakdown of the parasitic load. Improvements in the parasitic load will provide only marginal reduction in the ownership cost of a SMES unit.

Table 7-4. Estimated Cost Breakout of a SMES System Cryogenic Load

Cryogenic refrigerator	50%
Isolation switch	25%
Other	25%

The load for the isolation switch includes the resistive losses and the required cooling.
Losses are at steady-state operation.

The present total system cost of short-duration SMES systems is in the $600/kW to $1000/kW range, 40 to 67 times the cost of the magnet. As with FES, market strategies are focused on energy applications that are less well suited for lead-acid batteries. Marketing efforts are aimed at finding niche applications in which the unique characteristics of the SMES power output have high value.

The cost target for FES systems in power quality applications (of $400/kW) is also roughly applicable to SMES systems. However, the allowable cost for a SMES system is actually slightly lower because the SMES system has a higher base-case parasitic load than a FES system (4% versus 2%). Therefore, if developers can lower the cost of SMES systems, they will be more likely to achieve broad market penetration. One concept for achieving that goal is to increase the current in the coil. The use of HTS leads removes a resistive heat source at the 4 K interface and enables higher current operation. Because the energy stored is proportional to the square of the current, increasing the current by a factor of three could potentially provide a factor of ten reduction in the coil and cryogenics cost per unit of energy storage capacity. Figure 7-6 shows the estimated decrease in SMES unit cost with a jump from 1,000 A to 3,000 A (second to third generation), all else being equal. Power electronics components with a higher voltage rating are necessary to enable the higher current.

7.3.3 Sensitivity Analyses

The output of the models (IRR) for a specific storage system was not the final result of the analysis of either the SMES or FES portions of this study. IRR output of the models depends on cost and performance characteristics that have a range of potentially representative values. Consequently, iterative

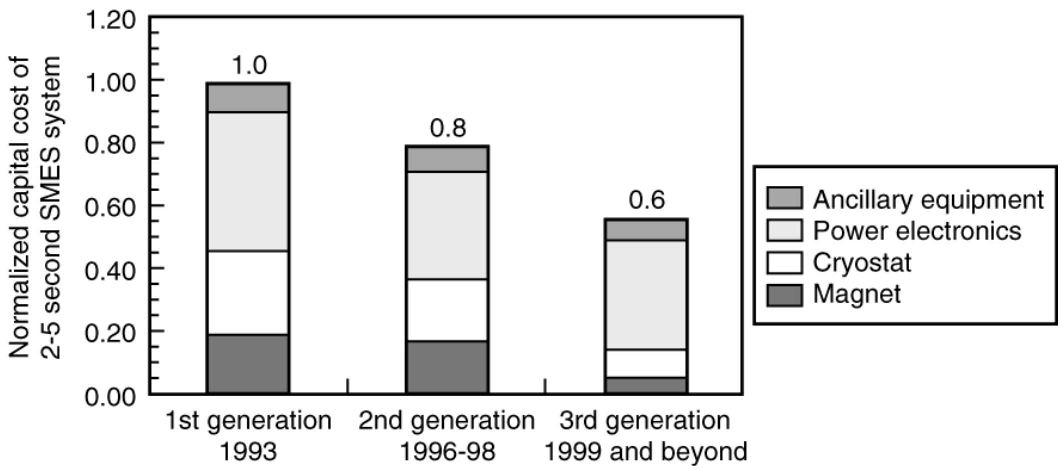

Figure 7-6. Costs of Components as a Percentage of Total Cost of Several Generations of SMES Systems.

modifications of those characteristics between the upper and lower bounds of their ranges are necessary to produce a family of IRRs for the SMES and FES systems of interest. Analyses of these families of IRRs are necessary to determine the sensitivity of the IRR to specific parameters. The conclusions from the sensitivity analyses have the following bases:

- favorable comparison of IRR with industry hurdles indicates likely market acceptance;
- large contribution to total system cost by any subsystem indicates need for R&D;
- sensitivity of the IRR to variation of subsystem cost and performance correlates with the likely impact of R&D in those areas;
- large contribution to total revenue by any revenue stream indicates where technical and cost improvements will yield the greatest economic benefits;
- sensitivity of IRR to variation of specific revenue stream inputs indicates areas where the uncertainty of the utility industry environment could radically affect the value of R&D; and
- inputs that are controversial or that require expert experience to estimate are high-priority areas for additional analysis.

7.3.3.1 Uncertainty in Results

The following are areas of uncertainty associated with the flywheel model. These areas result from the need to use simplifying assumptions and qualitative expert input instead of exact calculations and quantitative inputs:

- Analysts assumed an O&M cost for the flywheel system of roughly 2% of capital per year for 20 years. If the O&M were to increase to 4%, the allowable cost for an FES system in UPS applications decreases from $400/kW to $350/kW, all else being equal.
- If the base-case UPS FES system parasitic load decreases from 2% to 1%, the allowable capital cost increases from $400/kW to $420/kW, all else being equal. For a one-hour system, a decrease in the parasitic load from 4% to 1% increases the allowable cost from $800/kW to $840/kW.
- The safety factor for composite rotors was assumed to be 25% (that is, the operating speed [rpm] is 25% less than the maximum burst speed). At present, no established safety factors exist for composite rotors. Twenty-five percent is a target that depends on developing a body of rotor failure data and verification of fail-safe rotor designs.
- The model's base-case analyses for composite rotor systems assumed that no containment system would be required for the rotor (as

suggested by several of the developers). Early systems will likely be buried or contained, increasing their cost.

- Significant uncertainty exists about the estimates for the cost of fabricating composite rotors and also for the cost of ancillary equipment needed for levitation systems.

The following are areas of uncertainty associated with the SMES system model:

- Analysts assumed an O&M cost for the SMES system of roughly 3% of capital per year for 20 years (based on input from developers). However, this estimate is not firmly associated with any operating system.

- Significant uncertainty is also associated with the "learned-out" cost of the SMES power conversion system and the cost of fabricating a superconducting magnet. Both of these costs, backed out of several sources, should be refined.

7.3.3.2 Cost Goals for SMES and FES System Market Penetration

Sensitivity studies using the models identified a range of threshold costs (based on performance, availability of components, and economic value of applications) for SMES and FES systems in electric-power applications. As shown in Figure 7-7, each application has a range of costs in which SMES and FES systems begin to compete successfully with other technologies. Systems with costs that are below the lowest value in the range marked by the horizontal bars are very likely to penetrate the market. Systems with costs at the left end of the bars have some potential to successfully compete with established applications that do not address safety, national security, or tremendous economic cost. Costs at the right end of each bar will allow SMES and FES systems to successfully compete only with applications that involve tremendous risk or cost (for example, defense applications, semiconductor manufacture, healthcare).

7.4 Efficacy of the Models and Correlation with Actual Systems

The SMES and FES systems spreadsheet models incorporate both technical and economic characteristics of SMES and FES system technologies to model the subsystems and, in some places, even the components of systems. The level of detail to which the models treat technical attributes is a function of two variables:

- relative value of the detail to the quality of the models' output, and
- availability of valid information to support a detailed subsystem or component model.

Therefore, the modeling of some subsystems and components is detailed and involves many inputs and internal calculations. Conversely, the modeling of some subsystems has little detail and treats entire

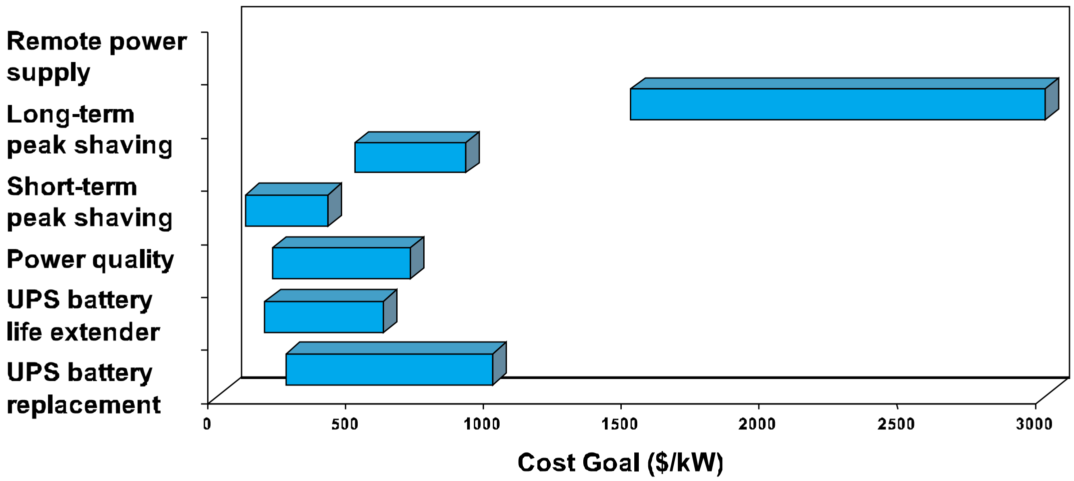

Figure 7-7. Cost Thresholds for Adoption of SMES and FES Systems in Electric Power Applications.

subsystems as "black boxes" that require only a few inputs and intermediate calculations to represent a tremendous number of elements. As a result, the worksheets that model the technical attributes of various subsystems in the spreadsheet models fall into the four broad categories shown in Figure 7-8. Analysts used this categorization of worksheets in their decisions regarding the content of the models and the recommendations given later in this report.

Specifically, assessing whether a particular subsystem fits into Case 1 (important) or Case 2 (less important) is crucial to the efficacy of the models and the analytic results from them. A model that consists mostly of Category I worksheets in which the content is both important and exact will generate more useful results than a model that consists mostly of Category III and IV worksheets in which the content is less important to the analysis. Also, a model that contains mostly Category I worksheets will generate more meaningful results than a model that consists of a large number of Category II worksheets in which data are inexact. Table 7-5 presents the categories in which the SMES system model worksheets fall. Table 7-6 presents the worksheet categories for the FES system model.

In both the SMES and FES system models, more than 50% of the worksheets fall into Category I, and 20% of the worksheets fall into Categories III and IV. Only about 25% of the worksheets for either model fall into Category II.

These statistics suggest that the models are likely to be useful because most of the worksheets are important to the results of the model (80% are in Category I or II). However, the relatively high percentage of Category II worksheets suggests that the results of the models are meaningful only if the "black box" treatment of those important items is representative of subsystems in actual SMES and FES system devices. Project analysts validated that the models were representative by using the models to predict performance of existing systems with known characteristics.

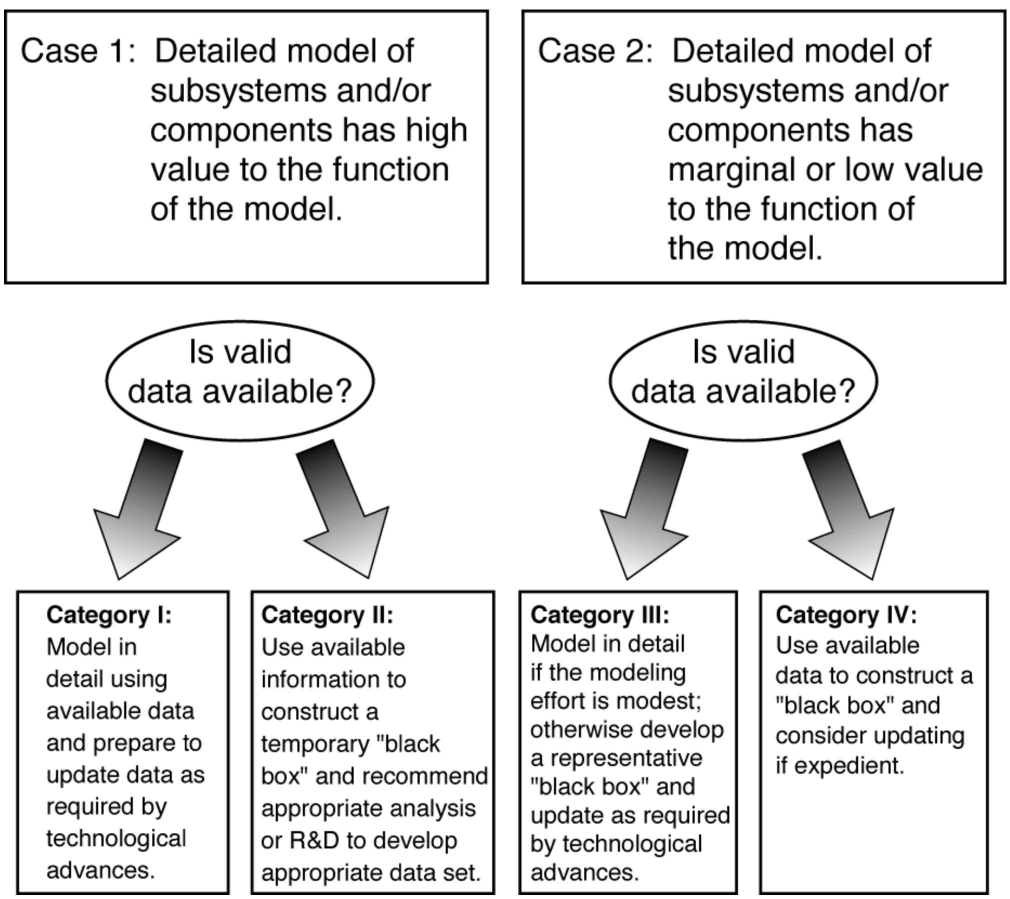

Figure 7-8. Four Categories of Subsystem Worksheets in the SMES and FES System Models.

Table 7-5. Categories of Worksheets in the SMES System Model

Category I Important/Data Available	Category III Less Important/ Data Available
Current	Containment
Inductance	Cryogen
Magnet	Safety
Cryostat	
Capital costs	
O&M costs	
Revenues	
Finance	
Category II Important/Data Unavailable	**Category IV Less Important/ Data Unavailable**
Current lead	None
Isolation switch	
PCS	
Grid interface	

Table 7-6. Categories of Worksheets in the FES System Model

Category I Important/ Data Available	Category III Less Important/ Data Available
Flywheel	Containment
Rotor	Cryogen
Energy storage	Safety
Hub	
Capital costs	
O&M costs	
Revenues	
Finance	
Category II Important/ Data Unavailable	**Category IV Less Important/ Data Unavailable**
Motor/generator	Vacuum
Motor/generator	
PCS	
Grid interface	

By modeling existing SMES and FES systems, project analysts determined that the cost and technical performance characteristics of the modeled systems correlated well with those of the actual devices. (The FES system model did not initially identify the huge cost contribution of carbon fibers to the total system cost for a FES system with a discharge duration of greater than five minutes. However, subsequent modifications to the model have corrected that exception.) Therefore, analysts are confident that the models produce both useful and meaningful results.[1]

7.5 Limits of the Model

Both models calculate an IRR for storage systems from the technical and economic attributes of components. However, the models are neither investment analysis tools nor design tools. For performance inputs when appropriate data were unavailable, analysts made approximations based on input from industry participants, analysis of related information, and the analysts' own expertise (backgrounds include mechanical, chemical, and electrical engineering, material science, economics, finance, and policy). The IRR, as calculated by the model, is a reference value meaningful only in a sensitivity analysis. It is not appropriate, in an absolute sense, as an investment analysis tool or to support system design efforts. The sensitivity analyses can identify areas of potentially high-impact R&D. Any other use is inconsistent with the capabilities of the tool.

[1] The acquisition of detailed data for Category II worksheets (that would enable analysts to move them to Category I) would be valuable, but not essential, to using the SMES and FES system models to identify high-value R&D. This corollary assumption was a significant consideration in making the recommendations later in this report.

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8. Conclusions

Using the models, project analysts identified the cost goals shown in Figure 7-7 in Section 7.3.3.2 that SMES and FES system technologies must achieve in order to compete with other technologies and gain widespread acceptance. Given the cost thresholds and technical capabilities of SMES and FES systems, both technologies are now applicable to short-duration peak shaving power quality, and they provide a means to extend the life of batteries in UPS. Long-duration peak-shaving and remote power-supply applications will become feasible for these technologies only when the SMES and FES systems can supply several hours of energy in a cost competitive manner.

The greatest cost improvements in SMES systems are most likely in the area of cryostats. Projected improvements for the next generation include further technical advances in cryogenics and reduced cryogenic demands from the use of more high-temperature superconducting materials and improvements in magnets. For FES systems, cost reductions are possible through improved bearings (and reduced O&M) and reduced carbon fiber costs (and reduced capital cost).

Iterative exercise of the models showed that, with respect to 20-year cash flows, both the SMES system and the FES system represent a large up-front expenditure, but after the first year of operation, costs are limited. Compared with existing technologies, SMES and FES systems have higher initial cost, but lower operating and maintenance costs. For this reason, cost of capital will be critical to market penetration for early systems. A higher cost of capital favors the established technologies, all else being equal. If the cost of equity were to increase from 15% to 20%, the base-case allowable cost for a FES system in UPS applications would decrease from $400/kW to $370/kW. If the capital cost were to decrease to 10%, the allowable cost would increase to roughly $430/kW.

Figures 7-4 and 7-5 in Section 7.3.1 show the cost contributions of components for FES systems at present. Researchers emphasize the need for R&D on advanced bearings although they represent approximately only nine percent of the total system cost. The R&D is needed to achieve the reduced operating and maintenance costs that are possible with advanced bearings (less friction, greater efficiency, long bearing life, fewer replacements). The increased efficiency from improved bearings also reduces the relative cost of the PCS.

The cost of the PCS, which is relatively independent of the duration of discharge, becomes a smaller fraction of the entire system cost as discharge duration increases. Conversely, rotor cost increases with the amount of energy that the system stores. This increase is the result of the need to use composite rotors for high-energy capacity, and the need to use more expensive carbon fibers in rotors that serve long-duration discharge applications. These effects on total cost components, as shown in Figure 8-1, are driving R&D of bearings and rotors, not R&D of the PCS. Integration of a FES system remains an R&D area for the future.

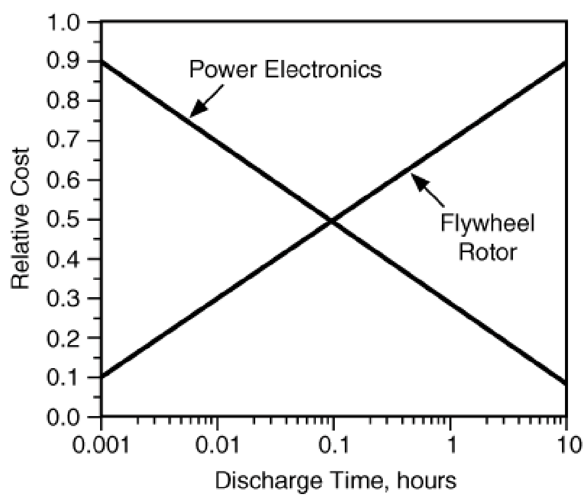

Figure 8-1. Relative Costs of FES System Components as a Function of Discharge Time.

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9. Recommendations

This study culminated in recommendations for R&D that have the potential to advance SMES and FES systems in electric power applications.

identifies R&D areas that have the potential to advance SMES systems. The R&D goals shown at the left side of the graph are relatively easy to achieve compared to those on the right side. Also, the achievements shown at the top of the graph have the potential for high impact on SMES cost and performance compared to those at the bottom. Therefore, SMES would benefit most from R&D that is high on the vertical axis and to the left on the horizontal axis. Such R&D includes improving coil materials and winding processes in which the difficulty is moderate and the potential impact is high.

Figure 9-2 illustrates areas of R&D with the potential to advance FES systems. The goals on the left side of the graph are relatively easy to achieve compared to those on the right. Those objectives at the top of the graph have greater potential impact than those on the bottom. As before, R&D with moderate technical difficulty and large influence over cost and/or performance is most likely to advance FES system penetration. Therefore, R&D in rotor manufacturing and operation, development of codes, and development of advanced motors meet these requirements. Development of multi-incident bearings and advanced sensors also show promise to advance FES systems in the electric power market.

Developers are involved in many of these R&D areas. However, much of the R&D is expensive and represents a relatively high-risk investment for private companies. R&D of coil materials and manufacturing processes and specialized isolation switches may be outside the reach of private-sector SMES system developers. Similarly, development of advanced bearings, and optimization and codification of the manufacturing and operation of composite rotors represent R&D that may require federal involvement.

Table 9-1 summarizes the R&D that is recommended as priorities for SMES and FES systems because it has the following attributes:

- High impact on the performance or cost of SMES and FES systems in electric power applications,
- Moderate technical difficulty, and
- Relatively high risk for private sector developers.

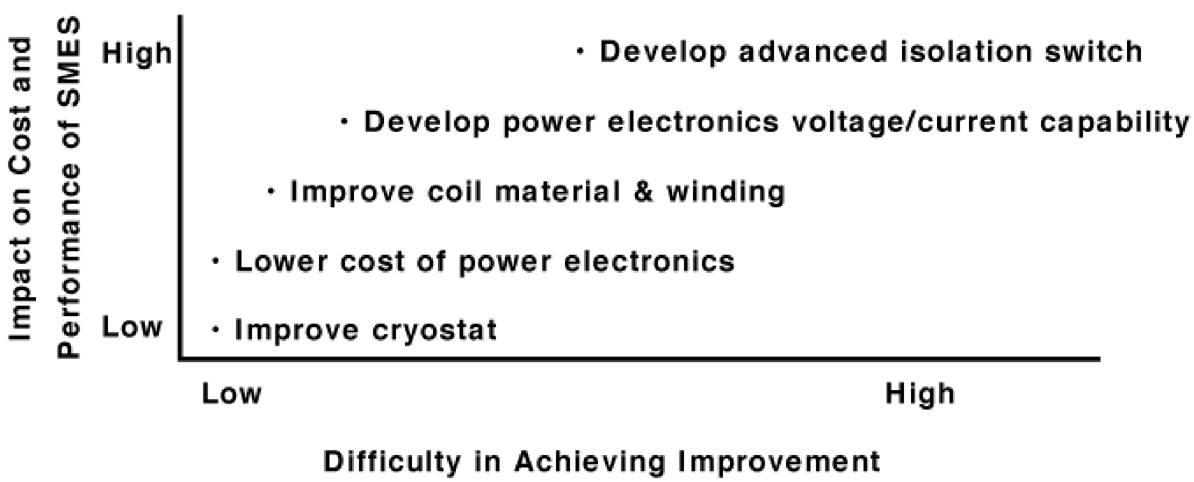

Figure 9-1. Areas of R&D for SMES Systems Based on Impact Versus Difficulty.

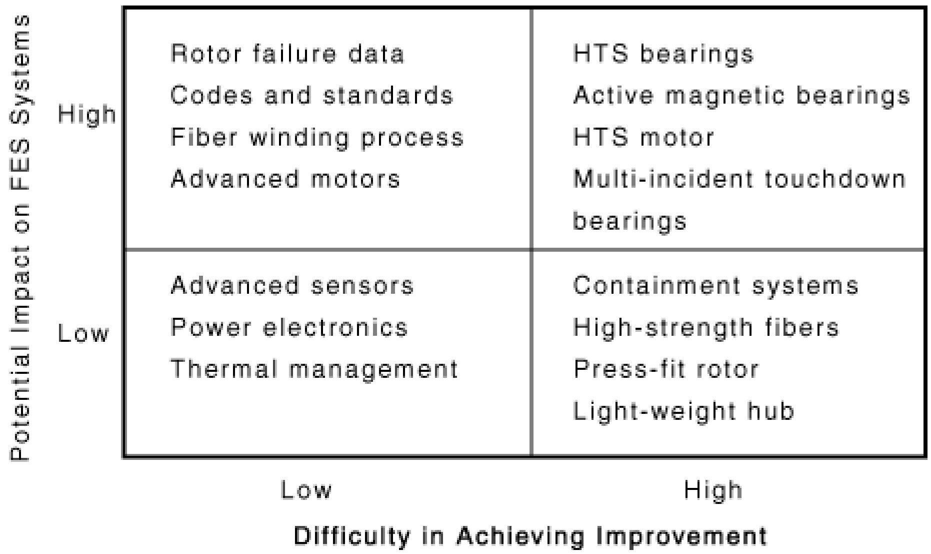

Figure 9-2. Areas of R&D for FES Systems Based on Impact Versus Difficulty.

Table 9-1. High-Priority R&D for SMES and FES Systems

SMES R&D	FES R&D
• Improve coil material and winding process – to increase power and energy – to reduce demands on power electronics – to increase efficiency • Improve power electronics • Develop advanced isolation switch – to reduce system thermal losses – to eliminate transients caused by ambient/cryogenic interface	• Develop components to improve system efficiency and reduce O&M costs – advance bearings – HTS materials – active and passive magnetic types – multi-incident touchdown types • Assist in development of codes and standards (and failure data) for composite rotors for – manufacture – operation

10. Appendices

10.1 Storage System and Related Technology Primers

10.1.1 Superconductivity and Cryogenics in SMES

10.1.1.1 What is Superconductivity?

In 1911, when superconductivity was discovered, prevailing theory held that free electrons in a metal would eventually stop moving at sufficiently low temperatures. Researcher H. K. Onnes was conducting experiments to show a steady increase in resistivity with decreasing temperature. Instead of the relation that he predicted, Onnes found that only semiconductors show rising resistivity as temperature becomes very low. Metals, which are good conductors at room temperature, level off to a low resistivity at temperatures near absolute zero (mainly because of impurities). But as shown in Figure 10-1, some metals that are poor conductors at room temperature have virtually no resistivity at very low temperatures. Thus, the material becomes superconducting. The temperature at which resistivity approaches zero is called the critical temperature, T_c. This near absence of electrical resistance enables current to flow for very long times without significant loss. Under certain conditions, the decay time can be on the order of 10^5 years (for comparison purposes, the decay time of a current in a normal metal is about 10^{-12} seconds).[1] Superconductors with T_c's near 4 K are considered LTS, and superconductors with T_c's near 77 K are considered HTS. Relative to daily experience, even 77 K is a very low temperature. HTS SMES requires a cryogenic system to keep the coil superconducting.

A second important discovery about superconductivity is the Meissner Effect. A superconducting metal that is below its T_c expels magnetic field from its interior. By expelling the field and distorting nearby magnetic field lines, a superconductor creates a strong enough force field to overcome gravity, as shown in Figure 10-2. Numerous photos, including the one in Figure 10-3, of a small magnet floating freely above a cooled block of superconductor, illustrate the result of the Meissner effect.

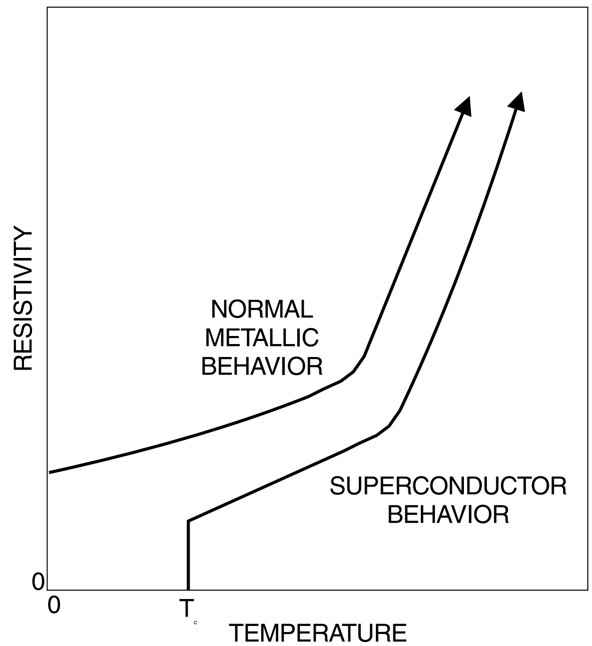

Figure 10-1. Normal Versus Superconductive Resistivity.

When a superconducting metal below its T_c is in an existing magnetic field, the magnetic field is expelled. However, no superconductor can completely exclude very strong magnetic fields. In fact, the Meissner Effect ceases to operate for all of the known superconductors when exposed to a magnetic field of sufficient strength, and the superconductor's resistivity increases to a finite value. The field that arrests the Meissner Effect and eliminates superconducting behavior is known as the critical magnetic field for the material, and is denoted by $H_c(T)$. At absolute zero temperature, the upper limit of critical magnetic field is $H_c(0) = H_0$. At T_c, the critical magnetic field goes to zero: $H_c(T_c) = 0$. Superconductors with high critical field values, generally associated with materials having a high T_c value, are the most desirable for SMES devices.

[1] Sheahan, Thomas P., *Introduction to High-Temperature Superconductivity*, Plenum Press, New York, 1994.

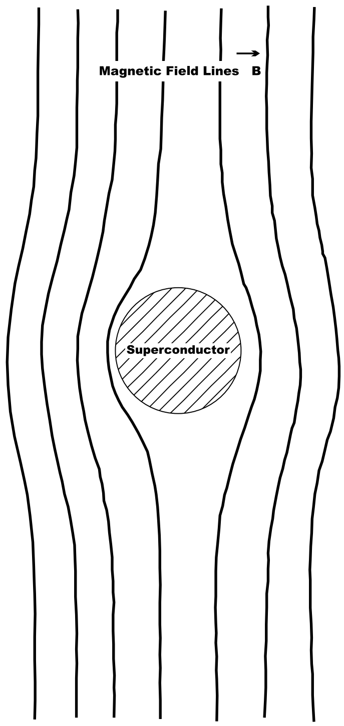

Figure 10-2. Illustration of Meissner Effect.

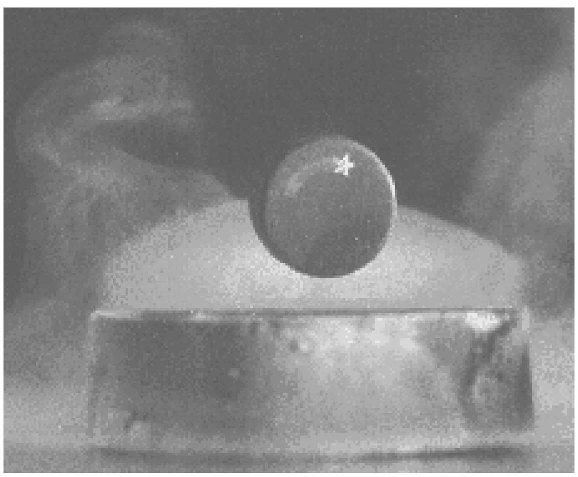

Figure 10-3. Example of Meissner Effect on Superconductors.

Type I and Type II Superconductors

In addition to the magnetic and temperature properties of superconductors, each superconducting material also has a critical current that limits its practical application. Before 1960, superconductors were of interest to physicists but had no practical applications because they could not carry a significant current. Only when a new type of superconductor was discovered did practical applications for them become possible. The two types are classified as Type I and Type II superconductors and have a dramatic difference in their magnetic and current-carrying properties.

The current density, (j), that a superconductor carries is current divided by the cross-sectional area through which it flows and is usually given in amps per centimeter squared. The critical current density (Jc) is the upper limit to the current density in a superconductor. For a wire of radius, a carrying current, I, the magnetic field at the surface is $I/2\pi a$. The current (I_c) cannot exceed the current that produces a critical magnetic field, H_c, at the superconductor, which implies a critical current can be expressed as shown in Equations 10-1 and 10-2:

$$I_c = 2\pi aH_c \qquad [10\text{-}1]$$

and

$$J_c = 2H_c/a \qquad [10\text{-}2]$$

These equations are theoretically correct. However, in real superconductors, the actual current density is less than this upper limit, and the actual current is limited by other physical mechanisms.

For a Type I superconductor, critical current is simply a consequence of the magnetic field H_c. Because H_c is low in Type I superconductors, critical current densities are also low, and practical applications are limited.

In a Type II superconductor, the relationship is much more complicated. Figure 10-4 shows the critical surface in the 3-dimensional space of temperature, magnetic field, and current density. This graph is known as the THJ plot. At any point on the surface or inside the volume it defines, the material is superconducting.

10.1.1.2 What is SMES?

An SMES system uses the advanced technology of a superconducting electromagnet to store electric energy. SMES systems store electric energy in the magnetic field created by DC flowing through a coiled superconducting wire. An SMES system includes a superconducting coil, a power conditioning system, a cryogenic refrigerator, and a cryostat/vacuum vessel to keep the coil at low temperature.

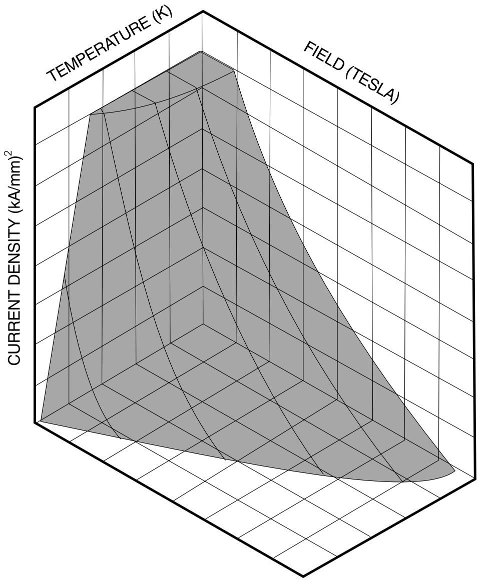

Figure 10-4. Three Key Variables in Superconductivity.

SMES is an outgrowth of the Strategic Defense Initiative (Star Wars) Program. During research of laser weapons systems, the DoD discovered that SMES could provide the large amounts of power necessary to operate and fire lasers at incoming missiles within a very short time.

SMES devices are very efficient from a purely electrical viewpoint. Future units may achieve DC to DC energy efficiencies as high as 90%. In addition, because SMES coils contain no internal moving parts, they are highly reliable and promise long service life.

10.1.1.3 How Does SMES Work?

The amount of energy stored in a magnetic field is expressed by Equations 10-3 and 10-4.

$$E = \int \frac{B^2}{2\mu_0} dV \qquad [10\text{-}3]$$

$$E = L\frac{I^2}{2} \qquad [10\text{-}4]$$

In Equation 10-3, E is the stored energy, B is the magnetic field, V is the volume of the coil, and Φ_0 is a constant that represents magnetic permeability of the material through which the magnetic field must pass. In Equation 10-4, E is, once again, stored energy, L is the inductance of the magnet, and I is the current in the magnet. The first equation shows that the stored energy is related to the strength of the magnetic field in the coil. The second equation shows that the stored energy depends on the current in, and the inductance of, the coil.

10.1.1.4 SMES Components

Coil (Magnet)

The parameters of temperature, magnetic field, and current trade off against one another in all superconductors. In an ideal case, a single material could maximize all three. However, nature is not that cooperative. Furthermore, additional trade-offs exist in manufacturing wire with good stability and AC loss properties. A composite of many fine filaments of superconductor embedded in copper achieves the best set of characteristics. Ductile metals are superior to brittle crystalline materials to make fine filaments.

Table 10-1. Superconducting Materials and Their Properties

Material	NbTi	Nb_3Sn	Ceramic (HTS)
Critical temperature (K)	9.2	18	90–120
Upper critical field (T)	12	22	>100
Theoretical critical current density (GA/m^2)	8	16	Very high
Ductility	Excellent	Poor	Poor

A clear example of the trade-offs involved in material selection is evident when comparing Niobium-titanium (NbTi) with Niobium-tin (Nb_3Sn), as illustrated in Table 10-1. While Nb_3Sn has better thermal, electric, and magnetic properties (higher T_c, H_c, and J_c), it is brittle. Therefore Nb_3Sn is difficult and expensive to form into wire. NbTi, on the other hand, is a ductile metal alloy that forms wires well, while still providing acceptable thermal, electric, and magnetic performance. Consequently, the material of choice for most superconducting wire applications is NbTi.[2]

SMES coils vary in size depending on the amount of energy that they must store. Currently, the most widely used LTS wire is an NbTi alloy with a T_c of 9.2 K. Each wire typically contains tens of thousands

[2] Sheahan, Thomas P., *Introduction to High-Temperature Superconductivity*, Plenum Press, New York, 1994.

of filaments embedded in copper. HTS wires that operate at liquid nitrogen temperature or above 77 K (−196°C) are not yet technically mature enough to be considered for SMES applications. However, some of the current leads between the copper wires on the outside of the SMES system and the superconducting coil on the inside are now HTS materials. This transition material makes the electrical interface between room temperature (30°C) and the coil (−269°C) easier to achieve.

Researchers have worked with two different types of coil shapes: the solenoid and the toroid. As shown in Figure 10-5, the solenoid coil is tube-shaped, and the superconducting wire is wrapped around the tube. The toroid is donut-shaped, and the superconducting wire is wrapped as shown. The toroid winding consumes nearly twice the length of superconductor wire of the solenoid, but the toroid coil design does not allow the magnetic fields that store the energy to penetrate into the surrounding area as far as solenoids.[2] A perfectly wound toroid, as illustrated in Figure 10-5, would prevent any field from forming outside of the coil. Unfortunately, this optimum configuration is only theoretically possible. Real toroidal coils consist of a large number of solenoids linked together in a ring. These real-world, imperfect toroids limit the range of the magnetic fields much better than solenoid shapes, but are difficult and expensive to construct.

In toroids, the asset of containing the magnetic field in the coil also creates a practical limitation on the design. The magnetic field in the donut shape causes strong outward forces (Lorentz Forces)[3] that would cause the device to self-destruct without significant mechanical containment (in reinforced structures placed above ground or underground). This requirement limits both the physical and economic practicality of the toroid. Solenoids allow the field to protrude from the ends of the coil; therefore, they do not experience the same magnitude of Lorentz Forces. Hence, existing SMES designs incorporate the more economical and readily constructed solenoid coils despite their comparatively large external magnetic fields.

Power Conditioning Systems

The coil requires a PCS at the coil/grid interface. The PCS uses solid-state DC/AC converters as well as other filtering and control circuitry. See Section 10.5.7 for more details on PCSs.

Cryogenics

The following discussion describes the basis of cryogenics, how it applies to SMES devices (and superconducting bearings for FES systems), and how improvements in superconductors may affect future designs.

Because refrigeration represents a source of inefficiency in a SMES device, elaborate measures are undertaken to improve refrigerator efficiency and reduce sources of heat leaks and heat generation within the superconductor. While necessary to reduce O&M costs, such measures make SMES capital costs higher and make cryogenic devices more expensive and complex (and reduce their reliability). For this reason, SMES developers seek to operate their systems at as high a temperature as possible to simplify cooling requirements. Currently, only LTS technology is being used for SMES coils, and the refrigeration requirements are rigorous. Heat generated within the cryostat can be reduced by using more superconductors or one of higher quality. Either choice increases the costs of the superconducting material. Heat leaking into the cryostat can be reduced by building a better, but more complicated, cryostat, which also increases the cost of the cryostat and may decrease its reliability. Until high-temperature superconductors are more prevalent, these two sources of heat will continue to be present in SMES.

Background - History of Superconductivity and Cryogenics

The discovery of superconductivity is deeply intertwined with advances in cryocooling. As described above, Onnes first discovered superconductivity in 1911 while using a new refrigerator capable of producing liquid helium. He found that when mercury was cooled to approximately 4 K, it lost all electrical resistivity. Since this discovery, superconductors and refrigerators have been intrinsically linked. Researchers have discovered other superconductors and have developed a number of prototype cryogenic refrigerators and superconducting devices. Today, the only large commercial use of superconductors is in MRI devices. These LTS devices use a pool of

[3] For a complete discussion of Lorentz Forces, see *Engineering Electromagnetic Fields and Waves* by Carl Johnk.

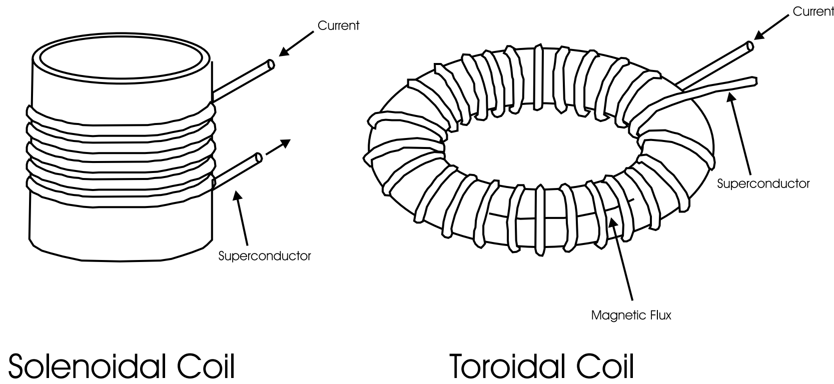

Figure 10-5. Solenoidal and Toroidal Coils for SMES.

liquid helium to maintain superconductivity in concert with a liquid helium liquefier/refrigerator. SMES is the other commercial application of cryogenics for superconductivity. Figure 10-6 shows a cutaway diagram of a current magnet and cryostat assembly for a SMES unit. For the superconductors within the SMES unit to operate properly, they must be refrigerated using liquid Helium at approximately 4.2 K. Figure 10-7 illustrates the boiling temperatures of several elements including helium and compounds at atmospheric pressure.

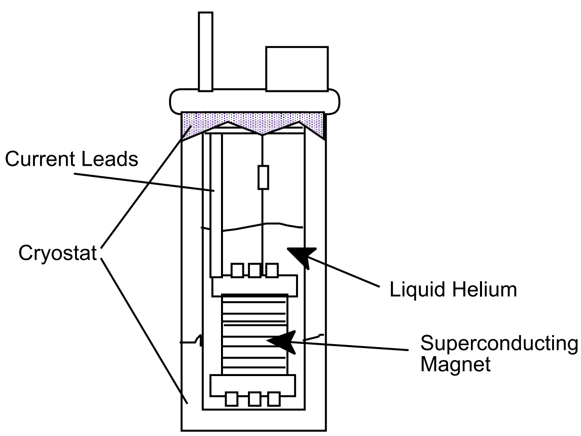

Figure 10-6. Cutaway of Coil and Cryostat of SMES Unit.

Cryogenics, from the Greek word meaning "creation or production by means of cold," means to produce appropriate changes in gases, into liquids or solids, to achieve a desired result. An important application of cryogenics is the separation and purification of air into its various components (oxygen, nitrogen, argon, and the rare gases). For this study, the desired result is the liquification of helium for the cryogenic refrigeration of SMES units (or flywheel bearings).

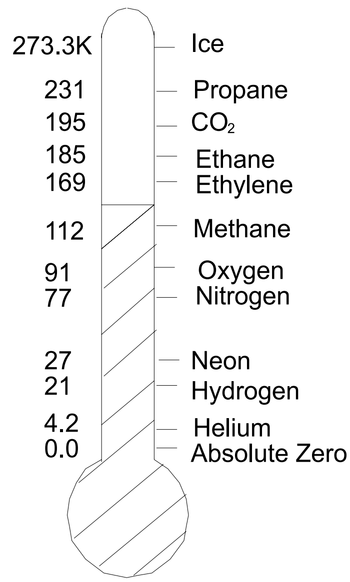

Figure 10-7. Cryogenic Thermometer Showing Normal Boiling Temperatures (K) at Atmospheric Pressure.

Cryogenic processes can range from ambient conditions to the boiling point of the cryogenic fluid. Cryogenic cycles must also incorporate two or more pressure levels. These properties must also cover the vapor, vapor-liquid, liquid and sometimes the solid states. Therefore, the physical properties of fluids over a great range of temperatures and pressures must be known. The main physical properties needed for design of contaminant removal are fluid flow, heat transfer, and the like. Properties such as density, viscosity, thermal conductivity, heat capacity, enthalpy, entropy, vapor pressure, and vapor-liquid equilibriums are generally obtainable through tables or equations and are functions of temperature and pressure. Selection of materials for low-temperature application depends on the properties of these materials at the desired temperatures, especially regarding brittleness, elasticity, thermal conductivity, and thermal expansion.

Figure 10-8 shows the theoretical work required for ideal refrigeration at various temperature levels. The figure illustrates the rapid increase in work with decreasing temperature. Work becomes infinite at absolute zero. For a real-world cryogenic system, this relationship means that tremendous energy is required to reach very low temperatures. The actual work for low-temperature refrigeration increases at a more rapid rate than that indicated by the theoretical curve.

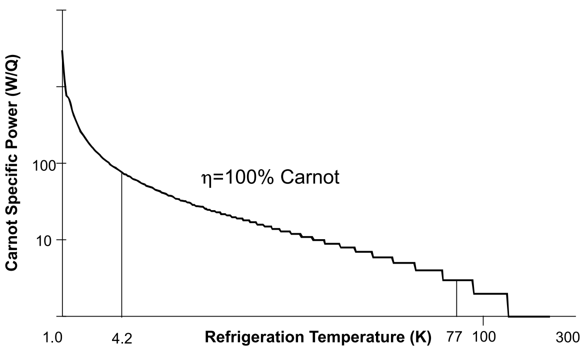

Figure 10-8. Ideal Input Power per Watt of Refrigeration for a Carnot Refrigerator as a Function of Lower Operating Temperatures.

Just as no ideal Carnot cycle exists, no truly ideal gas exists. However, the deviations from ideal-gas behavior are what make building refrigerators to liquefy gases possible. The Joule-Thomson expansion process uses a refrigeration method that is unlike the vapor compression process widely applied in conventional refrigeration.

Joule-Thomson Refrigeration

In the Joule-Thomson refrigeration process, a gas at high pressure is expanded through a restriction to a low pressure, with a resulting change in gas temperature. If the high-pressure gas is initially below its inversion temperature, the gas temperature decreases as a result of this "throttling." By passing such a gas through an effective countercurrent heat exchanger prior to or during the expansion process, it is possible to obtain extremely low temperatures and to partially liquefy the gas.

Figure 10-9 illustrates a typical Joule-Thomson refrigerator. High-pressure gas (p_1) enters the heat exchanger at a certain temperature (t_1) and is cooled by a countercurrent stream of low-pressure gas. At a low temperature, the gas is expanded to a low pressure through a restriction, shown here schematically as a Joule-Thomson valve, and a portion is subsequently liquefied. The liquid is vaporized at constant temperature by the heat leak and load (Q). The saturated gas at low pressure returns through the heat exchanger, cooling the incoming high-pressure stream, and leaves the exchanger at temperature (t_2) and pressure (p_2).

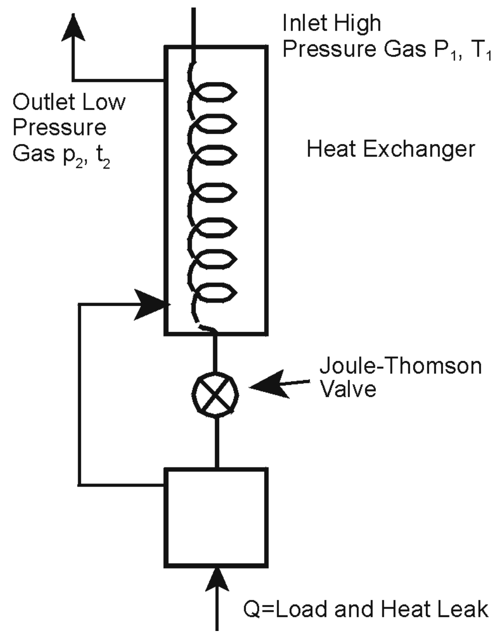

Figure 10-9. Simple Joule-Thomson Refrigerator.

An energy balance around the refrigerator shows that the sum of the heat leak and load, Q, equals the enthalpy difference between the low- and high-pressure gas streams as expressed in Equation 10-5:

$$Q = H(p_2, t_2) - H(p_1, t_1) \qquad [10\text{-}5]$$

Introduction of the enthalpy of the low-pressure gas stream at the temperature t (the enthalpy of the gas stream if it is warmed completely to the temperature of the inlet gas) yields Equation 10-6:

$$Q = \left[H(p_2, t_1) - H(p_1, t_1)\right] - \left[H(p_2, t_1) - H(p_2, t_2)\right] \qquad [10\text{-}6]$$

The first term is the isothermal enthalpy change for a Joule-Thomson expansion process. It equals the maximum or theoretical refrigeration available for such a process. The second is an energy term caused by the temperature difference at the warm end of the heat exchanger. Since this term can be expressed in terms of the specific heat of the gas and the temperature difference, Equation 10-6 may be rewritten as Equation 10-7:

$$Q = (\text{Theoretical refrigeration}) - c_p \Delta t \qquad [10\text{-}7]$$

in which Δt equals the difference between temperature t_1 and t_2. Because t_1 must be greater than t_2 for a finite heat exchanger, the second term in Equation 4-1 is positive, thus representing a loss in refrigeration as a result of the heat exchanger inefficiency. Because this loss is proportional to the temperature difference, the most efficient exchangers obtain the maximum amount of refrigeration.

The J-T throttling process is irreversible, and its improper use in a refrigeration process can cause poor process efficiency. The entropy increase in a throttling process decreases with decreasing temperature and is the least when in the throttling liquid phase. For maximum process efficiency, therefore, the J-T throttling valve is always located at the lowest possible temperature.

The inversion curve is a set of points represented by Equation 10-8, where

$$(\Delta T / \Delta P)_n = 0 \qquad [10\text{-}8]$$

In this equation, *h* or enthalpy, is a constant. As pressure increases, temperature increases to a point and then proceeds to decrease. This is called the inversion point. In the temperature-pressure regime where temperature continues to increase as pressure is increased, refrigeration is possible. A gas that starts off extremely hot must first be reduced in temperature to lie within its inversion curve before it can be liquified.

One of the most important differences in cryogenic refrigeration for superconductors is the inversion temperature of gases. Nitrogen has a maximum inversion temperature of 621 K, whereas Helium's maximum is below 50 K. Thus, helium is as extremely "hot" at room temperature and even at 77 K. Neon has a maximum inversion temperature 250 K (and hydrogen 205 K). So a multistage refrigerator is necessary to reach 4 K. First, nitrogen is cooled from room temperature to 77 K. Then neon or hydrogen is placed in thermal contact with the liquid nitrogen. The cool hydrogen can then be liquified, reaching about 20 K. Helium gas exchanges heat with that second bath to get below its inversion temperature of 45 K. Finally, the helium can be liquified using the J-T principle as shown in Figure 10-10.

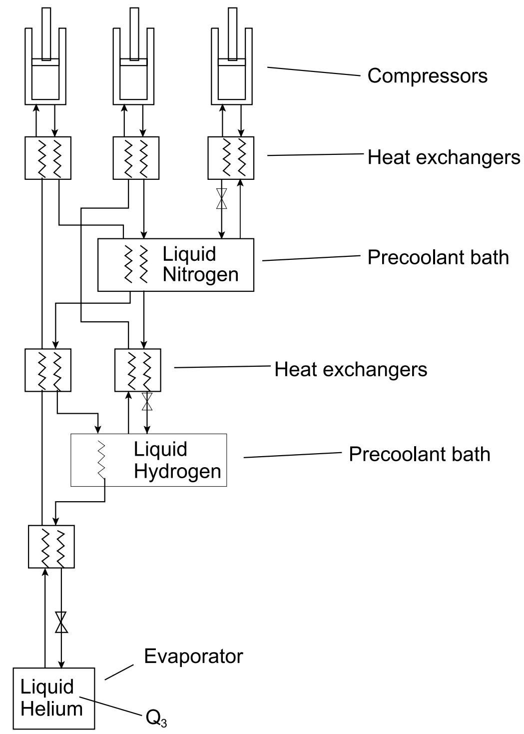

Figure 10-10. Three-Stage Joule-Thomson Liquid Helium Liquifier.

Helium is the only liquid that is able to cool to 4 K, the superconductivity temperature for niobium titanium (NbTi), which is the LTS material used in existing SMES systems. Helium is one of the most difficult gases to liquefy and its unusual properties have created so much interest in the element that it has been the object of more experimentation and theoretical research than any other cryogenic fluid.

Although the Joule-Thomson refrigeration process is the most prevalent method for refrigerating helium, several other methods are effective. Because the Joule-Thomson valve on which the process is based clogs easily and requires expensive down-time to repair, these alternate methods are gaining favor.

Future Technology

If SMES systems used HTS rather than LTS refrigeration, other methods could be employed that would significantly reduce costs of refrigeration and the complexity of the SMES design. The Gifford McMahon refrigeration process could be used up to about 60 K, while other processes would replace the Joule Thomson and Collins methods. Figure 10-11 illustrates the various refrigeration methods and their temperature ranges.

The use of HTS could reduce both the capital and operating costs associated with refrigeration of a SMES unit. In principle, the use of an HTS conductor in a SMES unit might greatly reduce or even eliminate the helium-related and refrigeration costs, reducing SMES capital costs by up to 10%. In addition, power consumption for refrigeration might be reduced by a factor of 50, thereby greatly improving the efficiency of a SMES unit, especially that of smaller units. Operating at 77 K could simplify the operation of a SMES unit and increase reliability. Cool-down time and the forces associated with cool down would be reduced, and conductor stability would be vastly increased.

Some disadvantages are associated with the present HTS technology, however. Should a fault develop during routine operation of the SMES unit, the slower propagation velocity of the normal zone in HTS relative to LTS could make protection of the SMES magnet more difficult. In addition, the present brittleness of HTS materials could make dealing with the forces associated with magnet energization and cool down more difficult. It is expected, though, that advances in technology will yield improvements in cost and a subsequent reduction in the overall costs of a HTS-based SMES unit.

The cost of the coil, which is determined in large part by the cost of the conductor, is the most expensive item in a SMES system. The cost of an HTS conductor is estimated to be about one order of magnitude more than that of an NbTi conductor. Although the likely future cost of HTS is not known, developers hope to achieve a cost comparable with that of Nb_3Sn, which is somewhat more expensive than NbTi. It is estimated that the cost of HTS in magnetic energy systems operating at 77 K is likely to be significantly higher than that of the NbTi conductor used in present designs of SMES units. Because HTS conductor performance increases dramatically at temperatures at or below 20 K, the design of an HTS-based SMES system operating at 20 K might be more feasible. The reduction in refrigeration costs would be less noticeable.

Although an all HTS-based design of a SMES unit does not seem promising, an HTS-based current lead could offer a significant reduction in the refrigeration load associated with the warm-to-cold leads in present SMES designs. Several studies have demonstrated that an HTS-based warm lead operating between 77 K and 4.2 or 1.8 K could reduce the refrigeration load associated with the warm-to-cold leads in present SMES designs by up to a factor of 10.

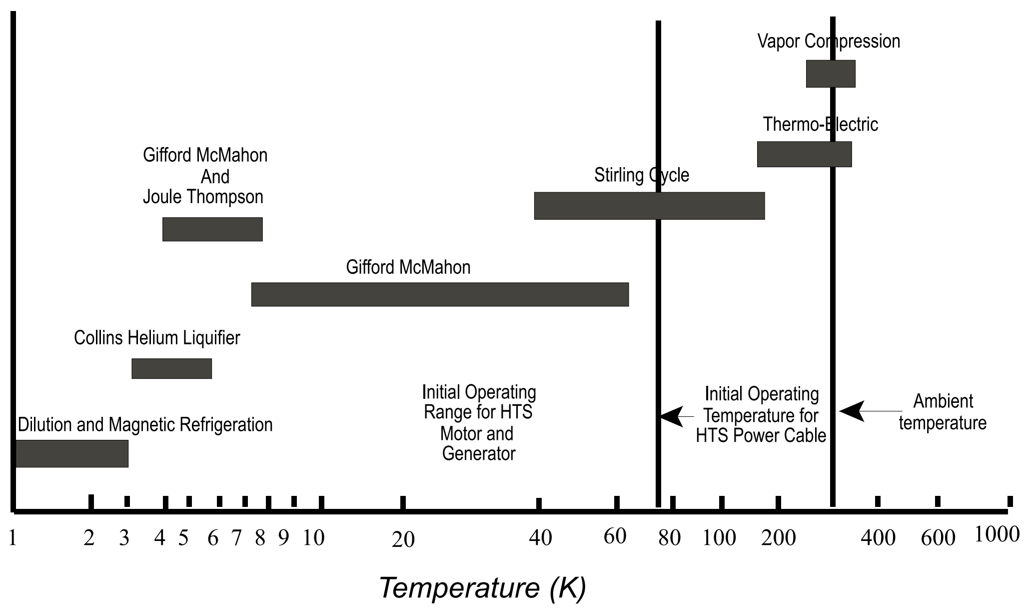

Figure 10-11. Temperature Ranges for Commercial Refrigerators.

Current leads in present SMES units represent a significant part of the refrigeration load. HTS-based leads would greatly reduce both conduction and other losses relative to conventional current leads. At present, at least one developer uses the HTS-based current leads to extend the ability of the liquid helium system to carry over in the event of a loss of refrigeration, rather than decrease the refrigeration capacity.

Present LTS-based SMES consumes approximately 2720 MJ/d, while an HTS-based SMES might only consume 148 MJ/d. As a percentage of storage capacity (1 MJ), both of these numbers are huge compared with a large-scale unit, for which daily consumption for refrigeration is only a few percent of the energy stored.

In addition to the various types of refrigeration techniques available, there are several systems designs from which to choose: once-through (open-cycle) and closed-cycle systems. Open-cycle systems represent the simplest and lowest initial cost refrigerators. It consists of a dewar that is vented to the atmosphere and a bath of liquid cryogen that both absorbs heat generated within the superconductor and intercepts heat penetrating the dewar. This causes the cryogen to evaporate and leave the system. Because the system is passive and contains no moving parts, it is highly reliable. As a method for cooling, however, it is relatively expensive, especially for large applications running for extended periods because the cryogen is not recycled. Table 10-2 shows representative prices for the delivery of various cryogens to a facility.

Table 10-2. Various Cryogens and Price per Liter

Cryogen	Price ($/L)
Helium	4.00
Hydrogen*	.30
Neon	100.00
Nitrogen	.25

* Requires purchase of expensive explosion-proof storage tank

Helium is the only cryogen currently used in LTS-based systems because it is the only cryogen that is liquid at 4 K. In the United States, helium is obtained by separating natural gas deposits, some of which are relatively rich in helium. When obtained through this process, helium is less expensive in the United States than it is in other parts of the world. Despite the relative cheapness of the gas, it has a commodity cost approximately an order of magnitude more than either hydrogen or nitrogen. Consequently, helium is most frequently used in closed-cycle systems.

Ancillary Systems

In addition to the superconducting coil, the PCS and the cryogenics, the major elements comprising a SMES unit are ancillary systems such as vacuum pumps, monitors, controls, heating, and air conditioning systems.

10.1.1.5 How Much Does a SMES System Cost?

The cost of a SMES system consists of the costs of the coil and all associated components, the cost of the PCS, plus the balance of plant costs. The cost of the coil depends on the storage capacity and design of the coil, and is nearly independent of the power rating. The cost of the PCS depends on the design configuration, power rating, and current rating, but is nearly independent of the energy storage capacity of the system.

A commercial 2.2 kWh unit (SSD system), developed by ASC suited for industrial power quality applications has the ability to protect customers from momentary outages, voltage dips/surges, and to correct harmonic distortions and power factors. ASC estimates that the cost of the superconducting energy storage unit represents 30% of the cost of this product. ASC estimates that the PCS contributes 30% of the system cost and that the balance of plant (cryogenics, monitors, controls, electrical connections, housing) represents the remaining 40% of the total system cost. ASC predicts that the storage component cost will decrease by 30% to 50% over the next five years.

IGC has developed a 6-MJ/750-kVA SMES system for which the cost of the storage component is about 70% of the total system cost.

A SMES system proposed for the Railbelt utility network near Anchorage, Alaska would be a 30-MVA system that can provide power for up to 45 seconds (1350 MJ or 375 kWh). This system is expected to improve power quality for the entire Railbelt grid. Of the total projected system cost of $44 million, the magnet and PCS are estimated to cost $20 million each, and the balance of plant will require about $4 million. Figure 10-12 shows a schematic of the costs of various components in a SMES system over a range of energy capacities.

10.1.1.6 What Are the Advantages of SMES?

One of the assets of a SMES coil is that it can release large quantities of power within a fraction of a cycle, and fully recharge in just minutes. This quick, high-power response is very efficient and economical. SMES manufacturers cite controllability and reliability and no degradation in performance over the life of the system as prime advantages of SMES systems. SMES systems are compact, self-contained, and highly mobile; a single semitrailer or equivalent space can deliver megawatts of power. It can be kept at remote locations. Also, SMES units contain no hazardous chemicals and produce no flammable gases. The estimated life of a typical system is at least 20 years.

10.1.1.7 What Are the Challenges to SMES?

SMES devices produce large magnetic fields, and they have the potential to rapidly pressurize their cryostats if their coils go normal (become non-superconducting). Other than these well-understood and managed safety issues, the challenges to SMES are in expanding their energy capacity and gaining market acceptance.

The present niche for SMES is in power quality. The proposed system in Alaska would also address transmission stability. In the future, SMES may be able to store enough energy to support renewal generation sources. Therefore, the main challenge for this new technology lies in the enhancement and full commercialization of smaller systems and the development of systems with greater energy capacity (and affordable cost). There are a number of design issues, which, if addressed, will improve the commercial potential of SMES technology. For small SMES systems, the issues are designing the conductor to minimize parasitic losses such as air conditioning, refrigeration (including HTS leads and coil), and designing the PCS to minimize costs. Because coil characteristics drive PCS requirements, coil and PCS advances will greatly affect each other, as shown in Figure 10-13 projections.

10.1.2 Flywheels and Their Physics

10.1.2.1 What is FES?

Flywheels, one of the first major inventions of man, are devices that capitalize on Newton's first law of physics that states, "an object in motion tends to stay in motion unless an outside force acts on it." Flywheels use the kinetic energy of a spinning mass to do work. The earliest flywheels, such as potters' wheels and grindstones, are still in use today. These relatively simple devices immediately transfer the energy that they receive to some other object. Some more recently developed flywheels also transfer energy immediately; others store energy for dispatch at some later time. Modern flywheels that transfer energy immediately include the flywheels that help

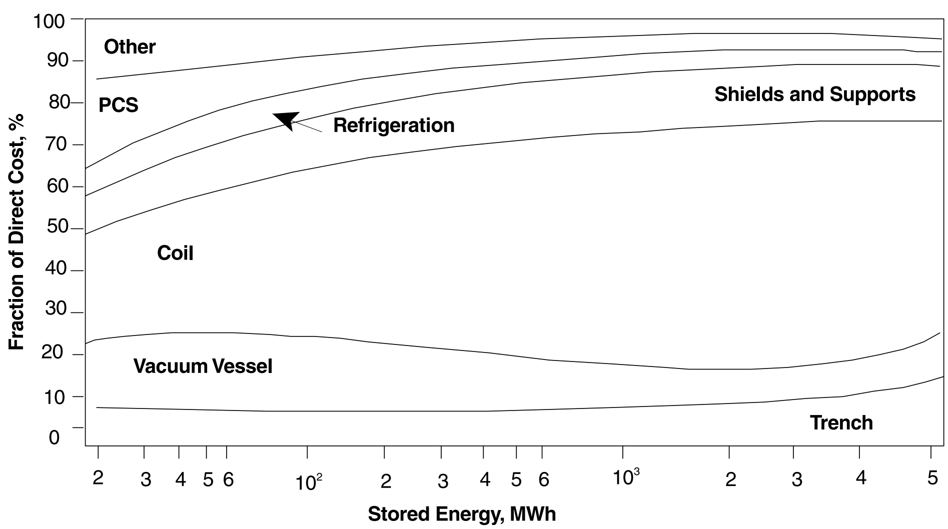

Figure 10-12. Breakdown of SMES Components.

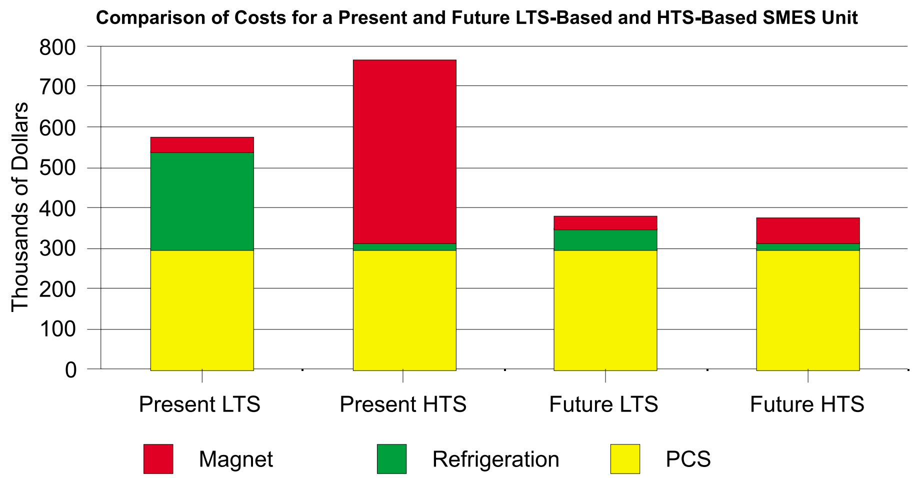

Figure 10-13. Comparison of Costs for a Present and Future LTS-Based and HTS-Based SMES.

start internal combustion engines and that convert and transfer the pulsing bursts of energy from internal combustion engines into smooth continuous power for machine drive trains. In addition, nuclear weapons developers used centrifuges similar to flywheels in enrichment processes for uranium. Flywheels in aerospace systems transfer energy immediately to help orient orbiting satellites and store energy collected by photovoltaic arrays. The ability to store energy for later use, however, is central to recent interest in flywheels as a technology for automotive and electric power applications.

Universities, national laboratories, telecommunications companies, electric utilities, and commercial developers are working independently and in teams to develop fully integrated flywheel energy storage systems (FESS) that collect energy from one source, store it as kinetic energy, and deliver it at another time. Researchers are working on FESS as part of the energy system for efficient, nonpolluting electric vehicles and hybrid vehicles (that depend in part on traditional fuels). Researchers are also developing FESS as a technology for electric power applications. By storing energy that is available during non-peak times or from renewable resources, FESS has potential to provide uninterrupted power for critical loads (the most likely near-term niche), to reduce peak power demands for industrial and commercial customers (a potential mid- or long-term application goal), and to support solar and wind generation (a potential long-term goal). A number of flywheel and flywheel system developers are advertising their intent to bring a wide variety of flywheel products to the electric utility market in the next decade.

In electric power applications, a flywheel system converts electrical energy to mechanical energy; stores the mechanical energy in the form of a rotating flywheel; converts the mechanical energy to electrical energy on demand; and delivers electricity for use. Flywheel systems are relatively complex devices that include a rotor, a shaft and bearings, a motor/generator, power conversion electronics, a vacuum chamber or system, monitors, controls, and possibly a cryogenic refrigeration system.

The flywheel itself is a balanced mass that spins on a fixed axis—the shaft of a motor generator. Some rotors are made from a single piece of metal, often steel. Others are made from resin/fiber composites. As will be discussed in more detail in the next section, the material, size, and shape of the rotor determine the amount of energy that the flywheel can store. In general, a flywheel made from a strong, light material that can withstand fast rotation has superior energy storage capacity. However, strength, weight, and processing requirements cause designers to balance trade-offs between energy storage capacity, safety, and cost. Balancing trade-offs between performance, safety, and cost is a consistent part of the design considerations for the entire flywheel system. Current design strategies for composite materials are using multiple thin layers of materials to get the best combination of properties.

One design consideration is efficiency. Air friction on the rotor and friction of the bearings on the shaft are “outside forces” that “act on” a flywheel and slow its motion. The energy lost when friction slows the flywheel is energy that is not available for dispatch. In addition, the friction detrimentally heats the flywheel and shaft. To limit energy loss and frictional heating, flywheel systems for electric power applications generally include placing the flywheel in a vacuum to eliminate air resistance on the flywheel and low-friction magnetic bearings to reduce friction on the shaft. Some of the magnetic bearings are relatively simple; others are sophisticated active magnetic bearings that have their own monitors and controls; still others are superconducting magnetic bearings. Superconducting magnetic bearings require cryogenic refrigeration to operate. Each additional level of system sophistication increases the efficiency of the system, but also increases initial cost, operating costs, and system complexity. Flywheel system developers are working to find designs that afford the best efficiency and performance at the lowest cost.

10.1.2.2 How Do FES Systems Work?

While the flywheel assembly (including the rotor, shaft, and bearings) is the actual energy-storage device in the system, the motor/generator, the device that converts electricity to mechanical energy and back again, is the component that enables a flywheel system to serve electric power applications. During charging, the motor uses electricity to drive the flywheel and build or maintain its speed. During discharge, the generator uses the rotation of the flywheel to drive the generator and produce electricity. The efficiency of the motor/generator, like friction on the rotor and shaft, dramatically affects the amount of energy that the system loses during conversions between electrical and mechanical energy. Therefore, developers are investigating motor/generators built with superconducting wire to achieve high efficiency and enhance the amount of energy that flywheel systems can effectively store and deliver. Like superconducting magnetic bearings, superconducting motor/generators require cryogenic refrigeration that increases initial cost, operating costs, and system complexity.

The Motor/Generator

In general, a motor/generator takes advantage of current created by a magnet passing over a conducting material. A generator moves a magnet or set of magnets over a coil of conducting wire. The magnetic field causes the electrons in the metal to move in a specific direction, or creates an electrical current, in the coil. As shown in Figure 10-14, a generator in a circuit can provide current to operate an electrical load. In the case of a flywheel system, magnets attached to, embedded in, or that are an integral part of the rotor, move inside the coil, and the induced current is the electrical product from the rotor's rotation (discharge). The motor is essentially the generator operated in reverse to cause rotor rotation from electrical input (charge).

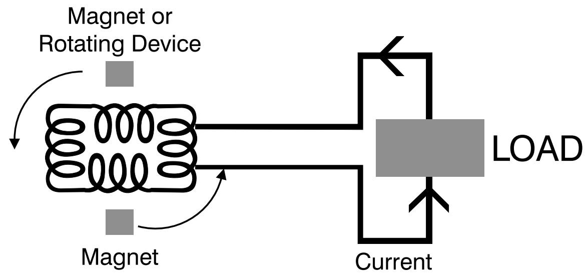

Figure 10-14. Schematic Generator and Load Circuit.

Motor/generators that are commercially available can produce either DC or AC electricity to meet requirements of various electric power applications. However, performance characteristics of flywheels and requirements for standardized electric power have made most flywheel system designers elect variable-speed AC generators (to accommodate the gradual slowing of the flywheel during discharge) and diodes to deliver DC electricity as at least an intermediate product of the system, even if the final product is AC. These design choices help flywheel systems deliver electricity with stable voltage, current, and frequency (for AC).

If an application requires DC electricity, the flywheel system can deliver stabilized DC directly to a DC-to-DC converter. Flywheel systems that serve applications that require utility-grade AC power, however, include an inverter—a device that uses very fast microelectronic switches to convert DC electricity into AC electricity. The flywheel system could deliver either single-phase or three-phase power, as required directly to a transformer that serves the load. At present, flywheel system developers see a role for flywheels to supplement or replace electrochemical batteries in UPSs to critical loads. In that application, the flywheel system could deliver either DC or AC power, or both. Figure 10-15 illustrates how a flywheel module could fit in a UPS to supplement batteries. In this case, the flywheel shares the inverter and other components with the batteries. The integrated system delivers 3-phase AC power to protect a critical load. The ability of the FES to store the energy depends on efficient, long-term storage of energy in a spinning rotor.

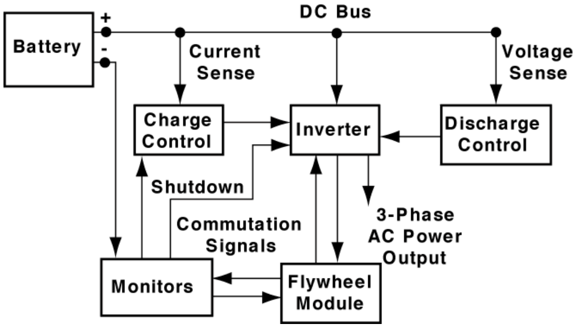

Figure 10-15. Schematic UPS with Flywheel and Battery.

Rotor Strength and Energy Storage

The energy that a flywheel can store is proportional to the square of its rotor speed. The equation for kinetic energy of a flywheel rotor is expressed by Equation 10-9:

$$\text{Kinetic Energy} = \frac{1}{2}(I)\omega^2. \qquad [10\text{-}9]$$

The symbol ω represents the flywheel's rotational velocity, and the symbol *I* represents the flywheel's ability to resist changes in rotational velocity (this ability is called "the moment of inertia"). This equation shows that flywheels with larger moments of inertia can store more energy than flywheels with low moments of inertia. The moment of inertia for any object is a function of its shape and mass. The dominant shapes for the flywheels under development are a solid circular cylinder or disk (the shape that approximates a solid steel flywheel) or a hollow circular cylinder (the shape that approximate a steel or composite rim attached to a shaft with a web). The moment of inertia for a solid circular cylinder (like the one represented in Figure 10-16) is expressed by Equation 10-10:

$$I = \frac{r^2 ma}{2}. \qquad [10\text{-}10]$$

Where *r* represents the radius of the cylinder; *m* represents mass/unit volume; and *a* represents the length of the cylinder. This equation is similar to the equation for a hollow circular cylinder (like the one shown in Figure 10-17). However, the equation for the hollow cylinder addresses the solid material between the outer radius r_o, and the inner radius r_i; appropriately. Equation 10-11 for a hollow cylinder accounts for the absence of material between the axis of rotation and the inner radius.

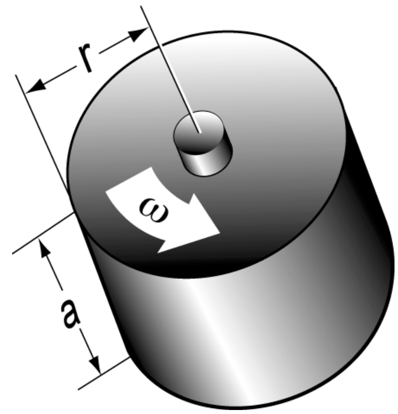

Figure 10-16. Solid Cylinder Rotating About its Axis with Angular Velocity Omega.

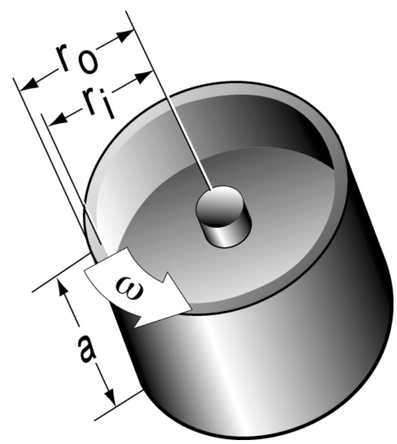

Figure 10-17. Hollow Cylinder Rotating About its Axis with Angular Velocity Omega.

$$I = \frac{\pi ma\left(r_o^4 - r_i^4\right)}{2}. \qquad [10\text{-}11]$$

If the specific mass, radii, and length of a solid cylinder and hollow cylinder are identical, the moment of inertia for the solid cylinder is greater than the moment of inertia for the hollow cylinder.[4] The moment of inertia for cylinders increases with increasing length. These relationships indicate that the ideal flywheel would be a long, solid cylinder. However, the moment of inertia, while important, cannot completely define the ideal shape. As the flywheel spins,

[4] For cylinders with specific mass, length (a), and outer radii of 1, a solid cylinder has a moment of inertia that equals π/2. The moment of inertia for a hollow cylinder equals $(\pi\ (1 - r_i^2))/2$, something less than the moment for a solid cylinder; both types have a moment of inertia that increases proportionately to length a.

stresses develop in the flywheel material, and the shape of the flywheel affects the magnitude of the stresses. If the stresses exceed the strength of the material, the flywheel will break apart. Therefore, the stresses that certain shapes promote and the strength of the material from which the flywheel is made must also be considerations in designing its shape.

Stresses in a Solid Object

In a one-dimensional object (like the thin metal wire shown in Figure 10-18), an equation known as Hooke's law completely defines the stress that an applied axial force causes in the material, as expressed by Equation 10-12:

$$\text{Stress}_1 = \sigma_1 = E_{\varepsilon_1}. \qquad [10\text{-}12]$$

The symbol E stands for Young's modulus, a constant for each material that represents the material's elastic properties; ε_1 is the symbol for strain, or change in length of the object.

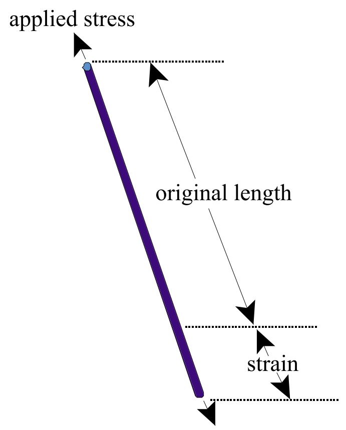

Figure 10-18. One-Dimensional Object Under an Applied Axial Stress.

In a two-dimensional object made from an isotropic material (a material that has identical strength and elasticity in all directions like the thin metal disk shown in Figure 10-19), Hooke's law defines the stress in the material in only one dimension (a plane perpendicular to the applied force). Two more equations are necessary to define other stresses in the material. The stress in the plane parallel to the applied force is expressed by Equation 10-13:

$$\text{Stress}_2 = \sigma_2 = E_{\varepsilon_2} = E_{\nu\varepsilon_1}. \qquad [10\text{-}13]$$

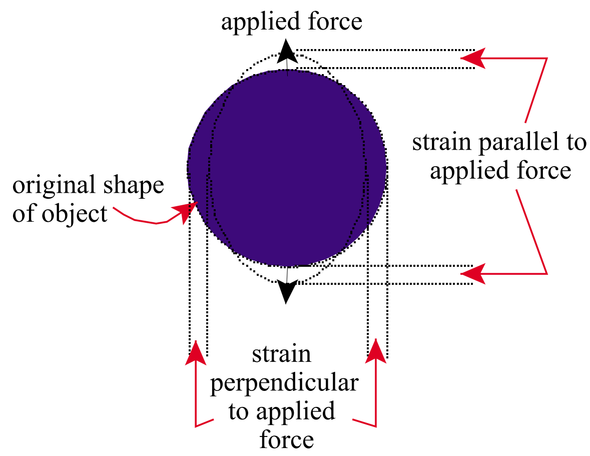

Figure 10-19. Two-Dimensional Object Under an Applied Axial Stress.

The symbol, ε_2, represents the change in length in the direction perpendicular to the applied force, and ν is a constant known as Poisson's ratio that is a measure of a material's tendency to develop stresses in directions perpendicular to applied forces. The material's tendency to shear as a result of the applied force is expressed by Equation 10-14:

$$\text{Sheer Stress}_{12} = \tau_{12} = G\gamma_{12} \qquad [10\text{-}14]$$

G is a material constant called the shear modulus that represents the material's tendency to shear under an applied force, and γ is the shear strain or distortion of the material that the applied force causes.

In a three-dimensional object (an object that has significant length, height, and thickness like the cube shown in Figure 10-20), calculation of the stresses requires multiplying a six-by-six matrix of material constants, c_{ij}, called elastic stiffness coefficients.[5] The complexity of the mathematics reflects the complexity of the interaction of the stresses that an applied force creates in the material. And, as shown by Equation 10-15 for the stress perpendicular to the applied force, the interaction can increase the stresses that the material experiences. In composite materials (which are nonisotropic), differences in the strength and elasticity of the material in different directions makes the interaction of stresses in three dimensions

[5] For a complete discussion of stresses in solid objects, please refer to *Deformation and Fracture Mechanics of Engineering Materials*, third edition, Richard W. Hertzberg, John Wiley & Sons, Inc., 1989.

even more complex.[6] And, the fact that the stress in a flywheel rotor results from rotation, not simple axial tension, requires the use of polar rotation instead of rectangular rotation. Therefore, the equation for the stresses in a rotor are in terms of the radius of the rotor layers, the speed of rotation, and the rotor's material properties.

$$\sigma_{yy} = c_{21}\varepsilon_{xx} + c_{22}\varepsilon_{yy} + c_{23}\varepsilon_{zz} + c_{24}\gamma_{yz} + c_{25}\gamma_{zx} + c_{26}\gamma_{xy} \quad [10\text{-}15]$$

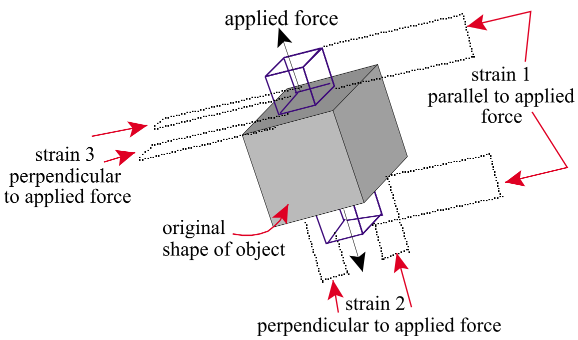

Figure 10-20. Three-Dimensional Object Under Applied Axial Stress.

Without three-dimensional interaction of material stresses, a long solid circular cylinder would be the ideal shape to achieve a high moment of inertia and high energy capacity for a flywheel. However, stress interactions in such a long, thick object limit the practical dimensions of the rotor. In fact, safety issues stemming from the potential for catastrophic flywheel failure are major concerns in flywheel system design. Therefore, designers balance decreases in flywheel energy capacity with improvements in the ability of the flywheel to safely operate. Many of the resultant flywheel designs are based on a hollow cylinder (Figure 10-21), in which material stresses created by three-dimensional effects are minimized.[7] In short designs, the two stresses of primary concern are the stress in the radial direction of the flywheel and the stress in the hoop direction of the flywheel. Designers optimize the length and thickness of the rotor to be able to predict rotor stresses adequately with an equation for each of these dominant stresses.

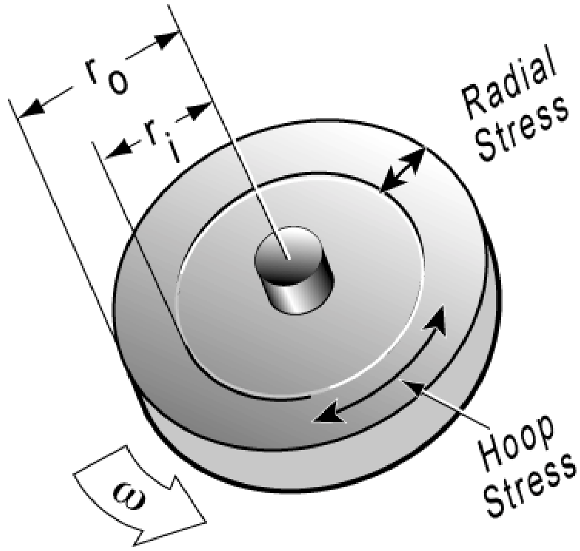

Figure 10-21. Stresses in a Short, Hollow Cylinder Rotating About its Axis with Angular Velocity Omega.

Radial stress is expressed by Equation 10-16:

$$\sigma_r = \frac{3+\nu}{8}\rho\omega^2\left(r_o^{\,2} + r_i^2 - \frac{r_o^{\,2} r_i^2}{2} - r^2\right). \quad [10\text{-}16]$$

The symbol ρ represents the mass density of the material, ω is the rotor speed, ν is Poisson's ratio, r_o is the outer radius of the rotor, r_i is the inner radius of the rotor, and r represents any radius within the rotor. Equation 10-17 defines the hoop stress:

$$\sigma_\theta = \frac{3+\nu}{8}\rho\omega^2 \left(r_o^{\,2} + r_i^{\,2n} + \frac{R^2 r_i^{\,2}}{2} - \frac{1+3\nu}{3+\nu} r^2\right) \quad [10\text{-}17]$$

Figure 10-22 shows graphs of Equations 10-16 and 10-17. The maximum radial and hoop stresses develop inside the wall of the cylinder; the maximum radial stress occurs at the center of the rotor wall; the maximum hoop stress occurs at the inner surface of the cylinder.

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6 For a complete discussion of stresses in fiber-reinforced composites, please refer to *Analysis and Performance of Fiber Composites*, Bhagwan D. Agarwal and Lawrence J. Broutman, John Wiley and Sons, Inc., 1980.

7 At Penn State, researchers are developing multiaxially fiber-reinforced, elastomeric composite cylinders with long, epoxy/fiber composite rotors to increase the axial strength of the rigid motor without inducing three-dimensional stress interaction and the associated loop of hoop ductility.

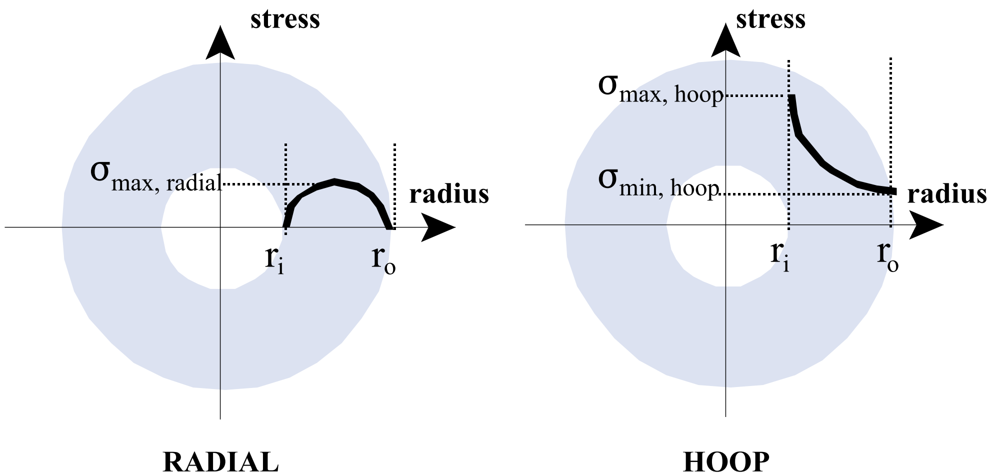


Figure 10-22. Radial and Hoop Stresses in a Rotating, Short, Hollow, Cylinder Made from a Rigid Elastic Material.

Failure Modes of Rotating Cylinders

The locations of the maximum stresses will make crack initiation more likely at the inner surface and inside the wall of the rotor. Under operation-induced stresses, the cracks grow; when they reach the outer surface of the flywheel, the rotor can break in large fragments (Figure 10-23) and fail catastrophically. The most likely location of crack initiation and the most prevalent direction of crack growth depend on the ratio of the inner and outer radii of the rotor, β, and the speed at which the rotor operates Figure 10-24.

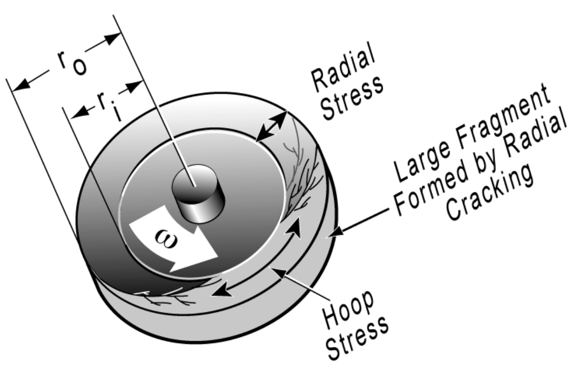


Figure 10-23. Cracks Propagating from the Inner Radius and Mid-Wall of a Hollow, Cylindrical Rotor.

While the optimum β varies somewhat for each composite, theoretical predictions of the failure behavior of one carbon-epoxy material demonstrates that designers can control the mode of failure by optimizing rotor thickness. As shown in Figure 10-25, rotors with an optimum thickness, or β, fail at much higher speeds than rotors that are too thin or too thick. The mode of failure also depends on the thickness ratio of the rotor. This understanding allows flywheel developers to design rotors that operate safely at higher speeds, and fail more predictably. But failures still occur. Even with optimized βs, designs reduce, but do not eliminate, catastrophic failure and concerns over safety. For this reason, researchers are exploring a number of other design strategies that address safety issues, maintain acceptable energy capacity, and are amenable to cost-effective manufacturing.

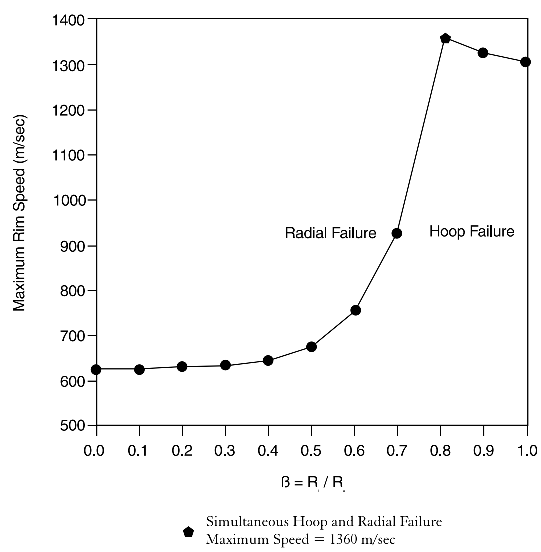


Figure 10-24. Maximum Rim Speed and Associated Failure Modes of Carbon-Epoxy Composite Rotors with 0<β<1.

One approach is to design flywheel containment vessels to keep rotor shrapnel where it cannot cause damage. The containment designs include thick steel and/or concrete chambers, underground vaults, and—a more recently considered option—energy-absorbing, fiber-reinforced composite chambers. A second approach to prevent damage is to avoid catastrophic failures and design flywheels that fail safely.

Four "fail-safe" rotor design strategies are prevalent; all four capitalize on material properties of polymer/ fiber composites. Strategy 1 employs epoxy/fiber composite rotor materials that disintegrate into "cotton candy" rather than breaking into shrapnel that can cause damage. While this approach was prevalent in the late 1980s and early 1990s, none of the developers contacted in this investigation still considers this option a desirable strategy. Instead, the focus at present is on the other methods.

Strategy 2 relies on the nonisotropic behavior of fiber-reinforced composites to prevent catastrophic rotor failure. Many fiber-reinforced composite manufacturing processes produce materials in which the fibers are all oriented in one direction. Because the fibers are the constituent that contributes most of the strength to the composite (the matrix is essentially an adhesive to hold the fibers together), these materials have different strengths in different directions. As shown in Figure 10-25, uniaxially reinforced composites withstand higher loads parallel to the fiber orientation and lower loads transverse to the fiber orientation. Some researchers are attempting to use this property to build flywheels that fail safely.

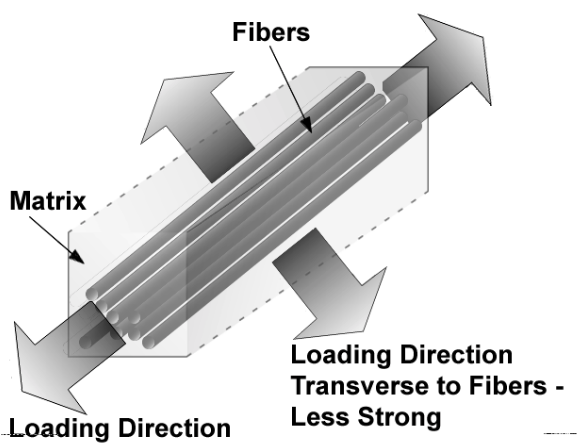


Figure 10-25. Strength of Uniaxial Fiber-Reinforced Composite.

Specifically, the researchers are making fiber-reinforced composite rotors with circumferentially oriented fibers. Because the fibers are stronger than the matrix and the bond between the fiber and the matrix, the rotor is stronger around its hoop than across its radius. Therefore, as shown in Figure 10-26, the flywheel is more likely to develop circumferential cracks than radial cracks. Circumferential cracks are much less likely to produce free-flying projectile fragments. And, cracking causes the rotor to be somewhat eccentric. Resultant vibration early in the development of the crack occurs well before catastrophic failure occurs.

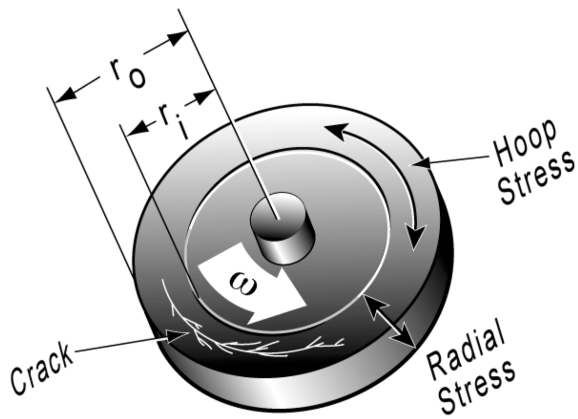


Figure 10-26. Circumferential Cracks Propagating Around the Wall of a Hollow, Cylindrical Rotor.

Because sensors can be installed in a flywheel system to detect vibration, a system with properly calibrated vibration sensors, a carefully designed rotor, and appropriate monitors and controls can allow a computerized control system or a human operator to arrest operation before catastrophic failure occurs. Circumferential cracks at different distances from the axis of the flywheel have characteristic vibration frequencies, and that flywheels with circumferential cracks can safely operate at reduced speed. If developers are able to completely correlate crack size and location, vibration frequency, and safe operating speeds, flywheel system designs may emerge that allow cracked rotors to operate at lower speeds until rotor replacement is possible.

Strategy 3, another fail-safe strategy, also uses vibration as a measure of crack-detection before catastrophic failure of the rotor. But, instead of measuring the vibration caused by the rotor being "out-of-round" like the previous method, this strategy measures vibration caused by bending along the length of a relatively long rotor. As shown in Figure

10-27, a longer cylindrical rotor that develops cracks in any of its composite layers is prone to bending. The bending causes eccentric rotation and measurable vibration. An electronic or human operator can stop the device when vibration levels indicate that an unsafe condition is developing. In the extreme case, the cylinder would actually contact the vacuum wall and eventually slow to a stop.

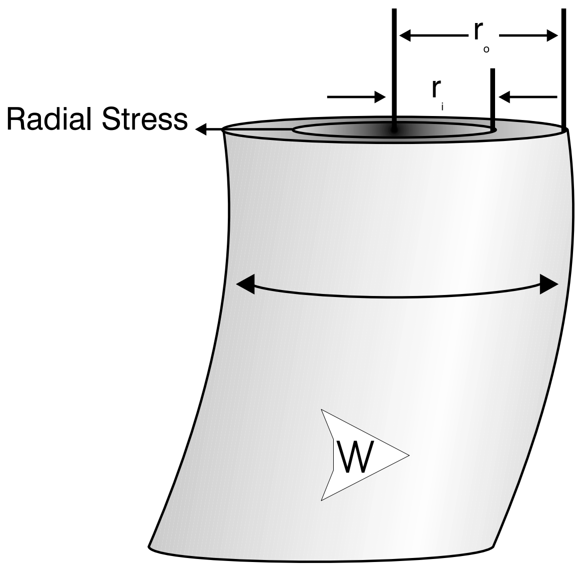


Figure 10-27. Damaged Rotor Cylinder Bending and Causing Detectable Vibration.

Strategy 4 promotes safe failures and employs circumferentially-oriented fibers, but is a long-term goal rather than a near- or mid- term likelihood. This fail-safe design depends on the performance of a unique matrix of rubbery elastomeric materials. Elastomers respond to loading differently than elastic materials[8] (see Figure 10-28). These differences make researchers[9] believe that maximum stresses in a rotor made with an elastomeric matrix will occur near the outside edge of the flywheel as opposed to occurring at the inner surface or middle of the ring as they do in flywheels with rigid elastic matrices (compare Figures 10-22 and 10-28).

As shown in Figure 10-29, failures that do occur in an elastomeric rotor begin near the outside surface of the flywheel, and propagate only a short distance to the outside surface. If spin testing of elastomeric-based rotors fulfills expectations, this design would produce rotors that “fail” by shedding small shreds of material rather than dangerous large projectiles. This could also allow a flywheel system that has a rotor with operation-induced damage to continue to operate (probably at a lower speed) until rotor replacement is possible.

Practical flywheel designs are hybrids of the approaches discussed. One design is based on the assembly of concentric rings into a multi-layered composite rotor, as shown in Figure 10-30, in which each ring has an optimum thickness. The layers can be made from the same materials or from different fibers or matrices. When the materials differ, the design is such that relatively small amounts of expensive, strong, resilient materials form outer layers reinforce inner layers of less expensive, less robust materials (a discussion of materials for composite rotors follows later in this section). In multi-layer designs, research is needed to optimize the ratio of the inner and outer radii (the β) of each layer for high-speed (high-energy) operation. Researchers are also exploring a variety of manufacturing processes including continuous filament winding and press-fitting to enhance rotor service life and reduce the cost of multi-layered composite rotors.

The rotor design strategies discussed above attempt to find an optimal trade-off between the amount of energy that the flywheel can store, the amount of stress that the flywheel experiences, the strength of the flywheel material, and the feasibility of manufacturing. Implicit in all of these considerations is the speed at which the flywheel rotates. Recall from the earlier discussion (Equation 10-9) that the energy of the flywheel is related to its moment of inertia and angular velocity.

In fact, energy capacity increases exponentially with increased rotational velocity. However, the maximum practical speed of a flywheel (like the maximum practical moment of inertia) has limits that depend on the stresses that develop in a rotating flywheel. As shown earlier, the equations for radial

8 For a complete discussion of elastomers, please refer to *Engineering Materials and Their Applications*, fourth edition, Richard A. Flinn and Paul K. Trojan, Houghton Mifflin Company, 1990.

9 Researchers at Penn State University are investigating elastomeric matrices for fiber-wound composite rotors that have maximum radial and hoop stresses near the outside surface of the flywheel. Such flywheels would ‘fail safe’ because small amounts of material would shed from the edge of the rotor rather than producing large fragments that fly loose as shrapnel.

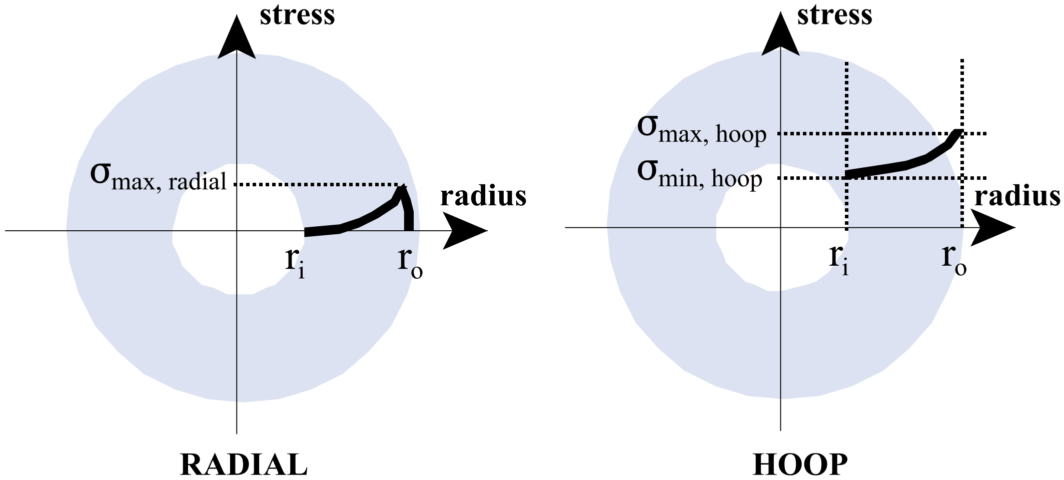


Figure 10-28. Radial and Hoop Stresses in a Rotating, Short, Hollow Cylinder Made from a Resin/Fiber Composite with an Elastomeric Matrix.

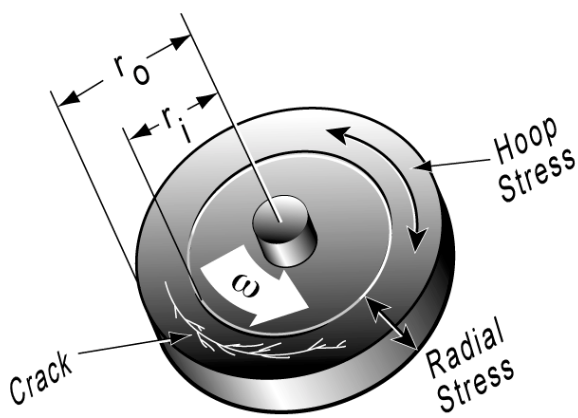


Figure 10-29. Circumferential Cracks Propagating Near the Outer Edge of a Hollow, Cylindrical Rotor Made from a Fiber-Reinforced Elastomer.

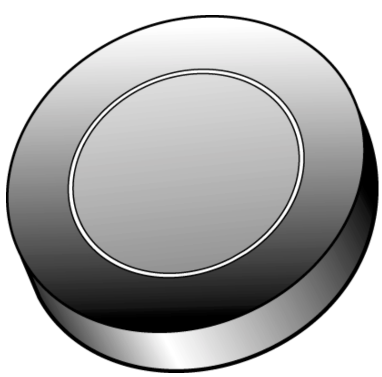


Figure 10-30. Multi-Layer Composite Rotor Concept.

and hoop stresses in a short, cylindrical flywheel (Equations 10-16 and 10-17) show that material stresses also increase exponentially with rotational velocity. Because the strength of the rotor materials limits the maximum operating stress, and stress and energy capacity are both functions of the flywheel velocity, the strength of the rotor materials limit the energy capacity of flywheels. Flywheel developers have materials and processing methods that produce rotors that perform well at low speeds (7,000 rpm). While some materials and processing methods exist to produce rotors that perform at high speeds (up to 200,000 rpm), materials and processing R&D are critical issues in the development of flywheels with energy capacities appropriate to the mid- and long-term goals for flywheel systems. At present, developers are exploring a wide range of flywheel designs that include monolithic metallic rotors for low-speed operation and low-density, high-strength composites rotors that operate at very high speeds. The steel rotors are essentially isotropic materials that are simpler to design, but less versatile. The composite rotors are complex, but they are very versatile materials that will require some additional R&D but have promise to increase energy capacity.

Rotor Materials

The characteristics of rotor materials that are of interest to flywheel developers include density, strength, cost, processability, and availability. The table below presents these characteristics for the materials that are currently prevalent in flywheel development. Table 10-3 also presents the characteristics of fibers and matrices commonly used or under development for rotor composites.

Table 10-3. Characteristics of Materials for Monolithic and Composite Rotors

Material	Density (kg/m^3)	Tensile Strength (GPa)	Cost ($/kg)	Assets/Liabilities
Monolithic Material				
4340 Steel	7700	1.52	1	available, inexpensive, well understood mass-limited
Fibers for Composites				
E-glass	2000	.1	11.0	available, inexpensive composite complexity, weak
S2-glass	1920	1.47	24.6	available composite complexity
Carbon T1000	1520	1.95	101.8	available, strong composite complexity, very expensive
Carbon AS4C	1510	1.65	31.3	available, strong, relatively inexpensive composite complexity

Rotor Manufacturing Processes

For flywheels made from stainless steel, the manufacturing process includes die casting, machining, heat-treating (several times), and balancing the rotor. These processes are conducted at very high temperatures and are time-consuming. Despite the expense of such processes, steel rotors are relatively inexpensive in comparison with composite rotors.

For composite flywheels, the manufacturing method[10] chosen depends on the matrix material fibers from which the composites are to be made. The prevailing composite rotor manufacturing processes are filament winding and resin-transfer molding. In the filament-winding process, a continuous bundle, or tow, of resin-impregnated fibers wraps over a mandrel to form a part. The most common filament winding process, shown in Figure 10-31, uses a machine to drive a rotating mandrel; uses spools, feeders, and an application head to dispense fibers; and has a resin bath through which the fibers pass to become impregnated. This process is called “wet-winding” and is appropriate for both rigid elastic matrix materials and elastomers. Fibers suitable for filament winding include E- and S-glass, carbon and aramids (Kevlar). While some fibers and matrices require specialized treatments, all viable material combinations undergo a similar basic treatment during filament winding.

[10] For a complete discussion of composite manufacturing, refer to *Fundamentals of Composites and Manufacturing: Materials, Methods, and Applications*, A. Brent Strong, Society of Manufacturing Engineers, 1989.

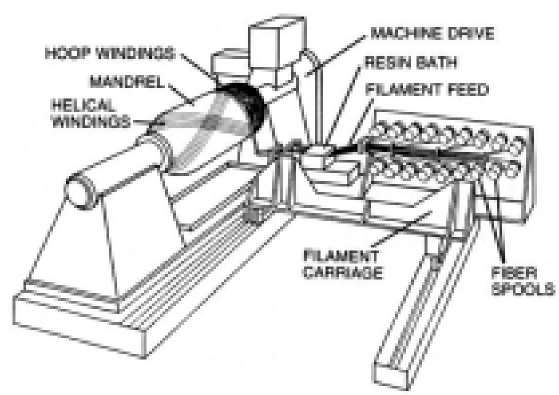


Figure 10-31. Filament-Winding Machinery Including Mandrel, Application Head, Filament Tows, Resin Bath, Fiber Feed, and Spools.

During filament winding, the mandrel rotates, and fiber tows draw from the spools and pass through the fiber feed, resin bath, and the application head. The application head moves longitudinally over the length of the mandrel to deposit the tows evenly. The part thickness increases as successive layers of fibers and resin wrap around the mandrel. Filament winding can change fiber spools or types during the process that allows the manufacture of multi-layer rotors in a single continuous process. Several researchers have investigated press fitting several rings with carefully designed inner and outer radii to manufacture multi-layer rotors. However, most research is moving away from press fitting and toward continuous processes.

Issues involved in filament winding include the pot life of the resin, cure time of the resin, tension of the fibers, and the maximum rate at which layers can deposit on the mandrel without resin squeeze-out or fiber-buckling. At present, researchers are investigating in-situ curing and incremental (or staged) curing to reduce the processing time and cost of filament-wound rotors by increasing maximum deposition rates. Most developers indicated, however, that the cost of carbon fiber, not manufacturing speed, is the real economic hurdle for commercial rotor manufacturing.

Resin-transfer molding (RTM) is another process that researchers have investigated to make flywheel rotors. RTM uses an injection-molding machine to impregnate a mat or weave of reinforcement fibers that are strategically oriented to achieve optimum strength for a particular part shape. As shown in Figure 10-32, a resin-injection machine forces resin into a mold that contains a fiber reinforcement. When the resin cures sufficiently, a clamping press that holds the mold together opens, and the part can be removed. RTM requires resins that have low viscosity and a relatively long pot life, and can use glass, carbon, or aramid fibers for reinforcement. However, the fibers generally must be in a mat or weave so that they do not migrate during resin injection and so that their deliberate orientation enhances the strength of the part.

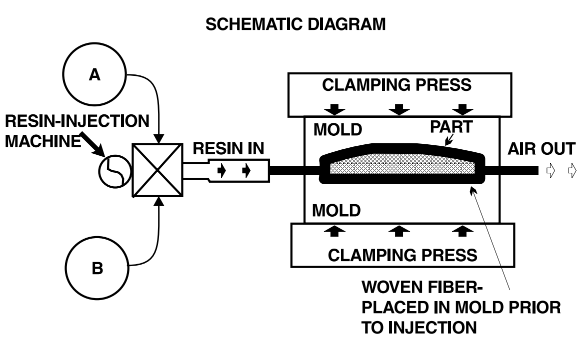
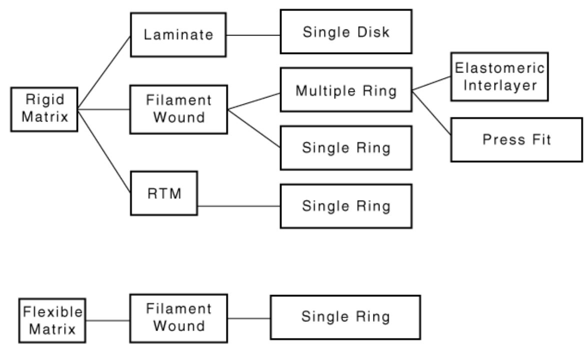


Figure 10-32. RTM Equipment Including Resin-Injection Machine, Clamping Press, Mold, and Fiber Reinforcement.

The design of the mold and the resin-injection speed are critical to distributing resin uniformly and wetting the reinforcement fibers without moving them. Therefore, RTM molds have vents to allow air to push out ahead of the resin and tight temperature controls to promote even resin curing. As shown in Figure 10-33, RTM is used in the manufacture of rigid, but not elastomeric, matrix composite rotors. In general, RTM is a process most suited to the manufacture of large parts, especially for high-volume manufacturing of large parts. Because RTM is faster than filament winding, RTM might gain dominance in rotor manufacture if significant markets emerge for flywheel systems and high-volume manufacturing is necessary. However, material properties of RTM-manufactured parts are not as consistent as filament-wound parts, and RTM rotors may not have predictable enough performance and service lives to meet applications requirements. A potential area of research for RTM processes could be improved consistency in the material properties of RTM parts.



Source: Presentation by Charles Bakis of Penn State University, Feb. 16, 1998

Figure 10-33. Manufacturing Processes for Composite Rotors.

At present, filament winding dominates the other composite manufacturing processes for rotors with either rigid or elastomeric matrices. Also, filament winding is the only process by which developers have made multiple-ring rotors.

Bearings

For the near-term niche application of flywheels as a supplement or replacement for electrochemical batteries in UPS systems, bearings are a less important issue than mid-term and long-term application goals. For applications that require flywheel systems to store or dispatch energy for longer periods of time, many researchers believe that bearings are the critical issue for flywheel system success. Ideal flywheel system bearings have low friction at high speeds and have long service lives. Magnetic bearings approach this ideal.

Magnetic bearings do not contact the rotor shaft. Instead they suspend/levitate the shaft with magnetic fields. Because relatively small magnetic fields are the only resistance that magnetic bearings exert on the rotation of the flywheel shaft, magnetic bearings are more efficient than mechanical bearings. Because magnetic bearings do not contact the shaft and have no moving parts, they experience little wear and require no lubrication. Magnetic bearings can operate in the vacuum that is necessary for efficient flywheel operation, and they can isolate the rotor from external vibrations.

In addition to levitating/suspending the flywheel shaft, "passive magnetic bearings" also provide alignment and stability using magnetic fields. One type of passive magnetic bearing is made from powerful rare-earth, permanent-magnet elements (neodymium-iron-boron and samarium-cobalt). These permanent magnets also have innovative geometries that help shape the magnetic fields that support and stabilize the spinning rotor shaft. In contrast to a passive magnetic bearing, an "active magnetic bearing" suspends/levitates the flywheel shaft with its magnetic field, but employs active position sensors and electronic feedback circuits to align and stabilize the shaft. Developers are working to develop bearings that can carry the full weight of the rotor without needing to be replaced after each incident (multi-incident bearings).

Flywheel developers are using both passive and active magnetic bearings and are beginning to explore magnets made from HTS magnets. While HTS magnets require cryogenic cooling to 4 K (liquid nitrogen temperature), they have even lower friction than other magnetic bearings, and increase system efficiency even further. HTS materials also have an intrinsic property called "flux pinning" that acts as a built-in stabilizer for the rotating flywheel shaft.[11]

Stability of the rotor is essential in a flywheel system. If the shaft assembly and bearing response is insufficiently rigid, the shaft could potentially escape from the designed axis-of-rotation; the rotor could contact the containment vessel walls and lose energy or—in the extreme case—cause complete flywheel failure. Likewise, a shaft or bearing assembly that is too rigid is detrimental. A shaft assembly that is too rigid because of excessively tight bearing tolerances, magnetic stiffness, or other assembly constraints can increase stress in the rotor and shaft (through torque on the shaft that transmits to the rotor) and promote premature failures. Through too tightly constraining the shaft to its designed axis-of-rotation, a too rigid shaft/bearing assembly can also slow the flywheel and reduce system efficiency. In addition to investigations to determine optimum bearing and shaft-assembly rigidity, researchers are attempting to find an optimal balance between application requirements for power and energy and the performance, cost, and availability of mechanical, magnetic, and HTS magnetic bearings for flywheel systems. Table 10-4 summarizes selected attributes of mechanical and magnetic bearings.

Containment - Vacuum Integrity and Safety

High-performance flywheels must operate in a vacuum to minimize air friction on the rotor and the associated kinetic energy loss, rotor heating, and rotor instability. Therefore, the flywheel system must include a vacuum containment vessel. The system may or may not also include a vacuum pump to maintain the vacuum. In a simple system, the vacuum might be at 10 to 100 μTorr. In a system with a sophisticated vacuum pump, the vacuum could be as low as 0.1 μTorr.

The vacuum vessel also acts as part of a safety enclosure to protect people and equipment from injuries that could occur from unconstrained catastrophic rotor rupture. Some designs deliberately consider the vacuum chamber as the inner-most layer in an engineered multiple-barrier containment system to prevent rotor debris from flying free. As discussed in the section on rotors, containment system designs can include thick steel, concrete chambers, and/or underground vaults. Alternatively, the containment could be based on energy-absorbing, fiber-reinforced composite chambers.

Thick steel and concrete safety containment systems are heavy. These bulky containment systems, like underground vaults, require a lot of space, are expensive, and are not portable. Therefore, steel, concrete, and underground containment vaults are not well suited to flywheel systems for electric power applications that require light weight, small size, low cost, and easy portability. Researchers have invested considerable effort in finding alternative vessel

[11] Section 10.1.4 of this report provides an overview of high-temperature superconductor properties. For a complete discussion, refer to Sheahan, Thomas P., *Introduction to High Temperature Superconductivity,* Plenum Press, New York, 1994.

Table 10-4. Attributes of Bearings

Bearing Type	Approximate Power Loss (watts)	Advantages	Disadvantages
Air bearings	on the order of 1000	Τ acts directly on rotor	Ξ tight tolerances Ξ requires expansion compensation
Foil bearings	on the order of 1000	Τ acts directly on rotor Τ tolerates clearance variations	Ξ requires smooth surface on rotor Ξ wear & replacement
Roller/ball	50–200 + due to seals	Τ simple Τ low cost Τ compact	Ξ limited to rotors smaller than 30 Kg Ξ needs lubrication, seals, hubs, axle Ξ wear & replacement
Friction wheel	60 + due to seals	Τ low losses Τ adequate load capacity	Ξ complex Ξ needs lubrication, seals, hubs, axle
Permanent magnet	virtually zero	Τ acts directly on rotor Τ tolerates clearance variations Τ works in vacuum Τ requires no electronics	Ξ unstable Ξ used in conjunction with other types
Active magnet	10–100	Τ acts directly on rotor Τ tolerates clearance variations Τ works in vacuum Τ theoretically low O&M	Ξ large space requirements Ξ high cost Ξ requires “touchdown bearings” Ξ reliability issues
HTS	10–100	Τ low loss Τ high forces Τ theoretically low O&M Τ works in vacuum	Ξ high cost Ξ immature technology Ξ cryogenic refrigeration costs Ξ complex system

materials and designs, or designing flywheel rotors that fail safely (discussed in the section on rotors) and for which a vacuum chamber might provide sufficient containment. Some design strategies combine efforts to make fail-safe rotors and to develop strong, resilient, light, small, inexpensive, and portable containment vessels.

Fiber-reinforced composites have the best potential to achieve an optimum combination of strength, resilience, weight, size, and cost. Some of the material selections and manufacturing processes that have been developed for tanks for other applications (maritime, space, and fuel containment) are also appropriate for composite flywheel containment vessels. Many of the materials and manufacturing processes for composite rotors are also appropriate for flywheel containment vessels.

Some developers believe that containment for safety will be a non-issue. Instead of trying to design vessels, vaults, or fail-safe rotors, FES users may simply place the units in access-restricted areas similar to those in which conventional turbines operate in electric power plants.

10.1.2.3 What are the Advantages to FES Systems?

FES systems, as their developers envision them with multi-incident bearings, will have exceptionally long service lives and low life-cycle costs as a result of minimal O&M requirements. FES systems are compact and self-contained, and they contain no hazardous chemicals nor do they produce flammable gasses.

10.1.2.4 What are the Challenges to FES?

Containment remains an issue for all rotating energy equipment, and FES developers will have to address this concern with selection of sites, vault design, and/or material selection.

Flywheel developers use materials and processing methods that produce rotors that perform well at a wide range of rotor speeds. However, materials and processing R&D are critical issues in the development of flywheels with energy capacities appropriate to the mid- and long-term goals for flywheel systems. At present, developers are exploring monolithic metallic rotors for low-speed operation and low-density, high-strength composite rotors that operate at very high speeds. These two classes of devices represent two sets of R&D needs.

For rotors made of monolithic materials such as the one shown in Figure 10-34, areas of necessary research include bearing improvement and integration with traditional electrochemical UPS devices. For composite rotors, areas of necessary research include improved manufacturing processes, understanding fatigue in the constituents of the composites and in the overall composite, and chemical degradation mechanisms of the composites and the effects of degradation phenomenon on the performance and service life of the rotor and the components around it. (For example, will out-gassing from the rotor matrix in the vacuum chamber make vacuum pumps a requirement for systems that include composite rotors?). Significant numbers of "spin-tests" are necessary before flywheel developers will be able to accurately predict the performance and service life of composite rotors in commercial flywheel systems. R&D of health-monitoring technologies for composite rotors (similar to health monitoring of airplane wings) would help researchers develop the necessary performance and service life data. All of these activities will promote necessary standards for manufacturing, qualifying, testing, and operating FES devices. These types of standards will be essential for commercial systems with composite rotors to gain widespread acceptance in the electric power industry.

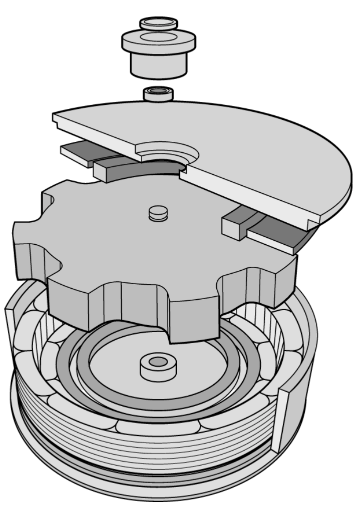


Figure 10-34. Steel Flywheel and Housing as Developed by Active Power.

10.1.3 Compressed Air Energy Storage

10.1.3.1 What is CAES?

CAES systems use power generated during off-peak hours to compress air into underground reservoirs for storage. As demand for energy increases, the compressed air is retrieved and heated with a gas combustor before being fed into an expansion turbine that drives a generator, as shown in Figure 10-35. Specifically, the compressor and the turbine are separate components, and each is linked to a motor generator through clutches. When low-cost, off-peak energy is available, the clutch between the motor/generator and the compressor is engaged and the motor is used to run the compressor.

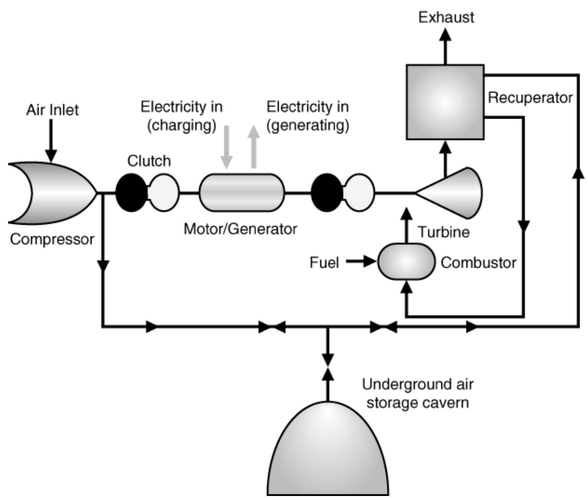


Figure 10-35. Schematic of CAES Plant.

10.1.3.2 How Does CAES Work?

A CAES system is made of above-ground and below-ground components that combine man-made technology and natural geological formations to accept, store, and dispatch energy through a series of thermodynamic cycles.

Above-ground Components

Five major above-ground components make up the basic CAES installation:

- The motor/generator that employs clutches to provide for alternate engagement to the compressor or turbine trains;
- The air compressor that may require two or more stages, intercoolers and aftercoolers, to achieve

economy of compression and reduce the moisture content of the compressed air;

- The turbine train, containing both high- and low-pressure turbines;
- Equipment controls for operating the combustion turbine, compressor, and auxiliaries and to regulate and control changeover from generation mode to storage mode; and
- Auxiliary equipment consisting of fuel storage and handling, and mechanical and electrical systems for various heat exchangers required to support the operation of the facility.

Underground Components

The cavity used for the storage of the compressed air can potentially be developed in three different categories of geologic formations:

- Underground rock caverns created by excavating comparatively hard and impervious rock formations,
- Salt caverns created by solution- or dry-mining of salt formations, and
- Porous media reservoirs made by water-bearing aquifers or depleted gas or oil fields (for example, sandstone, fissured lime).

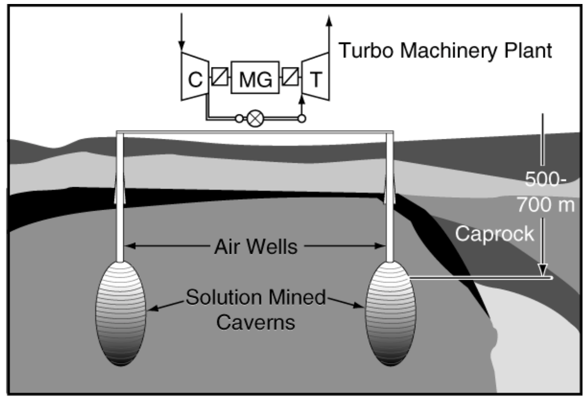
According to the Electric Power Research Institute (EPRI), geologic formations in 75% of the United States have the potential to provide reliable underground air storage required for a CAES system.

Salt Formations

Solution mining is relatively inexpensive, and salt caverns are simple and safe to operate and, as such, are the preferred site for a CAES, but siting opportunities are limited as domed salt formations are most predominately found in coastal areas. Solution-mined salt caverns like the one shown in Figure 10-36 are operated as constant-volume reservoirs and need to be relatively large if the storage pressure variation and associated losses during an operating cycle are to be kept at a minimum. Both CAES facilities operating today were situated in solution-mined salt domes.

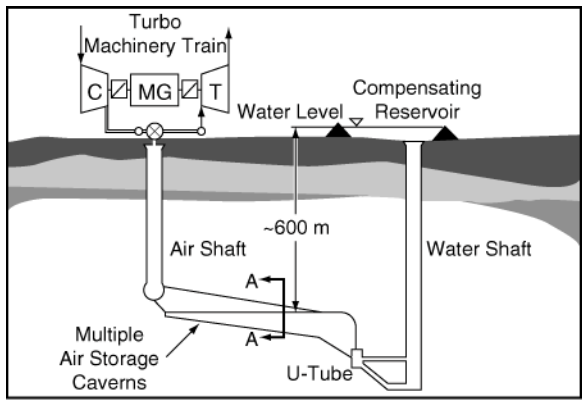
Hard Rock Formations

Hard-rock caverns such as those shown in Figure 10-37 provide the best locations for CAES systems in the United States, but they are more expensive to excavate than solution-mined salt caverns. To minimize the necessary storage volume, they would be designed and operated as constant-pressure reservoirs by incorporating water compensation. However, even with water compensation, the cost per kilowatt of hard-rock caverns is approximately 60% higher than that of solution-mined salt caverns. In the cavern, the water will absorb high-pressure air and eventually become saturated because of permanent contact between the two media. As long as the water remains at a pressure equal to or greater than that of the cavern, the air will remain in solution. However, during charging, saturated water flowing up the vertical water shaft will reach a level where the hydrostatic pressure is less than the dissolved air pressure. There the air will begin to come out of solution and create an unstable two-phase flow called the champagne effect. Under certain circumstances a cavern blowout is a possibility.



C = Compressor MG = Motor Generator T = Turbine

Figure 10-36. Salt Dome CAES.



C = Compressor MG = Motor Generator T = Turbine

Figure 10-37. Hard Rock CAES.

Aquifer Formations

CAESs like the one shown in Figure 10-38 can be built from aquifer formations. Aquifers are porous formations in sedimentary geology that are filled with water before they are developed for air-storage operations. The pressure of the water in an aquifer before a CAES system is created is approximately the hydrostatic head for the aquifer. When high-pressure air is injected into the aquifer through a system of wells, the water is displaced, and an air bubble begins to form. The pressure in the bubble is greater than the discovery pressure. However, the long-term stable pressure corresponds to the aquifer discovery pressure. The volume of the air bubble is typically around ten times the required working volume.

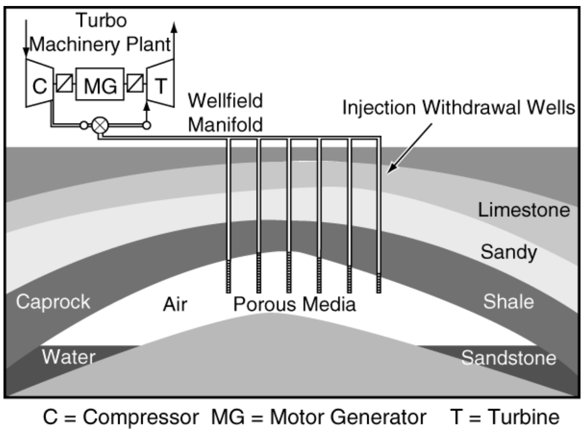


Figure 10-38. Aquifer CAES.

Thermodynamic Attributes

The above- and below-ground components of a CAES system work together to perform a thermodynamic process for storing and dispatching energy.[12] Figure 10-39 shows a diagram of the temperature and entropy of the thermodynamic processes involved in charging and discharging a CAES system. Steps 1, 2, and 3 of the process represent charging of the system in which the clutches engage the motor and grid-electricity powers compression of air in the CAES reservoir.[13] The initial part of charging involves compression of the air at constant entropy with a consequent increase in temperature (Steps 1 to 2). The final part of charging involves a constant pressure cooling of the gas (Steps 2 to 3). The CAES system remains at Step 3 while storing energy and progresses along the path between Steps 3 and 7 when demand for the stored energy initiates system discharge.

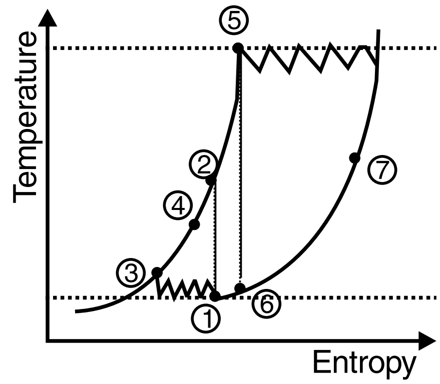


Figure 10-39. Thermodynamic Process of Charging and Discharging CAES.

During discharge, clutches engage the generator; the gas preheats in the recuperator at nearly constant pressure (Steps 3 to 4); the gas is heated at constant pressure in the combustor (Steps 4 to 5); expanded reheated gas transfers heat to the recuperator (Steps 5 to 7); and the overall process produces heat in the environment around the CAES system and produces electricity for the grid by driving hot dry gas through the turbine. Between each of the steps shown, numerous intercooling, aftercooling, and reheating steps also occur that are essential to the effective and efficient operation of the CAES system. This simple description of the process neglects these intermediate steps. It also neglects any treatment of the inefficiencies related to pressure loss through the walls of the reservoir, and it neglects thermal, mechanical, and electrical operation of the system components.

Energy storage systems designers must consider both the amount of energy that can be stored (energy density) and the efficiency at which it can be recovered. A CAES system is designed to cycle on a daily basis and to operate efficiently during partial-load conditions. This design approach allows CAES units to swing quickly from a generation to a compression mode (effectively doubling a unit's swing capability). Utility systems that can realize the greatest value from CAES can be generalized broadly as those whose load varies significantly during the daily cycle or whose costs vary significantly with the generation level or time of day. In addition, CAES plants can

[12] For a complete discussion of thermodynamic cycles, refer to *Marks Standard Handbook for Engineers*, 8th edition, McGraw Hill, New York, Baumeister, Avallone, and Baumeister, editors (1978).

[13] Per Alfors, Lars Eidensten, Gunnar Svedberg, and Jinyue Yan, "Efficiency Costs, Optimization, Simulation, and Environmental Aspects of Energy Systems," *Proceedings of ECOs'96*, Royal Institute of Technology, Stockholm, Sweden (June 25–27, 1996).

respond to changing load (provide load following) because they are designed to sustain frequent start-up/shut-down cycles. CAES systems also have improved environmental characteristics in comparison with conventional intermediate generating units. Two CAES systems are in operation today, one in Germany and one in the United States.

Huntorf, Germany CAES System

The oldest operating CAES system is in Huntorf, Germany. It has been in operation since 1978. The Huntorf CAES system is a 290-MW, 50-Hz unit, owned and operated by the Nordwestdeutche Kraftwerke, AG. The size of the cavern, which is located in a solution-mined salt dome, is approximately 8 million ft^3. It runs on a daily cycle with eight hours of charging required to fill the cavern. Operating flexibility, however, is greatly limited by the small cavern size. Compression is achieved through the use of electrically driven compressors. At full load, the plant can generate 290 MW for two hours. ABB provided the turbomachinery for this CAES system, which has proven the high reliability of the CAES concept.

McIntosh Alabama CAES System

The second CAES plant is about 40 miles north of Mobile in McIntosh, Alabama. It has been in operation since 1991. This CAES system, operated by the Alabama Energy Cooperative (AEC), has the attributes summarized in Table 10-5, and is referred to as McIntosh Unit 1. McIntosh 1 is supported by an underground cavern that is also located in a solution-mined salt dome. The storage capacity is 19 million ft^3 with a generating capacity of 110 MW. Natural gas heats the air released from the cavern, which is then expanded through a turbine to generate electricity. The turbomachinery for McIntosh Unit 1 was supplied by Dresser Rand. It can provide 26 hours of generation. The McIntosh CAES system is the first to utilize a recuperator that reuses heat energy from the gas turbine. This reduces fuel consumption by twenty-five percent. Since it came online in 1991, the McIntosh Unit 1 has generated more than 55 million kWh of electricity during peak demand periods. AEC was planning to install two additional combustion turbines to McIntosh 1 in late 1998. These turbines will add 226 MW of capacity to the facility.

Table 10-5. AEC CAES Plant Characteristics

Heat rate	4100 Btu/kWh
Normal start	13 minutes
Emergency start	9 minutes
Normal ramp rate	16.8 MW/minute
Emergency ramp rate	77 MW/minute

10.1.3.3 How Much Does a CAES System Cost?

CAES systems, like other energy technologies, have capital and operating costs associated with their purchase, installation, and use. EPRI estimates the total capital cost for CAES plants using salt storage caverns to be approximately $436/kW. Construction costs are greatly reduced when the CAES system is located in an existing salt dome rather than in a formation that has to be mined. In those instances that require mining, water must be pumped into the formation, and brine must be extracted and then processed on the surface. An aquifer-based system may cost less than a salt cavern system, while a hard-rock system would cost more, although even a hard-rock system would still cost only about half as much as a pumped hydro system, according to EPRI. Tejas Power, in a 1997 presentation, estimated the capital costs for construction of a CAES system at $320/kW to $370/kW, while the Energy and Information Agency estimates the construction costs for a natural gas-fired combined cycle plant at $419/kW. In comparison with other energy technologies, CAES system capital costs are somewhat higher than those of a combustion turbine and less than those for natural gas combined-cycle plants.

CAES systems allow utilities to operate their thermal baseload generation units at higher load factors to maximize efficiency and lower unit costs. In some circumstances, a new CAES plant may allow a utility to close or curtail the use of an existing intermediate or peaking plant with high operating costs. Calculating the exact cost of operating a CAES system, as shown in Equation 10-18, requires considering both the fixed and variable costs of the system.

$$C_{total} = AC_{capital} + C_{fixed_{OM}} + BC_{energy} \quad [10\text{-}18]$$

where C_{total} is the total cost per kilowatt-year ($/kW-yr)
A is the capital recovery factor of the unit (yr^{-1})
$C_{capital}$ is the capital cost the system ($/kW)
$C_{fixed\ OM}$ is the fixed operation and maintenance cost per year ($/kW-yr)

B is the capacity factor of the unit (hours/yr)
C_{energy} is the cost of energy to run the compressors, turbines and other devices ($/kW).

Each of the components of the total cost has its own subcomponents that depend on the physical and economic characteristics of the specific CAES system.[14]

10.1.3.4 What are the Advantages of a CAES System?

The technical benefits of a CAES system are direct. By storing energy that can then be used to regenerate electricity, utilities can defer the construction of additional power plants to cover peak energy demands. CAES systems, along with electromechanical and electrochemical ESS, are providing electric utilities with broader energy storage options. And, unlike the other storage options discussed in this document, CAES relies on commercially available combustion-turbine technology that electric utilities are familiar with. The economic benefits of a CAES system, like the technical benefits, have several components.

These CAES system economic benefits are typically expressed as a net annual benefit that is related, as shown in Equation 10-19, to the duration of discharge, the price charged for dispatched energy, and the plant's capacity factor.

$$Nb = \left(P_{discharge} - C_{energy}\right)B - C_{capital} - C_{fixed\,OM} \qquad [10\text{-}19]$$

where Nb is the net annual benefit ($/kW-yr)
$P_{discharge}$ is the price charged for dispatched energy ($/kWh)
and B, C_{energy}, $C_{capital}$, and $C_{fixed\ OM}$ are as defined in Equation 10-18.

As shown in Equation 10-20, an optimal benefit/cost ratio depends on the combination of many thermodynamic, technologic, and economic attributes of the system including the fuel costs for running the combustor; heat transfer limitations in the system and the relative benefits of additional recuperators, reheaters, intercoolers, and aftercoolers; the marginal capital cost of more efficient thermal, mechanical, and electrical components; and the geological challenges of the CAES reservoir itself. Researchers are working toward improvements on each of these areas and on analytic tools for achieving and optimal balance between cost and performance.

$$Benefit/Cost = Nb / C_{total} = Nb = \left(P_{discharge} - C_{energy}\right)B - C_{capital} - C_{fixed\,OM} \qquad [10\text{-}20]$$

10.1.3.5 What are the Challenges to CAES?

Overall, CAES is a mature, commercially available energy storage technology. The barriers to implementation of this technology appear to be economics and gaining the confidence of prospective owners. As the McIntosh CAES establishes a longer track history, utility confidence in CAES should increase. There are, however, areas that must be addressed before hard-rock caverns and aquifers can be successfully used as a site for a CAES system.

As described in the preceding discussion of hard-rock formations, the champagne effect requires more study. A reliable control system for the compressor and the cavern must be developed that would shut down the compressor when the cavern is fully charged to prevent inadvertent charging and eventually a blowout.

In aquifers, the challenges include the displacement of water to develop air storage and the matching of the air flow characteristics of the turbomachinery and the aquifer. For the storage system to operate according to powerplant specifications, the well manifold and the compressor and turbine characteristics have to be carefully matched. Because the turbogroup will most likely be constructed with existing components that would be expensive to modify, the challenge is to design and, if necessary, adjust the well field so that it satisfies a given duty cycle. The distribution and depth of wells will depend greatly on the air flow rates within the aquifer.

One improvement to CAES that is currently being pursued is compressed air storage with humidification (CASH). In CASH cycles, hot water mixes into the compressed air retrieved from storage to saturate and heat it, and to increase mass flow at the turbogenerator inlet. This decreases airflow requirements and thus storage volume requirements by 30% for a given electricity outlet. These benefits, combined with waste heat recycling, improve the electricity-input-to-

[14] For more detailed information, refer to Per Alfors, Lars Eidensten, Gunnar Svedberg, and Jinyue Yan, "Efficiency Costs, Optimization, Simulation, and Environmental Aspects of Energy Systems," *Proceedings of ECOs'96*, Royal Institute of Technology, Stockholm, Sweden, June 25–27, 1996.

electricity-received ratio to 0.5. Currently, the electricity-input-to-electricity-received ratios for CAES systems range between 0.75 and 0.82 (at the cost of additional fuel at a heat rate of about 400 Btu/kWh). Such ratios are lower (and therefore better) than those of other storage technologies that are greater than 1.0.

EPRI has also explored the possibility of developing a system that would combine coal gasification with a humidification air storage cycle. Humidification in a CASH system increases the MW output by adding moisture to the air. This means that the energy per unit mass flow through the turbine increases significantly. A CASH system promises coal pile-to-bus bar heat rate down to 8100 Btu/kWh and installed capital costs that are below $1000/kW. This is 20% to 30% lower than conventional coal-fired and low-emission pulverized coal plants. In addition, this type of system could potentially provide almost 99% sulfur removal. The high humidification of the combustion air would also result in low NO_x formation.

10.1.3.6 CAES Developers

While only two CAES systems are operating today, both utilities and nonutilities in the domestic and international markets are interested in this mode of energy storage as they position themselves to take advantage of the restructuring of electricity markets.

United States

Tejas Power of Houston, Texas, a company that pioneered the use of underground reservoirs for the storage of natural gas, is expanding into the development of CAES. No contracts had been awarded as of December 1998, but TPC is pursuing potential CAES customers. TPC will provide the expertise needed to prepare the underground reservoir, leaving the aboveground components to other vendors.

Westinghouse, which has been involved in CAES research since the 1970, views CAES as a promising growth area. Westinghouse engineers have made improvements to the compressor that they feel will result in improved energy efficiency. In their design, they took the compressor off of the shaft of the expander so that they can use multiple compressors for capturing off-peak energy. Instead of one large 150 MW compressor, Westinghouse will substitute three 50 MW compressors. Like TPC, Westinghouse has not yet completed a contract for the construction of a CAES, but marketing department representatives are confidant that it is only a matter of time before they enter this market. Dresser Rand is also actively marketing its capabilities in the CAES arena. After successfully installing the compressors at McIntosh 1, Dresser Rand has proven experience in this method of energy storage. Louisville Gas and Electric stated their intent to construct a CAES by 2004 in their 1995 integrated resource plan. One non-utility firm in New York that owns an existing cavern in a salt dome is investigating the possibility of developing a CAES if it is cost-effective to do so. The cavern has a storage capacity of approximately 2 million ft^3. While this volume is twice that of the Huntorf CAES, it is only 1/10 that of the Alabama CAES plant.

International

Chubu Electric of Japan is actively surveying its service territory for appropriate CAES sites. Chubu is Japan's third largest electric utility with 14 thermal and two nuclear power plants that generate 21,380 mWh of electricity annually. Japanese utilities recognize the value of storing off-peak power in a nation where peak electricity costs can reach $.53/kWhr. Eskom of South Africa has also expressed interest in exploring the economic benefits of CAES in one of its recent integrated energy plans.

10.1.4 Power Conversion Systems for Energy Storage Systems

10.1.4.1 Solid State Switches and Circuits

Power converters are devices that use specialized electronic switches to rectify, invert, or shift frequencies of electrical signals. The voltage, current, and switching frequency requirements of the specific application dictate the type of switch and the switching algorithm for the converter. Power converters for energy storage systems are based almost exclusively on one of three types of electronic switches: SCRs, GTOs, and IGBTs.

Early in the development of utility energy storage systems, SCRs were the most mature and least expensive semiconductor devices that were suited to utility-scale power conversion. SCRs can handle voltages up to 5 kV, currents up to 3000 A, and switching frequencies up to 500 Hz. An SCR switch has four layers of semiconducting materials and contains an excess of electrons in n-type material and spaces for electrons (or holes) in p-type material. The switch also has metallic layers at the gate, anode, and cathode that serve as electrical terminals that connect the SCR to the circuit in which it functions. Figure 10-40 shows the symbol used for SCRs in electrical circuit diagrams and a schematic of an SCR device.

When current enters the gate terminal, current carriers build up in the P_2 and N_1 regions; current flows between the anode and cathode; and the SCR allows electricity to flow in the circuit. Current continues to flow through the semiconductor layers until an external circuit introduces a reverse current at the anode to turn the SCR off. Hooked together in forward and reverse bridge circuits like the one shown in Figure 10-41, SCR-based devices can rectify AC power and invert DC power. This two-way conversion is useful in ESS that depend on DC storage of electricity from an AC source. However, SCR-based converters have some limitations.

Most SCR-based converters depend on an energized power line to provide the external on/off signals to the switches. Such “line-commutated” converters cannot support “black-starts” of equipment on unpowered lines. In addition, a storage system with a line-commutated converter such as the one illustrated in Figure 10-41 creates a phase shift between the AC voltage and current signals that make the storage system affect the AC power line in the same way as a lagging load. The phase-shift changes the relative sizes of the real and reactive powers and is problematic in systems that require VAR control. And, while SCR-based converters in a sequentially dispatched series can eliminate the undesirable phase shift, such a system would be much more complex and expensive than alternatives that have emerged in recent years.

Other semiconductor devices have overcome power limitations and cost issues and are now more available and less expensive. They are beginning to displace SCRs in power converters for utility-scale energy storage systems. One of the newer solid-state switching devices that is similar to an SCR now dominates in power converters for high-power energy storage systems. This device, the GTO, can handle voltages up to 6 kV, currents up to 2000 A, and switching frequencies up to 1 kHz. Like SCRs, GTOs have layers of p- and n-type semiconductor materials and metallic anodes, cathodes, and gates that connect the device to the circuit in which it operates. Figure 10-42 shows the symbol used for GTOs in electrical diagrams and a simple schematic of a GTO device.

Like SCRs, GTOs turn on with a pulse to the gate terminal. Unlike SCRs, which require a reverse current at the anode, GTOs turn off with a negative current to the gate. This attribute permits construction of GTO-based power conversion systems that allow current to flow in a closed connection between a DC storage device and the power conversion system’s AC terminals. This configuration creates “self-commutated” devices like the one shown in Figure 10-43 that do not depend on an energized line to function and can provide power for black starts.

In addition, the real and reactive power outputs from a GTO-based converter are independent, and ESS with GTO-based converters can deliver real and reactive power for power-factor correction, voltage control, and transient-line stability applications that line-commutated converters cannot address. GTO switches have two significant limitations. The gate current required to turn off the device is quite large (25% to 30% of the anode-cathode current). GTOs, while twice as fast as SCRs, are slower than some alternate technologies that have emerged in the last several years.

IGBTs are the solid-state switch devices that have the most immediate promise as an alternative to GTOs in power converters for energy storage systems. IGBTs can handle voltages up to 3 kV, currents up to 500 A, and switching frequencies that approach 100 kHz. IGBTs are very similar to metal oxide semiconductor field-effect transistors (MOSFETs), but have an additional layer. Like MOSFETs, IGBTs use an insulating layer between the electrical contacts and the semiconductor material in the switch. Figure 10-44 shows the symbol used for IGBTs in electrical-

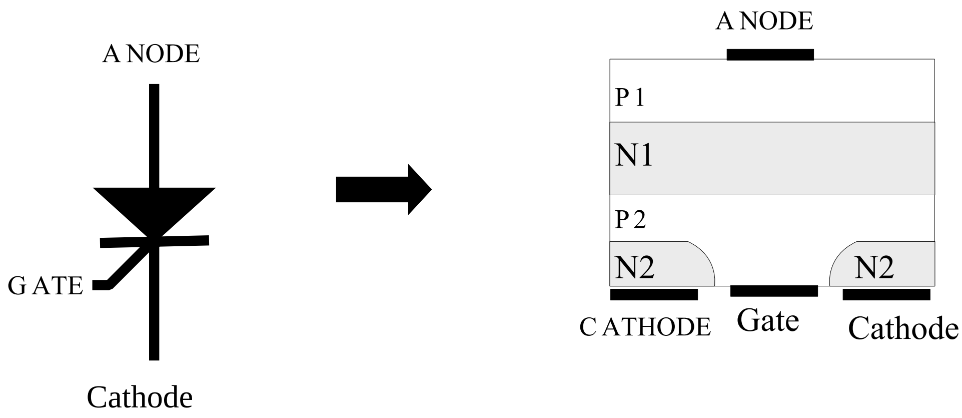


Figure 10-40. SCR or Thyristor Symbol and Schematic.

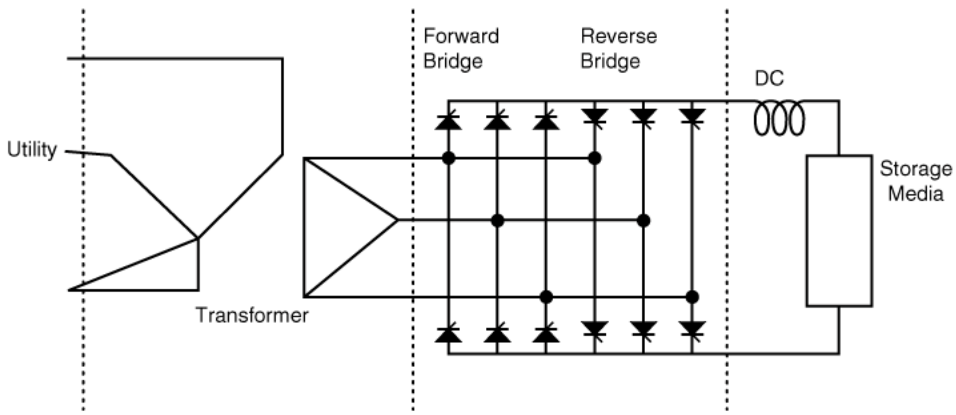


Figure 10-41. Schematic of an SCR-Based Line-Commutated Converter.

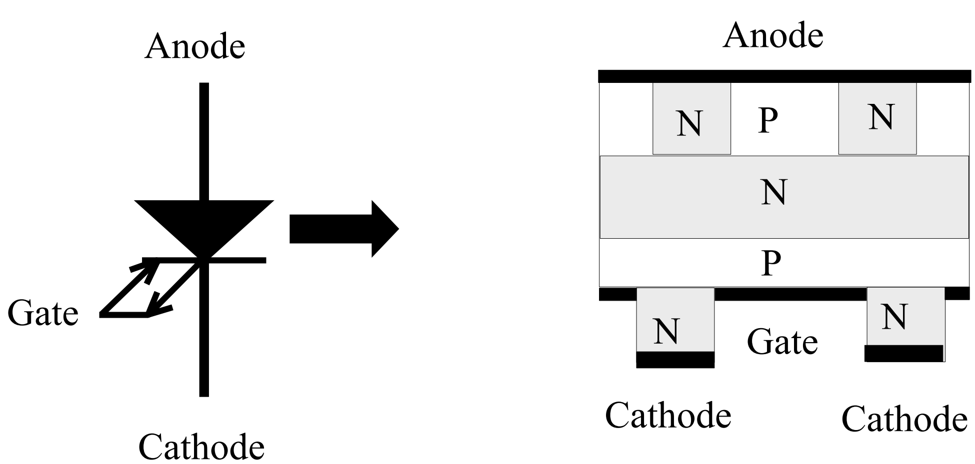


Figure 10-42. GTO Thyristor Symbol and Schematic.

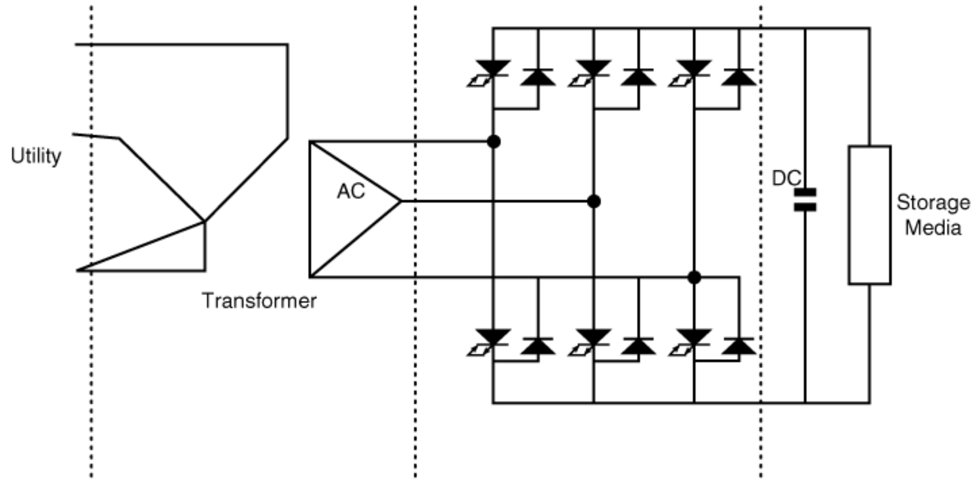


Figure 10-43. Schematic of a GTO-Based, Self-Commutated Converter.

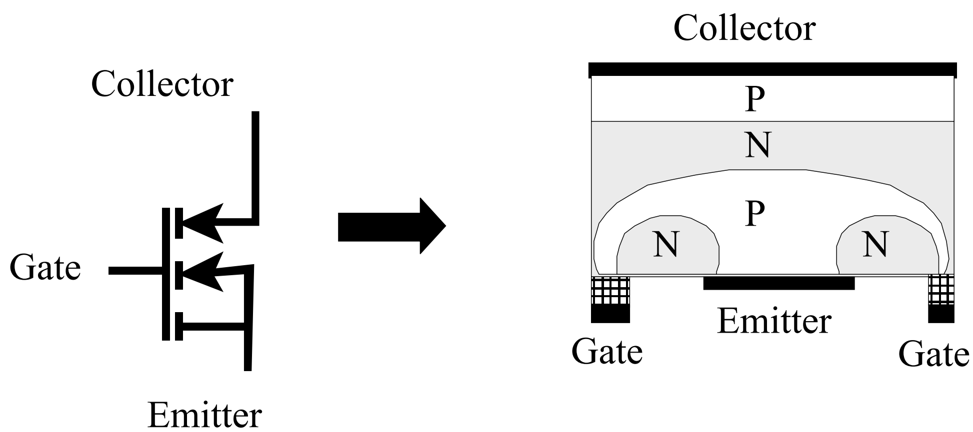


Figure 10-44. IGBT Symbol and Schematic.

circuit diagrams and a schematic of an IGBT device. Also like MOSFETs, IGBT switches turn on when the voltage between the gate and emitter of the device is large enough to cause current carriers to gather in the p-type material at the source terminal. This collection reduces the voltage between the source and the collector and causes current to flow from the emitter to the collector.

An IGBT switch turns off when the voltage between the gate and emitter is too small to attract current carriers. Because a voltage between two parts of the device controls current flow through the switch, IGBTs are referred to as voltage-source devices. Like GTO-based converters, IGBT-based power converters are self-commutated, can provide power for black starts, and can independently provide real and reactive power. IGBT switches are faster than GTOs and do not require the large gate current that reduces GTO turn-around efficiency. However, the IGBTs that are now available have only about one quarter of the power capacity of GTOs and must be connected in series/parallel arrays to deliver more than 3 kV and 500 A.

A series circuit of two or more IGBT-based converters is more complex than a circuit with a single high-power converter. However, strategic circuit design can make system reliability of several smaller units greater than the reliability of a system based on a single high-power device. If the circuit allows the individual converter units to operate and deliver lower power (through a failed unit in the case of a short-circuit failure, and around a failed unit in the case of an open-circuit failure), the system would be more reliable than a system with a single large converter that removes the entire system from service. Also, because IGBT technology is less mature than GTO technology, the industry expects significant advances in their power capacity. IGBT technology will most likely dominate the market for energy storage power conversion in the near term. In the mid- and long-term, development of some emerging semiconductor switching devices may influence converter technology selections that developers make in the near future.

Solid-state switches have advanced tremendously since Schottky developed the diode at AT&T/Bell Labs. Even as IGBTs are maturing and competing with GTOs for dominance in power converters, new solid-state switches are under development. The MOS-controlled thyristor (MCT) is among the most promising candidate technologies for energy storage systems power converters. Like IGBTs, MCTs are based on MOSFET technology in which an insulating layer separates the electrical contacts and the semiconductor material in the switch. MCTs turn on when current carriers gather between the islands of p-type material and conduct current from the anode to the cathode. The device turns off when current carriers collect between the islands of n-type material and prevent anode-cathode current from flowing. Figure 10-45 illustrates the symbol used for MCTs in electrical circuit diagrams and presents a schematic of a MCT device.

Academic literature indicates that MCTs can handle voltages up to 3 kV, currents up to about 750 A, and switching frequencies of up to 50 kHz, and the literature projects performance at 6 kV, 2000 A, and 100 kHz. Numerous developers of power converters for ESS have been working on MCTs for the Flexible AC Transmission System project. Currently, four MCT devices are commercially available, and a fourth device that is rated at 6 kV and 65 A will be on the market. According to the National Technology Transfer Center, the new MCT will switch four times as fast as existing devices and be more energy efficient.

In addition to advances in the device structure, development of new materials will be essential to improving the power, speed and efficiency of power converters. Silicon carbide (SiC), gallium nitride (GaN), aluminum nitride (AlN), and diamond are all semiconductor materials that have a wider band gap than silicon (the material in commercial semiconducting devices). In the long term, when devices made of these materials emerge on the commercial market, the wide band gap will allow switches to carry more power, to be less sensitive to heat and electromagnetic radiation, and to be more stable than the present silicon-based switches. PCSs based on these switches will be faster, more efficient, and more robust than the existing PCSs. Of the wide-band gap materials, SiC is the closest to becoming commercial.

10.1.4.2 Utility Signals and Harmonics

Electrical devices that use AC power are designed to operate with the fundamental frequency of the electricity that utilities produce, and can be damaged by electricity with other frequencies. As illustrated in Figure 10-46, all AC power contains signals with frequencies that are multiples of the fundamental frequency or harmonics. The amplitude of the harmonic signals decreases as the frequencies increase. The amplitude of the second harmonic is half the amplitude of the fundamental frequency; the amplitude of the third harmonic is one-third the fundamental, and so on. As the amplitude falls, so does the inductive current—the part of the signal that interacts

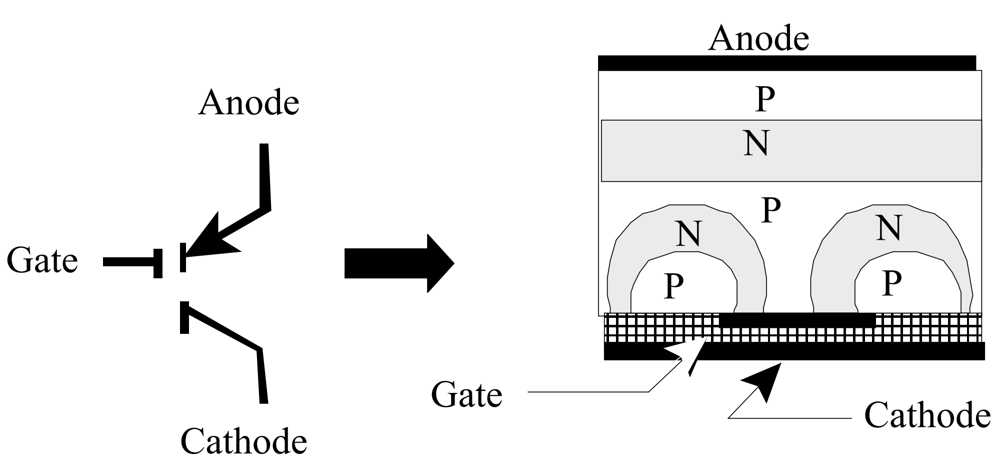


Figure 10-45. IGBT Symbol and Schematic.

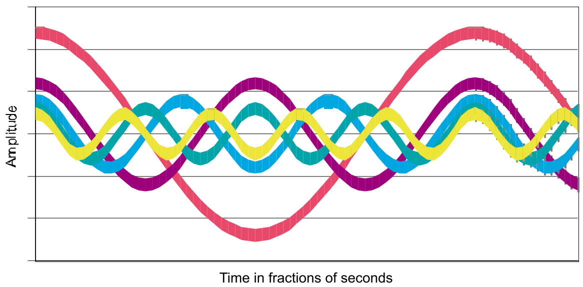


Figure 10-46. Frequency and Amplitude of Harmonics of an Alternating Electrical Current: I-Fundamental, II-2nd Harmonic, III-3rd Harmonic, IV-4th Harmonic, V-5th Harmonic.

with the impedance of the wires and devices through which the electricity flows. Lower inductive current correlates to less heating. Therefore, high-frequency harmonics have less damaging effects on electrical devices than low-frequency harmonics, and most strategies to eliminate harmonics focus on low-order harmonics.

Harmonic effects, when unmitigated, aggregate and cause computers to malfunction, real and reactive power meters to give inaccurate readings, transformers and motors to overheat, and circuit breakers to trip. To prevent such problems, utilities eliminate as many harmonics as they can, and limit the amplitude of the frequencies that they cannot wipe out. In general, the utility signal has very little harmonic content, and customers' loads—specifically, non-linear loads—cause most of the harmonic content in the signal on the grid. Power conversion systems are one of the non-linear loads that can introduce harmonics to the utility signal.

10.1.4.3 Power Converter Signals, Sine-wave Emulation, and Harmonics

An ideal PCS would deliver AC electricity that is perfectly synchronous with the utility's signal and contains no harmonics. However, the solid state switches that are the building blocks of a PCS draw current from the incoming signal during only part of the cycle and create pulses that induce harmonic frequencies in the electricity on both the AC and DC sides of the converter. Therefore, storage system developers must understand the nature of the PCS and the storage medium that they select, and incorporate specialized design attributes to achieve successful integration of the PCS, storage media, and system controls. For example, most PCSs have a harmonic effect, referred to as ripple current on the DC side of the converter, that may significantly reduce the service life of electrochemical batteries. A capacitor placed in parallel with the battery is a relatively simple and inexpensive way to eliminate the ripple current and make the integration of the PCS and storage medium successful.

In SMES, similar PCS/storage integration issues influence the superconductive behavior of the SMES coil. In FES, conversion of the variable AC signal from the flywheel to DC, stabilization at a set DC voltage, and inversion to a utility-compatible AC signal presents other unique PCS/storage integration requirements. While many of the resolutions of these issues are as simple as the capacitor to eliminate ripple current, knowledge of both the PCS and the storage medium are essential to recognize and implement resolutions to DC-side harmonics. Harmonic effects are not limited to the DC side of the PCS. Harmonics from the PCS can also affect the utility grid.

Harmonic voltages created by the operation of the PCS can leak across the output transformer onto the utility grid and affect the signal on the entire bus. To prevent harmonics from aggregating and affecting the entire utility, bodies that set national and international standards developed requirements for all connections to a utility grid that limit the harmonic currents that any piece of equipment or individual electricity customer may introduce to the grid. The American National Standards Institute (ANSI) and the Institute of Electrical and Electronics Engineers (IEEE) developed Standards 519–1992, 1001, 928–1986, and 929–1998 to address interconnection requirements for electronic devices in the United States. The International Electrotechnical Commission established the 60000 series of standards to define similar standards in Europe. This standard sets limits for the harmonic currents that any piece of equipment or individual customer may introduce to the system and helps keep the harmonic voltages on the overall utility at an acceptable level. Revisions of the existing standards and development of new standards for specific storage systems (and other devices connected to a grid through a PCS) are underway in several standards organizations.

To limit harmonics that their systems inject onto the grid, converter manufacturers have several options: increase the frequency at which the solid-state switches in the PCS operate, develop sophisticated switching strategies, use a transformer that contributes more than 10% of the impedance of the system, and/or include filters in the converter design.

Increased switch frequency is an option that is available for harmonics control because a PCS-output signal is not exactly an AC frequency. Instead, it is an aggregation of square wave forms created by switching solid-state devices. In the simplest case, an individual switch turns on and off at the same frequency as the AC signal that the PCS is designed to emulate. This strategy produces square waves like the half-wave form shown in the top graph in Figure 10-47. Because such signals poorly match the sinusoidal shape of an actual AC signal, designers use more sophisticated methods of switching that turn combinations of switches on and off to create a stepped wave like the half-wave form shown in the center graph in Figure 10-47. Just as stepped waves more closely resemble an AC signal, stepped waves created with faster switching are better approximations of sinusoidal waves. Faster switching makes the steps in the wave finer, like the steps in the half-wave form in the bottom graph in Figure 10-47. Therefore, the signal produced with fast switching is even more similar to an AC signal. Fast switching also helps to control harmonics. Because the inductive current drops with the frequency of the signal, the very high-frequency harmonics that fast switching generates have less damaging effects on electrical devices than low-frequency harmonics. PCS manufacturers have adopted switching strategies to smooth the output signal and reduce its harmonic content. These strategies capitalize on fast switching and the properties of the "three-phase" electrical power.

On "three-phase" AC electrical systems like the utility grid in the United States, electrical power consists of three separate sets, or phases, of current and voltage signals: Phases A, B, and C. Each phase has the same frequency and maximum amplitude. However, the utility deliberately staggers the oscillation of the signals so that they reach their maximum amplitude at three evenly spaced instants. The mathematics that describe the signals express time lags between the phases in terms of degrees. An entire cycle is equivalent to 360 degrees and one third of the cycle, or 120 degrees, equals the lag between the signals on each phase. The harmonic frequencies in each of the three phases also occur at 120-degree intervals. As illustrated in Figure 10-48, the third harmonics of the A, B, and C phases cancel each other out. PCS designers also take advantage of this signal cancellation in switching strategies to reduce the other harmonic frequencies.

In the basic, stepped square-wave approach, the PCS "overlaps" switch operations to produce a rough approximation of an AC signal. In a three-phase system, the PCS produces three sets of signals to correspond with the A, B, and C phases of the utility signal. Even though faster switching improves emulation of a sine wave, and the effects of the high-frequency harmonics are less damaging, some of the harmonics that are produced remain unacceptable. The strategies for eliminating these harmonics are based on coordinating switching to increase the frequency of the harmonics (and reduce the inductive current), and to force larger-amplitude harmonics to have frequencies that cancel out across the three phases. This family of switching strategies is called pulse-width modulation (PWM), because they alter (or modulate) the output signal by using the duration (or width) of the pulses created by a large number of switching operations.

Figure 10-49 shows how PWM eliminates all of the low-order harmonics (below the 18^{th} order) from the harmonic spectrum of a PCS signal. This figure also shows that while PWM can actually increase the amplitude of higher order harmonics, most of the remaining harmonics have amplitudes that are less than 20% of the fundamental frequency's amplitude. Most of the harmonics have amplitudes that are less than 10% of the fundamental frequency.

The speed and energy efficiency of the solid-state devices in the PCS place practical limits on the switching frequencies. For GTOs, which have relatively high speed but require a turn-off current that is about 30% of the total current they conduct, fast switching consumes a significant amount of energy. For devices like IGBTs that are faster and more energy efficient, high-switching frequency improves the PCS signal with fewer trade-offs. Even with these practical limitations, careful attention to switching patterns can eliminate harmonic frequencies and significantly reduce the magnitude of the frequencies that it cannot completely cancel.

To reduce the harmonic content of the signal after PWM, PCS designers use frequency filters that, in general, consist of capacitors and inductors connected on the AC side of the output transformer. Designers take advantage of the time dependence of capacitor voltage and inductor current, and put together capacitor/inductor circuits that create voltage and current frequencies that cancel harmonic frequencies in the output signal. While filter design for the PCS is relatively simple for a device that will not

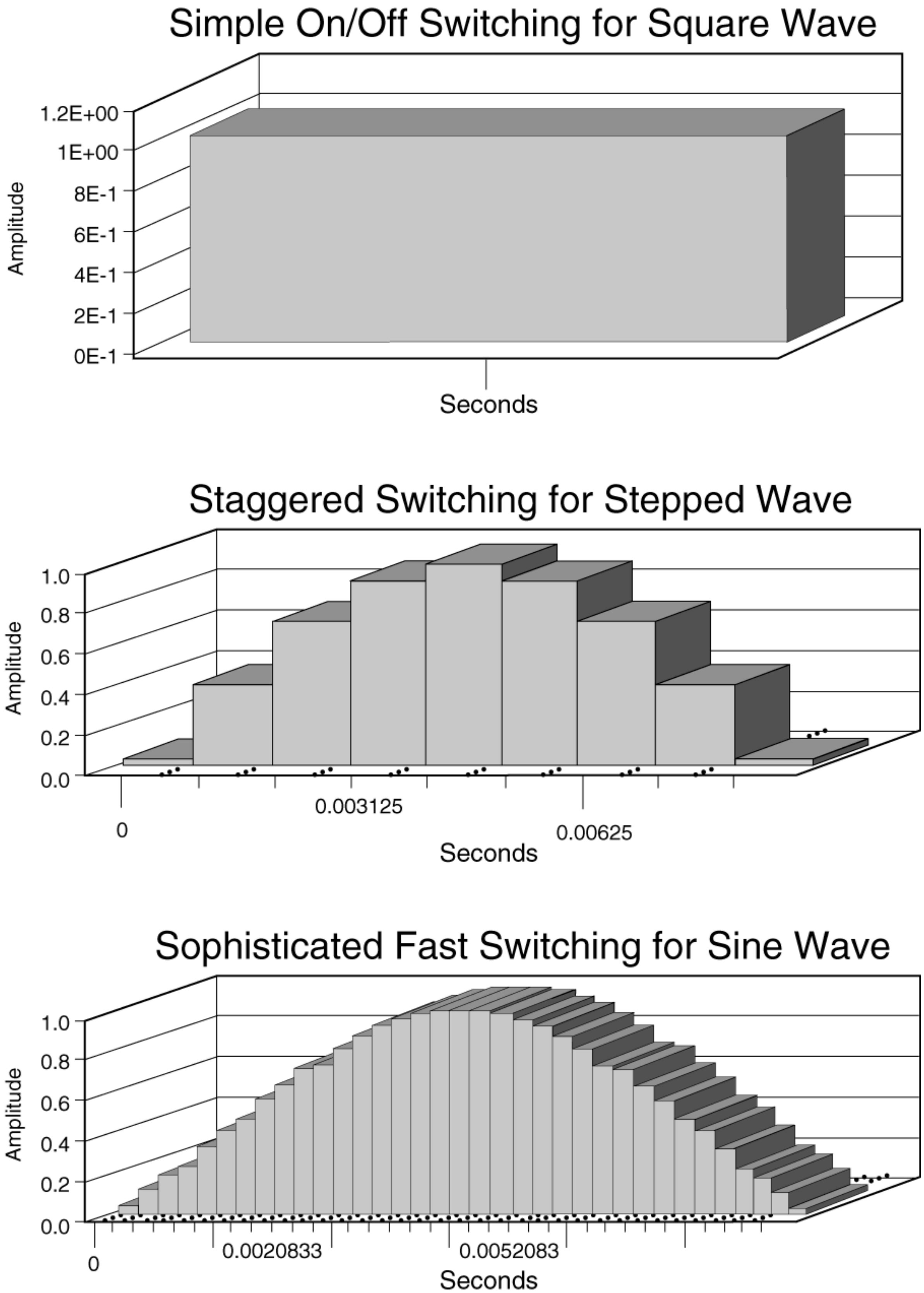


Figure 10-47. PCS Switching to Approximate a Sine-Wave.

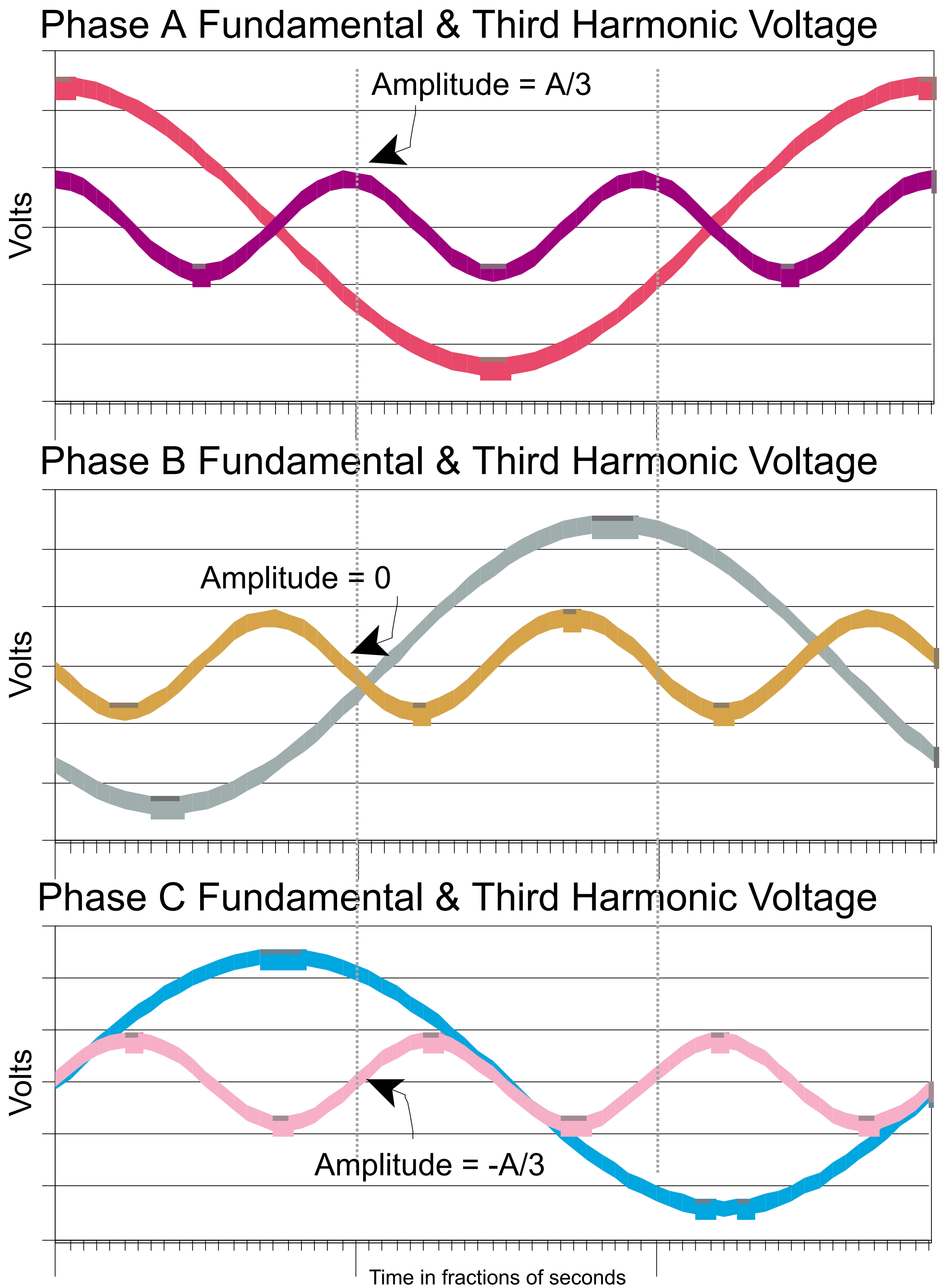


Figure 10-48. Three-Phase AC Electricity and Third-Order Harmonic Cancellation: at the Point Where the Magnitude of the Third Harmonic is Labeled on Each Phase, the Sum of the Amplitudes is Zero (A/3 + 0 – A/3 = 0).

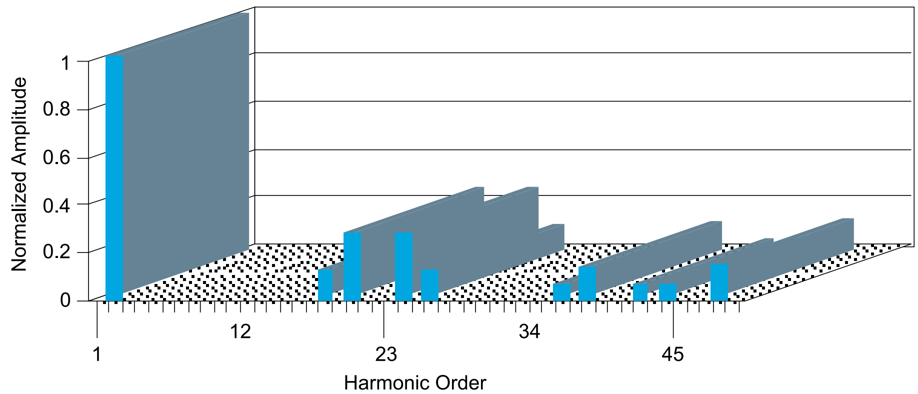


Figure 10-49. Harmonic Spectrum after Pulse-Width Modulation.

be connected to an active grid, it is not simple for a grid-connected device. Interaction between the PCS and loads on the bus to which the device is connected can cause unexpected harmonic frequencies that require more involved filter design. For this reason, thorough harmonic analysis is essential to successful installation of an energy storage system.

10.1.4.4 Converter Design Versus Application Requirement

The size of the converter depends on the requirements of the application for the storage system in which the converter operates. The following parameters are important influences on the power rating and configuration of the converter:

- the voltage of the storage media,
- the AC line voltage,
- unbalance in the phases of the AC line,
- impedance of the converter and transformer, and
- the reactive power that the system will have to provide.

These considerations can make the converter size (and cost) vary significantly.

Figures 10-50, 10-51, 10-52, and 10-53 illustrate four possible configurations of the following four major components of a PCS in an ESS:

- **the power stage** (the portion of the PCS addressed in detail in the preceding portions of this discussion) that consists of solid-state switched, semiconductor switch drivers, thermal management devices (to keep the switches and drivers cool enough to operate reliably and efficiently), and protective circuits (to limit voltage and current that might otherwise reach levels that are damaging to the switches);

- **the controller** that compares the output of the PCS with desired reference values for the AC source, the load, and the storage medium, and dispatches the power stage that is appropriate for the status of all of the measured values;

- **the AC interface** that consists of current and voltage sensors, inductors, circuit breakers, surge arresters, isolation switches, and the output transformer; and

- **the DC interface** that consists of current and voltage sensors, isolating switches, surge arresters, fuses, and a variety of filters.

These four components, which are typically arranged in one of four types of configurations, make up the state-of-the-art PCS devices for energy storage systems.[15] Of the four configurations, two serve grid-connected applications, and two serve off-grid applications. The examples in Figures 10-50, 10-51, 10-52, and 10-53 do not completely define the possibilities, but illustrate the range within the four categories of PCS configurations for energy storage systems. For example, the PCS configuration shown

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[15] For more complete information on PCS components, configurations, developers, costs, and R&D needs, see *Summary of State-of-the-Art PCS System Configurations and Recommendations for Future Research and Development*, Stan Atcitty, Satish Ranade, Amber Gray-Fenner, Summary of State-of-the-Art Power Conversion Systems for Energy Storage Applications, SAND98-2019, September 1998.

in Figure 10-50 employs a series transformer. This choice keeps the storage system continuously on-line for applications such as voltage sag protection. However, the efficiency would be greater with a shunt transformer in which current does not have to always pass through the transformer to make the system available. In a grid-connected parallel configuration with a shunt transformer, a solid-state circuit breaker allows the storage device, PCS, and load to disconnect from the utility signal and operate as if no service interruption had occurred.

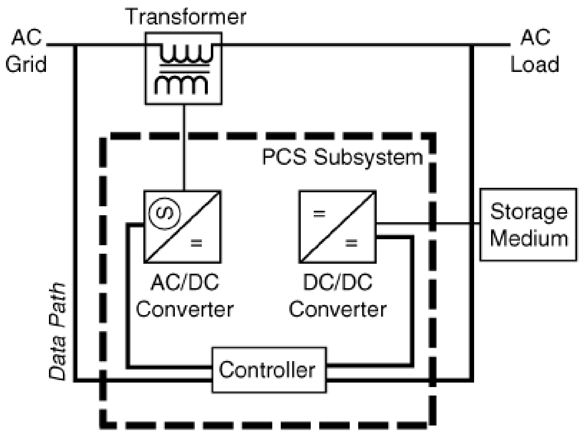

Figure 10-50. Grid-Connected Parallel Configuration (with Series Injection Transformer).

A grid-connected series configuration is always on-line with the load, and the power passes through two converters placed in series. While the efficiency is again a limitation, this configuration provides a stable DC bus between the converters that is essential to the operation of a flywheel system. The bus is the delivery point of the variable AC signal from the flywheel through the AC/DC converter. The by-pass switch in this configuration isolates the PCS for maintenance and allows utility power to reach the load directly in the event of a PCS failure. In general, parallel grid-connected configurations like the one illustrated in Figure 10-51 allow smaller PCSs for the same applications than series configurations; prevents system failure from affecting the load; and has a greater efficiency than the series configuration. However, series configuration ensures that no switching delays ever cause momentary service interruptions that can occur with parallel configurations.

The off-grid systems shown in Figures 10-52 and 10-53 are configurations used for storage systems that have no connection to a large utility network, but

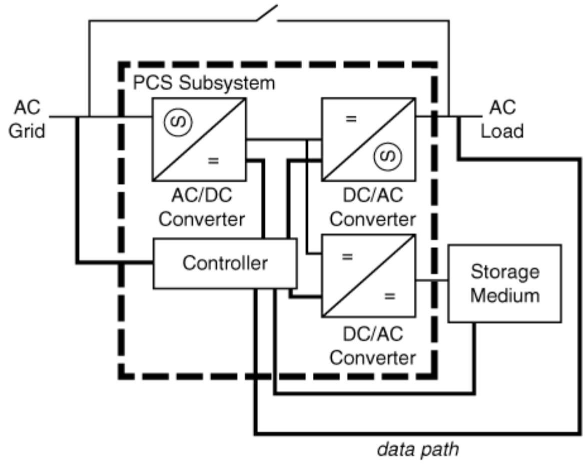

Figure 10-51. Grid-Connected Series Configuration.

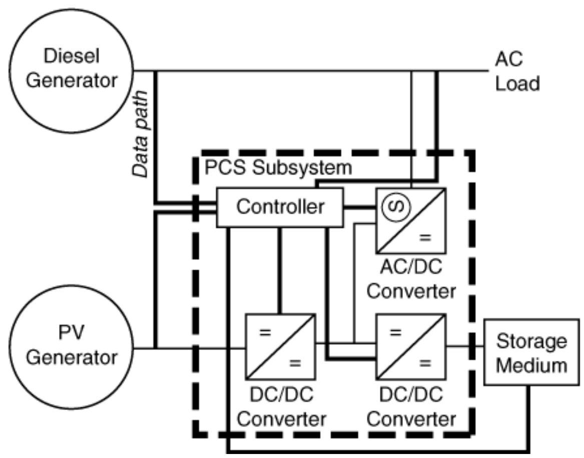

Figure 10-52. Off-Grid Parallel Configuration (with Diesel and Photovoltaic Generation).

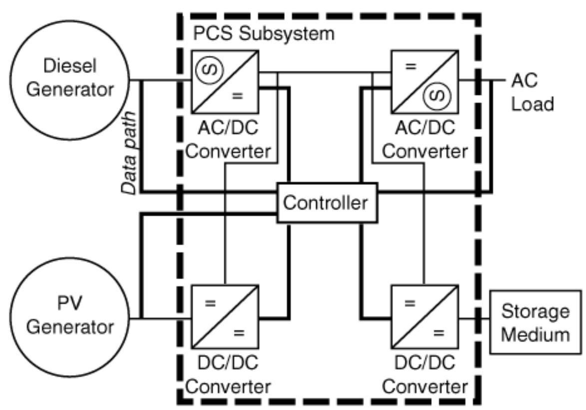

Figure 10-53. Off-Grid Series Configuration (with Diesel and Photovoltaic Generation).

are connected to a diverse group of possible AC and DC generation sources and loads. The specific configurations illustrated here serve AC loads, but can, with appropriate modifications to the converter type, serve DC loads in a similar way. The most significant difference between the two PCS configurations for off-grid systems is the way in which the diesel generator (or generator engine of another type) connects to the other parts to the system. In a parallel off-grid configuration, the diesel generator connects to the AC load in parallel with the PCS (the other components connect to the load through the PCS). In a series configuration, the diesel generator, like the other components, supplies the load through series connection to the DC bus of the PCS through appropriate converters. Each configuration has strengths and liabilities that make it more or less useful to specific applications.

The parallel off-grid configuration typically has greater availability than the series configuration because inverter failure in the parallel arrangement does not prevent the diesel from delivering power to the load. Also, the parallel configuration requires fewer converters than a series configuration for the same application. Therefore, both initial cost and energy efficiency are more favorable in the parallel configuration. However, the series configuration requires much less sophisticated AC switching and control algorithms than parallel, and the series configuration also ensures that diesel generator start-up and shut-down do not cause power disturbances for the load (such disturbances are possible in a parallel configuration).

10.1.4.5 What Do PCSs Cost?

Selection of specific components and configurations of the PCS depend on the application requirements and the characteristics of the storage medium involved. The only part of the system design characteristics that are independent of these issues are those characteristics that are mandated by standards for interconnection to a power grid. Therefore, the specifications for the PCS for any storage system are a careful set of trade-offs between performance and cost in the selection of solid-state switch type, switching strategies, control algorithms, transformer size and type, filters, and overall PCS configuration. As a result, PCS costs range anywhere from $50/kW to $1500/kW. In general, costs for PCSs for grid-connected systems range from $50/kW to $750/kW, and costs for off-grid PCSs range from $200/kW to $1500/kW. PCS manufacturers believe that better understanding of PCS requirements for storage systems, standardization of the devices that is based on that understanding, and a higher volume of production are all likely to reduce these costs.

10.1.4.6 PCS Developers and Manufacturers

Many PCS researchers, developers and manufacturers are working toward better understanding, standardization, high-volume production, and reduced costs along with development of new semiconductor materials and solid-state switch structures. Many manufacturers around the world are involved in the development of PCSs for storage systems. Manufacturers who participated in the study cited earlier in this discussion were ABB Industrial Systems, Abacus Controls, Advanced Energy Systems, Exide Electronics, Liebert Corporation, The New World Power Technology Company, Omnion Power Engineering Corporation, Orion Energy Corporation, Softswitching Technologies Corporation, and Westinghouse Electric Corporation.

10.1.4.7 What are the Challenges to PCSs?

As mentioned earlier, development of new semiconductor materials and solid-state switch structures promises to increase PCS power, speed, and efficiency. With the increased standardization of storage systems that are quickly being mandated for grid-connected systems and sought for off-grid systems, applications requirements for the PCS are likely to become more uniform and predictable. The defined base-line requirements will allow the development of more standardized PCS devices that can be manufactured in high-volume production. Such devices are likely to have better and more predictable performance and be lower cost than the PCSs for energy storage systems that are now often custom-order items. The study cited earlier in this discussion presents the following specific R&D recommendations to improve performance and costs of PCSs for energy storage systems:

- Support the development of advanced semiconductor switches;
- Explore the options available for developing cheaper, lighter, and smaller magnetics, and for reducing losses for filter inductors and line-frequency transformers;
- Research advances in hybrid PCS controllers, including reducing software development time and cost;

- Encourage further R&D of simple and advanced converter concepts for energy storage applications; and
- Support the development of standards and codes specifically related to the PCSs used with energy storage systems and renewables.

10.2 Assumptions

This study involved several technologies, numerous potential applications, and a large range of electric power industry influences. To make this diverse set of considerations manageable and model-friendly, analysts applied a number of assumptions that are detailed in the following sections.

10.2.1 Selection of Participating Companies

Because many companies are involved in the development and commercialization of the three energy storage technologies analyzed in this study, the project team developed a plan to interview companies that had already or were about to commercialize either SMES, FES, or CAES systems. The study involved system manufacturers, but did not directly involve component manufacturers for any technology other than FES. The nascent status of FES system development motivated the team to directly involve research organizations and academic institutions that are conducting R&D of critical components in FES systems (that is, the rotor and bearings). To encourage participation and a free flow of information, nondisclosure agreements were established with organizations whose members felt a need to protect business-sensitive information. As a result, key organizations in the SMES and FES arenas shared a significant amount of information that allowed development of spreadsheet models for SMES and FES systems that effectively represent those technologies in specific electric power applications. Therefore, the analysis conducted with the models has a reasonable confidence level for identifying appropriate R&D. This report contains no information that participating organizations identified as proprietary.

10.2.2 Applications Considered in the Models

Project analysts reviewed the results of a study conducted by the ESS Program (then referred to as the Utility Battery Storage Systems program) in 1993 to establish a starting point for the selection of appropriate applications for this study (Battery Energy Storage for Utility Applications: Phase 1 - Opportunities Analysis, SNL 1994 [SAND94-2605]). Although the 1993 study focused on BES systems rather than SMES, FES or CAES systems, subsequent ESS Program analysis conducted in 1997 showed that significant overlap could exist in the applications of BES, SMES, FES, CAES, and other energy storage technologies (Report on the Energy Storage Systems Program Executive Meetings Project, SNL 1997 [SAND97-2700]). Figure 10-54 illustrates the overlap between the capabilities and potential electric power applications of a variety of energy storage technologies.

At the time of the Phase 1 Opportunities Analysis, utilities were vertically integrated and regulated. Power quality problems were estimated to cost U.S. industry $26 billion annually. Since that assessment, electric utility deregulation, restructuring, and competition have changed the business environment in which electricity is generated, delivered, and sold. By the time this project was under way, an estimate by EPRI placed the annual cost of power quality problems to U.S. industry at $400 billion. A more recent analysis published by the ESS Program in 1998 estimated the cost at $150 billion per year (Power Quality Applications Study, SNL 1998 [SAND98-1513]). Even this more modest estimate suggests that the "value" of improved power quality in the restructured industry has increased significantly since 1993.

Mindful that other applications for energy storage may have undergone similarly dramatic changes in value, the analysts for this project considered the likely effects of changes in the United States electric utility industry on the value of applications in which SMES and FES could serve most effectively. The initial list of SMES applications included only power quality improvement. The initial list of applications for FES included power quality improvement, customer-demand peak shaving, and, in the long term, renewable generation support. Interviews with stakeholders in SMES and FES development who have conducted market studies to direct their

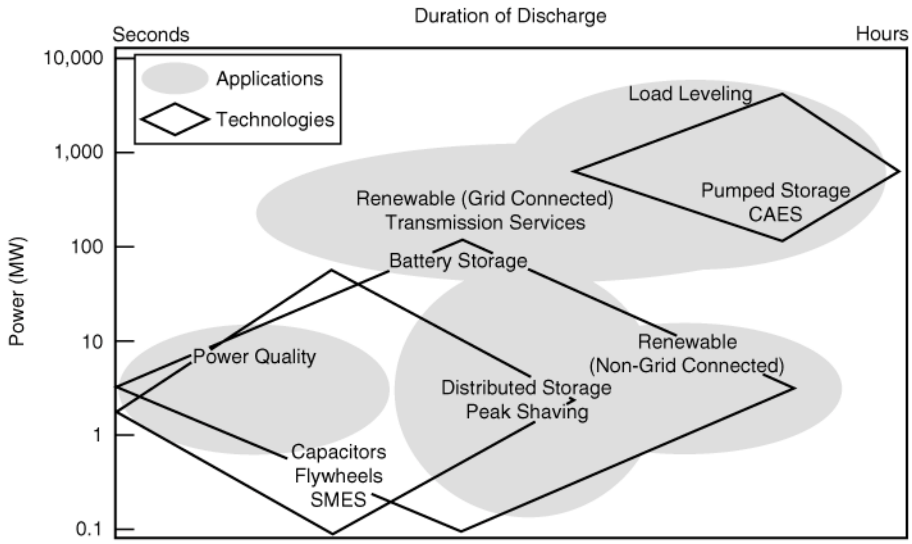

Figure 10-54. Capabilities and Potential Application of Energy Storage Technologies.

activities expanded the lists for both technologies. Table 10-6 presents the applications considered in the analysis documented in this report.

Table 10-6. Applications of SMES and FES Considered in This Analysis

Technology	Application	Size	Duration
FES/SMES	UPS battery replacement	<500 kW	<60 sec
FES/SMES	UPS battery life extender	<500 kW	<5 sec
SMES/FES	Power quality	>500 kW	<2 sec
SMES/FES	Short-term peak shaving	<1 MW	<5 min
FES	Long-term peak shaving	<10 MW	1–2 hr
FES	Remote power supply	<100 kW	1–2 hr

10.3 Industry Interviews

During the course of this study, numerous researchers and developers met with representatives of the ESS Program to assist with assembling data on SMES, FES, and CAES systems. The following sections are reports of discussions with eleven organizations that took especially active roles in providing information for this report and for the spreadsheet models of SMES and FES systems.

10.3.1 Active Power, Incorporated

11525 Stonehollow Drive, Suite 135
Austin, Texas 78758
January 7, 1998

Discussion Participants:

Joseph F. Pinkerton, President & CEO
Bryan Plater, Director, Product Marketing
Jim Balthazar, Vice President, Marketing
Bill Ott, Vice President, Sales

Active Power manufactures a steel flywheel. Their baseline product, the CleanSource flywheel, provides 400 kW of DC power for five seconds, but varied combinations of power and discharge duration are possible with the same rotor. Also, two or more rotors can be combined to serve loads up to 800 kW or more. Their marketing efforts are targeted at:

- extending battery life in UPS;
- eliminating outage/voltage sag/surge up to five seconds ("glitch protection"); replacing start-up batteries on standby gensets; and
- ride-through for low-power incidents up to one minute on gensets

Active Power has a peripheral interest in remote-power applications involving the incorporation of flywheels with diesel generation. The flywheel provides peak-power bursts, enabling the diesel generator to be smaller, which reduces cost and improves efficiency.

At the time of the interview, Active Power had installed eight flywheel units. The company is in the process of expanding its manufacturing capabilities, and they plan to deliver ten units in the first quarter of 1998. Southern Company has taken a special interest in Active Power's technology, and has tested and installed a 160-kW/15-second unit for glitch protection within their territory.

Active Power chose not to incorporate an inverter into its commercial products. This decision makes their flywheels complementary to a UPS, rather than competitive with them. The advantage of this strategy is that their product is marketed through established power quality sales and distribution channels.

In applications with UPS and chemical batteries, the CleanSource flywheel manages voltage fluctuations under five seconds, minimizing battery discharges. Previous analyses have shown that up to 85% of the total number of power quality incidents are under two seconds in duration, so the impact of a flywheel system on battery life could be significant. Moreover, Active Power is confident that many UPS customers will ultimately decide that the flywheel and inverter alone provide adequate protection. (This may explain the fact that Active Power has not been able to interest battery manufacturers in collaborative efforts.) Active Power wants to verify their battery life extension concept by conducting a test in which a standard UPS and a UPS/flywheel hybrid system are subjected to identical regimens of source voltage fluctuations. Active Power seeks to have a third party conduct the test. A key aspect of the test is the identification of an appropriate voltage fluctuation regimen.

The Active Power design includes the following innovations.

1. A single piece of forged steel serves as the flywheel, the charging motor, and the generator. This is made possible by shaping the rotor so that it has eight teeth along its edge. The teeth are magnetized and passed through a constant magnetic field to draw electric current. Timed pulses of magnetic field are induced to spin up the rotor.

2. An innovative magnetic coil design ensures that the rotor passes through a uniform magnetic field, minimizing eddy current losses. Because the rotor is spinning in a vacuum, it cannot readily reject heat, and can reach unacceptably high temperatures if the eddy current losses are not low.

3. Magnetic coils above and below the rotor are part of the bearings. A little more current in the top coil provides an upward force on the steel rotor and reduces the mechanical load on the bearings. Importantly, the rotor is not levitated. If the magnetic field fails, no touchdown occurs. The bearings are designed to support the full weight of the rotor for many months of runtime.

4. Electric energy is withdrawn from the CleanSource flywheel by inducing current through the copper coils, thus creating a magnetic field in the path of the spinning rotor. The rate of electric discharge is controlled by the strength of the induced magnetic field, and Active Power has developed a proprietary control system that enables both quick response to voltage fluctuations and precise control of the flywheel electric output.

Active Power believes that the advantages of a steel flywheel (low cost, safety, and high power density) are well suited for utility sector applications.

The list price for the CleanSource flywheel is \$150/kW, installed (400 kW for 5 seconds, \$55,000 FOB + \$2,500 installation). Active Power asserts that the maintenance cost of a flywheel system is low. The parasitic load for a 400-kW/5-second system is 1.5 kW. Active Power offers a service contract for the 400-kW flywheel system that costs \$2,000/yr. The owner of the flywheel would incur another \$500 to \$1,000/yr for maintenance activities not covered by the service contract.

In short-duration applications, steel flywheels are significantly less expensive than composite flywheels. A composite flywheel costs roughly \$50/lb, with an energy density of 40 Wh/lb, which is a materials cost of \$1,250/kWh. Steel costs \$0.50/lb, and the CleanSource flywheel has an energy density of 0.93 Wh/lb (0.56 kWh/600 lb), resulting in a materials cost of \$540/kWh.

The CleanSource flywheel is compact, largely because of the incorporation of the motor, generator, and flywheel functions in one piece of steel. Both a 400- and 800-kW unit take up 66 ft^3 of space (10 ft^2 of floor space).

The primary safety concerns associated with a flywheel are the rotor breaking apart and a failure of the bearings. Unlike composites, there is a large body of industrial experience with rotating steel equipment, and the CleanSource flywheel is operated within established guidelines (2.5 times below yield stress). Also, each rotor is tested at 20% above the operating speed.

The CleanSource flywheel is supported by ordinary ceramic bearings, which are a well developed technology. As described above, the rotor is not levitated. If the magnetic lift is disrupted, the full weight of the rotor is supported by the bearings, but there is no physical "touchdown" to cause an excessive instantaneous load and lead to catastrophic failure.

Sensors installed in the CleanSource flywheel system enable Active Power to remotely monitor key indicators (for example, bearing temperature, rotational vibration). If a critical situation is detected, the rotor can be braked by flooding the flywheel chamber with air.

Active Power believes that composite flywheels will displace steel in utility applications only in the distant future if at all. The company asserts that steel is better or as good as composites in the attributes that are important to utility customers: cost, safety, and size. The one salient advantage of composite flywheels, weight density, is irrelevant in stationary applications, according to Active Power.

10.3.2 American Superconductor Corporation (formerly Superconductivity, Inc.)

2114 Eagle Drive
Middleton, WI 53562-2550
January 8, 1998

Discussion Participants:

Christopher Strug, Director, Marketing,
Michael Gravely, EVP, Mkt. & Bus. Devel.
R.J. 'Jeff' Smith, Mgr., Sales & Metal. Engr.
Tom Abel, Manager, Government Programs

ASC manufactures SMES devices for utility power quality applications. The ASC product can provide 1 MW of electricity for one second within 5 ms of a disruption in the primary energy source. The unit is often called a micro-SMES because of comparison to early SMES concepts involving football-field size coils. The magnet is made of LTS coil, requiring a liquid helium-based cryogenic system. ASC installed the first permanent commercial SMES unit in 1993, and they now have nine installations worldwide. They sell a turnkey system contained in a semitrailer.

In late 1997, ASC introduced a new SMES system with HTS current leads and two "high-temperature" shields (50 K and 30 K). The HTS current leads are made of lead-bismuth-strontium-calcium-copper-oxide. The amount of the cooling loss by the system at 4 K has been reduced to 1 W, and the overall refrigeration load has been reduced to 18 kW_e. All of the cryogenic refrigerators are air-cooled, greatly lowering maintenance cost. The largest remaining single source of heat loss is conduction through the stanchion that supports the inner vessel.

Because of the reduced thermal losses and a larger liquid helium reservoir, the advanced SMES system can sustain normal operation for roughly 200 hours after an unplanned shutdown of the refrigeration system. This is a significant improvement over the old system and lowers the maintenance cost of deployed units. One drawback is that the new system does not contain a big helium liquefier that can be used to cool the unit down from atmospheric temperature during start-up. However, ASC has demonstrated that the logistics of starting up a unit are manageable.

The SMES magnet is a high-voltage current source, representing special power electronics challenges. Over the past several years, ASC has focused on developing the power electronics components of their system, and has obtained a number of patents.

The first-generation SMES unit, PQ DC, maintains the voltage on a DC bus. At the center of the PQ DC power electronics is a GTO power switch. When the SMES unit is in standby mode, the GTO switch is closed and current from the magnet runs through it at 2,500 V and 1,250 A. The switch is cooled to dissipate the heat caused by resistive losses. To compensate for the losses through the switch, 3 to 4 kW of electricity must be constantly charged to the coil.

When the voltage sensor sees a DC bus voltage that is out of range, an isolation switch is opened and the load becomes wholly supported by the SMES unit. The GTO switch is opened and closed, sending pulses of current from the magnet to a capacitor bank and creating a voltage source. Output from the capacitor bank is charged to a DC-DC converter to lower and stabilize the voltage to the DC bus range (400 to 480 V). The PCS contains choppers and snubbers to mute voltage and current spikes that occur when the GTO switch is opened and closed. The system is able to respond to a problem within 5 ms; it takes 4 ms for the GTO switch to open and 1 ms for the power electronics to react.

A drawback of the PQ DC is its invasiveness; that is, it must be connected to the internal workings of a DC machine or the DC bus of a UPS. Some equipment manufacturers have stated that installing a SMES or other device in such a manner voids their product warranty. In order to make their SMES product applicable to a broader range of applications, ASC sought to develop a unit capable of supporting an AC load. The AC systems are "add-ons" to the PQ DC platform.

ASC teamed with Asea Brown-Boveri (ABB) to develop the first SMES system with an AC output. It is similar to the PQ DC in that it isolates the load from the grid when it kicks in; thus, it is called a shunt-connected system. The unit is costly because it requires sophisticated switching and low-voltage (high-current) inverters. ASC recently developed a new AC design, which they have named the "PQ VR." The new system is connected to the load by a series injection transformer and does not contain an isolation switch. Pulses of current at controlled voltages (that is, voltage vectors) are combined with the source current. The voltage vectors are timed so that the sum of the SMES output and the voltage source equals an on-specification wave form. By utilizing the low-voltage energy from the primary source, the PQ VR system can protect a larger load from voltage sags than the shunt-connected system can. The PQ VR system reacts to each phase individually, so for disturbances involving one or two phases the leverage associated with the PQ VR system is greater. The PQ VR is also 15% to 20% less expensive than the shunt-connected system. A final advantage of the PQ VR is that "backing out" is easier. When the voltage source returns to normal, a shunt-connected SMES unit must synchronize the load to the primary energy source before the isolation switch closes. This is not necessary in a PQ VR because the load is never isolated from the primary source. The SMES unit simply stops injecting voltage vectors. A drawback of the PQ VR is that a load of 40 to 50 kW must be maintained to the injection transformer to prevent induction on the load.

Over the past six years, ASC has monitored grid electric voltage fluctuations at a total of 10 customer sites, accumulating data on 1,370 power disruptions. Their data show that for 84% of the power disruptions, the source voltage drops to a level that is no less than 50% of the minimum specified voltage and recovers within two seconds. Thus PQ VR can protect a facility from more than 80% of its power quality problems at a significantly lower cost than the shunt-connected system.

Table 10-7 below shows the cost contributions and standby loads for the three different PCS options.

Table 10-7. Costs of PCS Configurations

Configuration Type	% of System Cost	System Standby Load (kW)
PQ DC	22%	37*
Shunt-connected AC	44%	95
PQ VR	56%	86

* 18 kW because of to cryogenics, 4 kW to recharge the coil to account for resistive losses through the GTO switch, and 15 kW to operate a liquid cooler for the GTO switch.

ASC manufactures the magnet from niobium tin (NbSn) wire with a copper buffer. The copper buffer is used to provide ductility and also to provide a path for electricity in the event that portions of the NbSn wire lose their superconducting properties. The process of getting from NbSn and copper to a magnet is quite complex. Rods of NbSn are packed in a copper annulus and heat-treated so that the copper melts around each NbSn rod. Numerous rollings followed by heat treatment to restore ductility produce a 1/16-inch-diameter copper wire with little filaments of NbSn in it (that is, a NbSn copper matrix). Twelve of these wires are wound into a Rutherford-style coil and the coil is coated with epoxy.

The coated coils are then wound in a proprietary process to make a magnet. The quick discharges of a SMES duty cycle expose the coil to large changes in current over a short period of time (high dI/dt). The nature of the proprietary winding enables the coil to expand and contract with the resulting changes in Lorenz forces without causing significant eddy currents, thus giving the magnet good dI/dt capacity. The power output of the SMES unit is limited by the dI/dt tolerance of the magnet. A 1-MW SMES unit contains five miles of 1/16-inch wire.

In addition to its present supplier of LTS wire, ASC is seeking to develop another source of wire manufactured from a different process. The details of the new wire and its potential impact on the SMES system are proprietary.

ASC performs a significant amount of site-specific testing and engineering to support each deployment. The first task is identifying and quantifying the benefits that the SMES unit can provide for a potential customer. To do that, ASC must determine the sensitivity of the load to voltage fluctuations and the cost of equipment shutdowns. Also, they must assess the quality of power that the facility receives (the frequency, duration, and severity of voltage fluctuations and power outages). Often the quality of power depends on the local electricity transmission and distribution situation and nearby loads. Setting the tolerance of the system is a compromise between the desire to be certain of protecting the load and the desire to avoid cycling the SMES frequently in response to insignificant fluctuations in voltage; ±10% is a typical optimum.

After assessing the situation, ASC determines the required size of the SMES system, its control settings, and the optimum insertion point into a customer site. Importantly, from the deployment at Tinker Air Force Base, ASC has learned how to combine the standard 1-MW units in parallel, thus enabling them to serve loads over 1 MW.

ASC plans to continue incremental improvement of the LTS cryogenic system, and to continue to reduce manufacturing costs. They are also exploring more fundamental changes in the design that will (1) improve the dI/dt tolerance of the magnet and thus raise the power rating of the standard system, and (2) increase the current and voltage rating of the magnet to increase the stored energy. In the higher voltage design, ASC expects to split the current and discharge the magnet through parallel standard power control systems, rather than go to alternative switch technology. A mid-term goal of ASC is to develop a 10-MW system for utility substation applications.

10.3.3 Beacon Power

A SatCon Company
6 Gill Street, Woburn Industrial Park
Woburn, MA 01801-1721
February 19, 1998

Discussion Participants:

Joseph R. Saliba, VP, Marketing

Richard L. Hockney, P.E., VP, Engineering

Beacon Power is a newly formed subsidiary of SatCon Technology Corporation. SatCon is a diversified developer of power electronics and has become a leader in composite flywheel technology. Beacon Power was formed to focus on the development of near-term commercial flywheel products.

Beacon Power is planning to launch its first commercial product, a composite flywheel that can deliver 1 kW of DC electricity for two hours. Beacon hopes to displace lead-acid batteries in UPSs, especially in remote applications where battery maintenance is expensive, and also in warmer areas where battery life is short.

Beacon's general approach in designing their flywheel was to sacrifice density to reduce the flywheel cost. Their flywheel rotor weighs 150 pounds and is made of a carbon outer rim with a glass fiber interior. The rotor is manufactured through a proprietary continuous filament winding process. A proprietary steel hub connects the flywheel to the shaft, expanding and contracting with the flywheel.

The rotor is vertically oriented and is suspended by a large magnet using attractive force. A four-axis passive bearing system keeps the rotor centered, and the flywheel contains a touchdown bearing in the event of primary magnet failure.

An ion pump maintains the factory-drawn, weld-sealed vacuum while the unit is in the field. The primary load on the ion pump is degassing of the rotor resin. Beacon is seeking to identify an ion pump that will last seven years without maintenance (this is especially important for the buried units). The unit employs a brushless permanent magnet motor. The overall standby load for the 1-kW, 2-hour system is 30 W.

Beacon is focused on safety. The nominal rotor operating speed is 30,000 rpm, which is well below its estimated burst speed of 46,000 rpm. Also, Beacon is confident that they will be able to detect rotor cracks in the early stages by monitoring the rotational orbit of the flywheel. Other key data that Beacon will monitor are temperature and parasitic losses.

Beacon plans to bury the flywheels in the early installations. The UPS power electronics would stay above ground. After a significant amount of operating hours without incident, Beacon plans to offer above-ground installations to reduce costs. Interestingly, some customers like the buried system because of the reduced footprint.

Beacon presented preliminary cost targets for their flywheel systems. For small quantity orders the FOB cost for a 2-kWh system is projected to be $4,000 to $5,000 and the cost of the 4 kWh unit is projected to be $6,000 to $8,000.

10.3.4 Boeing Corporation

P.O. Box 3999
Seattle, WA 98124
September 2, 1998

Discussion Participants:

S.B. Wright, Bus. Dev. Tech./Process Mgr.
Alan Boutilier, Mgr., Bus. Dev., Res. & Tech.
Michael Strasik, Ph.D., Lead Principal Engineer
Arthur Day, Principal Engineer
Patrick Gallagher, Principal Engineer
Tom Martin, Structures Technology
Lynn Hanam, FESS Bus. Case Dev. Leader
John Barton, Mgr., Pwr. Sys. Research & Tech.

Boeing manufactures and develops commercial aircraft, military aircraft and missiles, space transportation systems, space systems, and information and communication systems. The company's core competencies include large-scale systems integration and lean, efficient design and production. Most representatives from Boeing are associated with Phantom Works, Boeing's R&D arm. In developing new technologies, Phantom Works seeks to develop new products for new markets and develop components that can improve existing integrated products offered by Boeing. Building on their existing capabilities in the areas of rotating equipment, carbon composite materials, and HTS materials, Boeing is developing flywheel-based energy storage systems. Their flywheel design and development efforts are focused on reducing the projected high-volume manufacturing cost of an integrated system.

Boeing's first experience with flywheel technology was in the development of gas centrifuge enrichment systems for the DOE in 1979. The separation efficiency is proportional to the cube of the centrifuge velocity; thus there is a strong incentive to spin the centrifuge at high speed. Boeing developed materials that could achieve top speeds of 960 meters per second, greatly improving the process performance. Unfortunately, the centrifuge technology was not as effective as laser isotope separation, and the DOE centrifuge project was canceled in 1983.

After the DOE contract ended, Boeing investigated the idea of using their flywheel capabilities to build a 1-MWh flywheel system with Argonne National Laboratory and Commonwealth Edison. Assessment of grid-connected load-leveling applications revealed a rotor manufacturing cost goal of $20/lb. At the time, Boeing's manufacturing costs were as high as $1,000/lb for carbonaceous structures. Boeing studied the cost basis for carbon composite materials, and found the cost of electricity used in the manufacturing process to be a major component. Boeing's cost projections were in the $50/lb to $100/lb range for large flywheel structures, and so load leveling was not pursued at that time.

Boeing is primarily interested in two target markets for flywheel products: terrestrial power supply and space systems. Power supply applications include power quality, UPS, and load leveling. Backup power systems for the telecommunications industry are a significant application need. As a part of their primary business area, Boeing is familiar with power quality issues and lead-acid battery UPS systems. Conversations that Boeing representatives have had with industry indicate that the market entry price for flywheel systems providing several minutes to an hour of power range from $500/kW to $1,500/kW. Boeing's approach is to build a standard rotor/bearing platform and match the motor/generator size to the discharge duration requirements of the various applications.

In a partnership with NASA, Boeing is developing a flywheel for space applications entitled Attitude Control and Energy Storage Experiment (ACESE). Experience has shown that the two most common causes of satellite "death" are failure of the batteries and depletion of propellant for attitude control rockets. The ACESE program objective is to replace nickel-hydrogen batteries with a flywheel-based energy storage systems. The advantage of a flywheel over a battery is that the flywheel system will last longer, will weigh much less, and is temperature insensitive, thereby simplifying satellite design. The flywheel system will be made up of two counter-rotating rotors, and the attitude of the satellite will be controlled by adjusting the relative rotational speed of the two rotors, thus applying gyroscopic force to the satellite body. The weight savings associated with flywheels also reduce launch costs, which average $10,000/lb.

Boeing plans to employ relatively thin-walled rotors. Boeing estimates that a rotor with an inner to outer radius ratio of 0.7 holds 75% of the energy stored in a solid disk and uses much less material. Boeing's current hub design uses filament-wound, carbon-fiber composite materials that expand and contract with the rotor at different speeds.

Boeing is also developing a rotor winding machine that uses tapes of carbon fibers in thermoplastic resin. The tape is several tows thick and the width equals the width of the rotor. The machine remelts the thermoplastic by conductive heating and applies the tape to a mandrel at a rate of half an inch per second. Boeing's tape-winding machine offers a ten-fold increase in manufacturing rate.

Boeing's passive bearing system uses a combination of ball bearings, conventional magnets, and HTS magnets. The rotor is fully levitated during spinning operation and Boeing expects system losses of 0.1% of the total energy stored per hour. Conventional magnets provide 95% of the vertical lift. The HTS magnets provide some incremental lift, but mostly lateral support because of flux pinning. Boeing has achieved success with their HTS bearings largely because they are able to produce high-quality YBCO superconducting magnets. They report a critical current of 4,000 A/cm^2 and a magnetic field of 1.25 T from a 1-inch-diameter disk. The bearing system will operate at roughly 70 K, and require 1 W of thermal energy per kilowatt hour of stored energy. Boeing is considering both conventional and advanced cryogenic refrigeration systems.

Figure 10-55 is a schematic of Boeing's flywheel assembly design. A ball bearing assembly supports the rotor at rest. During start-up, the rotor spins on the ball bearings until it has reached super-critical speed, at which time it is transferred to the magnetic bearings. The ball bearings maintain rotor stability as it passes through critical frequencies. During normal operation the rotor is maintained above its critical speed. Development efforts include achieving consistent magnetic fields from the magnet segments (both conventional and superconducting) and designing systems for start-up and shutdown.

A permanent magnet motor (using NdFeB) is attached to the rotor shaft and provides high efficiency and instantaneous response.

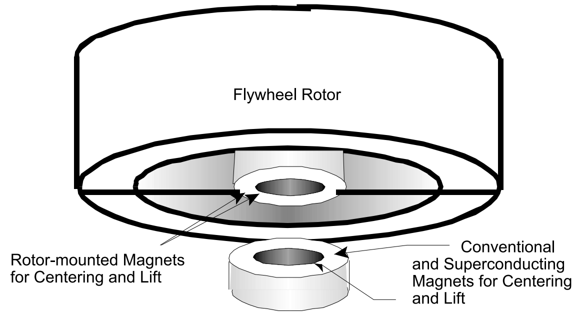

Figure 10-55. Schematic of Boeing's Flywheel Assembly.

The Defense Advanced Research Projects Agency (DARPA) is conducting spin tests of rotors from several flywheel manufacturers. Boeing plans to use these results to establish safety factors for their rotors. Boeing has significant experience with industrial safety and plans to use that experience on flywheel system design.

Boeing has also worked on a containment system design for which Boeing is seeking a patent. In modeling a rotor failure, Boeing treats the released rotor material that collides with the inner wall of the containment system as a liquid, which flows up the containment vessel wall until it reaches the top. Model results show the pressure on the containment vessel lid reaching 70,000 to 80,000 psi. Boeing has invented a novel containment wall design that absorbs the energy from the rotor material and minimizes the concentration of energy on the containment vessel lid.

10.3.5 Intermagnetics General Corporation

450 Old Niskayuna Road
P.O. Box 461
Latham, NY 12110-0461
518-782-1122

Discussion Participants:

A. Kamal Kalafala, Ph.D., Program Manager, Magnet Business Unit

IGC manufactures fully integrated superconducting magnetic energy storage systems that address momentary sags, spikes, and interruptions in electrical power. An IGC device installed at Tyndall Air Force Base in Panama City, Florida, is one of the company's IPQ-75™ products that are available in several configurations: transportable, relocatable, or fixed site, with or without site monitoring. The system at Tyndall includes a 6-MJ superconducting magnetic coil, a closed-loop cryocooler, and commercial-off-the-shelf power conditioning and remote monitoring units. The system is integrated into a relocatable shelter. Final acceptance testing of the system was completed in February 1998.

The micro-SMES system uses the controlled discharge of 6 MJ of stored magnetic energy to provide ride-through protection for loads up to 750 kVA. Housed in a mobile/relocatable shelter, the system minimizes on-site engineering and system integration and provides what IGC calls "plug-and-play" power conditioning. The system is intended for unmanned operation, similar to commercially available UPS systems.

The magnet has many design features that are based on Intermagnetics' industrial experience in magnetic resonance imaging (MRI) magnet production. Advanced features of the magnet include HTS current leads and a cryocooler-based, zero helium boil-off refrigeration subsystem provided by APD/Cryogenics, a wholly owned subsidiary of Intermagnetics.

The magnet control unit (MCU) is a microprocessor-based device that performs monitoring and control functions. The power conditioning system consists of a commercially available uninterruptible power module (UPM) and an magnet interface unit (MIU) designed for the IPQ-75™ system. The UPM is a standard 750-kVA/600-kW Series 600, provided by Liebert Corporation. Confidence in system reliability partially stems from Liebert's field experience with the UPM (more than 1,400 installed units, and nearly 1.5 million operating hours). The MIU extracts energy from the magnet at a set voltage (at Tyndall, 1,000 V) and delivers the energy, under control of a voltage feedback loop, to the 500 Vdc bus of the UPM. A DC/DC chopper circuit steps the voltage down from 1,000 V to 500 V. The MIU controls the magnet charge rate through an AC/adjustable DC voltage power supply.

Liebert also supplies the SiteScan® 2000 monitoring system in the SMES system. The system monitors day-to-day operations and gathers long-term trends in performance characteristics. Up to three remote monitoring stations can poll information from the system.

The shelter for the Tyndall system is about 12 meters long, 2.5 meters wide, and 2.6 meters tall. The SMES system weighs 24,991 kg. All utility and load electrical feed cables are connected on the outside of the one end of the shelter and are accessible through a secure enclosure. Apart from the electrical connection at the site, the system requires no on-site engineering or utilities. The inside of the shelter is a temperature-controlled environment.

Challenges to SMES system installation and operation include power integration issues, control optimization issues, and issues involving the integration of ancillary functions. At Tyndall, power integration issues included compatibility of semiconductor switch selection, proper snubber circuitry, proper power geometry and layout and optimum energy storage in the intermittent voltage level stages. Control optimization issues included:

- adjustment of the 1,000 Vdc and 500 Vdc chopper frequencies and duty cycles to match the demand characteristic of the UPM;
- elimination of noise on the magnet charge circuitry caused by a reflection of the chopper frequency (through the rectifier snubbers on the charger) on to the primary of the magnet charging transformer; and
- reduction of the time needed to transfer power to UPM input from the DC source following a utility outage and discharge of the magnet to take maximum advantage of stored energy in the magnet.

The primary issue involving the integration of ancillary functions was ensuring that the interfaces between protective and monitoring circuitry of the magnet, MIU, and UPM remain within specified limits.

IGC has also been active with the DOE Superconductivity Program in development of HTS magnetic bearings for FES systems.

10.3.6 Lawrence Livermore National Laboratory

P.O. Box 808, L-641
Livermore, CA 94551
June 19, 1998

Discussion Participants:

Ray Smith, Advanced Energy Research Engineer
Keith Thomassen, Deputy Associate Director, Energy Programs

The work on flywheels at LLNL originated with research for transportation applications. Important concepts for high-efficiency motor/generators and passive magnetic bearings were investigated. However, the lack of compact and light containment proved to be a critical issue for flywheels in vehicles. The motor/generator technology was licensed to Trinity Flywheel for commercialization.

The key development at LLNL was the use of a Halbach array as a high-efficiency motor/generator. Halbach published the array concept several years ago, but when inductively loaded circuits are moved relative to a Halbach array of magnets, current is induced that provides for a low-loss, integral motor/generator.

Another development is a passive magnetic bearing concept. Magnets are used to levitate the rotor and form a passive bearing that does not require active control. Whirl instabilities are countered by asymmetric placement of the array magnets and through electrodynamic damping elements. This concept provides a room-temperature, low-loss bearing system for the use of composite rotors for higher energy density flywheels. The bearings have been tested and destructed at about 70,000 rpm. Normal use would be at about 35,000 rpm, and limited-life testing has been conducted at lower speeds.

LLNL has investigated Toray carbon composite materials for rotors. It has conceptualized a flywheel system with the composite rotor, passive magnetic bearings, and Halbach array motor/generator and done some preliminary design work. Applications for this "electromechanical battery" are thought to include transportation, distributed stationary energy storage, UPS use, and pulsed power systems.

LLNL is also working on superconducting materials and coil designs for an internationally funded fusion energy development program. They have plans to test a 400-MJ toroidal superconducting coil with possible uses in SMES. However, the large inductive forces may crush the coil and be very difficult to control.

LLNL continues to work with Trinity, Toray, and other organizations.

10.3.7 Penn State University

Applied Research Laboratory
University Park, PA
February 18, 1998

Discussion Participants:

Charles E. Bakis, Ph.D., Professor of Engineering and Mechanics

Professor Bakis and his students are working with a number of private-sector flywheel and flywheel system developers in several areas:

- design, especially design rationale,
- composite rotor manufacturing, especially in scalable processes,
- spin testing of rotors,
- material characterizations involving creep, fatigue, and quasi-static behavior,
- health monitoring for multiple ring rotors, and
- novel approaches to relieving radial stress with elastomeric interlayers and/or matrices.

Professor Bakis reviewed the physics of flywheel design and the mechanics of flywheel performance, as discussed in the primer of this document (Section 10.1). The summary of the review is that a flywheel's energy capacity depends on the moment of inertia and speed of the rotor. The moment of inertia depends on both density and geometry, and speed is limited by material strength. Therefore, the energy capacity is governed by the specific energy of the rotor. While this relation would suggest using the strongest, lightest materials, Bakis believes that a cost/performance benefit seems to exist for 'cheaper' fibers. If this benefit proves to exist, it would indicate that the least expensive carbon fibers rather than the most expensive are the ideal selection for flywheels. Bakis provided ball-park prices for materials commonly used in rotors: e-glass: $1/lb, s-glass: $6/lb, AS4C carbon: $18/lb, T1000 carbon: $75/lb, steel: <$1/lb, resin: $5/lb.

Bakis projects that the infrastructure uses of carbon fiber may drive its price to approximately $10/lb between the years 2000 and 2005, but he believes that to reach a $5/lb mark, a lot more carbon fiber sales will have to occur. Right now, he estimates that approximately 10 composite rotor manufacturers exist, and either their number or the volume of their carbon-fiber purchases must dramatically increase for them to dominate the market and affect price. For now, the fiber use in other applications drives its cost. Bakis did not discuss Kevlar fiber properties or costs, stating that its use fell out of favor in the rotor arena.

Penn State has direct ties to the fiber industry through recent graduate student Chris Gabrys, who is now working at Toray, a major provider of fibers and prepreg materials for composites. (Gabrys is also a student with whom Bakis worked on elastomeric interlayers in multi-ring rotors and elastomeric matrices to change the stress profile of the rotor.) Toray, in addition to its fiber and prepreg supply business, is involved with development and manufacture of composite flywheel rotors. Other organizations in which Penn State has interacted in flywheel R&D are Commonwealth Edison, DARPA, NASA Lewis, and LLNL.

Most of Penn State's work with industry has involved circumferential filament winding. Bakis acknowledges RTM as a potential rotor manufacturing process, and believes that DOW is doing it. However, Bakis suspects that RTM rotors may develop matrix cracks that cause failures similar to those in steel rotors, in which the cracks are 120 degrees from each other and the rotor breaks into three large pieces. His experience is that laminated composite rotors tend to fail like steel.

Because the waste in filament winding is very low, it can support a very high manufacturing yield. However, experience at Penn State suggests that increasing manufacturing speed of filament winding will be necessary to reach production scale. In general, the matrix resin must cure enough to prevent the fibers in interior layers of the rotor from buckling when the outside layers are deposited. At present, Penn State is able to achieve an eight-inch per hour radial accretion rate of rotor wall on a mandrel by heating the mandrel to accelerate resin curing.

Many flywheel developers are interested in developing rotors with a shape that is more cylindrical than disk-like to increase the moment of inertia, and reduce the rotor speed required to achieve a given energy capacity. However, the cylindrical shape also experiences greater stresses than a disk, and the design requires a trade-off to balance energy capacity with the ability of the rotor to survive the stress of its own rotation. Rotor designers also have to concern themselves with the axial strength of cylindrical rotors. At present, no one has found a way in which elastomeric materials can add to the energy capacity of a rotor. Penn State is investigating using elastomeric materials to make cylinders more ductile along their axis without increasing parasitic losses during rotor operation.

In addition to the rotor, a flywheel also consists of a hub, shaft, bearings, and the vacuum in which it spins. The connection between the rotor and the hub of a flywheel is a design consideration. Designs include a number of types of rotor/hub interfaces: adhesive, spline, and spring. The shaft can be flexible or rigid. The appropriate shaft rigidity is related to the rotor material and the type of bearing. The rigidity of the shaft and the stiffness of the bearings can accommodate a shifting center of gravity for an elastomeric rotor (or other rotors that have a shifting center of gravity for other reasons). At present, developers use several kinds of bearings that range from ball bearings to magnetic bearings to high-temperature superconducting magnetic bearings. Some of the bearings keep the shaft centered through mechanical resistance to travel; others use active magnetic controls. The best bearing frictions are down to 10^{-7}. The level of vacuum for flywheel systems varies considerably, from 10 μTorr to 100 mTorr. Vacuums can be sealed, have roughing pumps, or be very sophisticated. While out-gassing of a composite rotor (as it heats from operation and is affected by a vacuum environment) may be an issue for vacuum maintenance in flywheel systems, Penn State's experience has not identified specific problems. The University's experience has instead directed the focus of R&D toward the rotor. The areas in which Bakis perceives the most need for work are:

- development of improved manufacturing processes (faster and more consistent)
- development of codes and standards for manufacturing processes
- determination of rotor performance and life through spin and burst testing
- development of codes and standards for rotor performance and life.

10.3.8 Trinity Flywheel Power

6724D Preston Avenue
Livermore, CA 94550
June 19, 1998

Discussion Participants:

John Eastwood, President
Donald A. Bender, VP - Engineering

Trinity has two flywheel rotor sizes, the MK2 and MK3, that have common attributes. The MK2 has a diameter of 9 inches and a height of 12 inches. The MK3 is 12 inches in diameter and 14 inches tall. The MK2 weighs 60 pounds, and the MK3 weighs 86 pounds. The MK2 operating speed is 43,800 rpm, and the MK3 operating speed is 40,800 rpm. Other than these distinctions, the two rotors have many similarities. Both rotors are made from glass and carbon fibers and epoxy composites. The rotors have a mechanical interface to a hub. Both rotors use ceramic ball bearings (future products may include passive magnetic bearings). Both rotors have a "drum-like" monolithic architecture with permanent magnets mounted on the inner diameter.

Trinity products can serve either AC or DC loads. The stationary applications for the systems include integration into OEM or installation into a power supply in existing equipment. The systems can provide 300 to 800 Vdc or 3-phase AC service via an adjustable speed drive. Mobile and custom configurations are also possible. At present, one DC product delivers 50 kW for 20 seconds at 300 Vdc (nominal range between 240 and 400 Vdc). A second product delivers 700 kW for five seconds at 800 Vdc. That system has outer dimensions of 24 inches × 24 inches × 32 inches, weighs 400 to 600 pounds, and requires about two minutes to recharge. Trinity is building stationary 100-kW/15-second modules that can provide instantaneous backup power for the DC bus of an adjustable speed drive and a 480 Vac version of the same unit.

Trinity also has an AC product in mind with Acumentrics power electronics that will have three bi-directional ports: one for a utility, one for a FES, and one for a battery. The voltage could be either 208 or 480 Vac. A prototype under development will use modules that have MK3 rotors and IGBT power electronics to provide 1 MW of power for 10 seconds. The unit will have sub-cycle response time, and be about 88 inches wide, 22 inches deep, and 60 inches tall. Trinity expects the system's price to be competitive with similar existing superconducting magnet and battery-based storage products for power quality (in the traditional terms of $/kW, SMES and battery systems are about $1000/kW now for short discharge, high power systems MW/s).

Trinity is exchanging ideas with the other developers including U.S. Flywheel, SatCon, and the University of Texas - CEM, Penn State – ARL, and is developing a relationship with NASA Lewis. Trinity is working closely with LLNL (Don Bender was at Livermore for 12 years as an engineer) on passive magnetic levitation, the magnet that is the most likely candidate for next-generation Trinity products and the subject of a bid for a federal request for proposal that is yet to be awarded. Bearings based on passive magnetic levitation are expected to compete with HTS bearing performance, only at ambient temperatures.

The ceramic ball bearings now being used in Trinity's products are outboard; neither they nor the motor transmit heat to the rotor. The rotor operating temperature is 10°C to 20°C above ambient. Experience with bearings during burst testing suggests that while the ball bearing is not viable for electric vehicle applications (in which "incidents" occur continuously), ball bearings can serve successfully in near-term development of flywheels for stationary applications (that require the bearings survive a few incidents in a lifetime). One event at Trinity demonstrated that the present bearings and flywheel itself can survive major incidents. During a spin test, a flywheel that was rotating at more than 50,000 rpm dropped and broke its quill shaft. The rotor spun on the stub for an hour and a quarter until it tipped. The rotor was unscratched and continued to be used in other spin tests. Trinity's fundamental reason for moving toward passive magnetic bearings is that the current warranty on the ceramic bearing life is about one year. With passive magnetic levitation, the warranty could be 10 to 20 years (the life of the system, or some large fraction of the life of the system).

Trinity is using a modular approach, "stacking" rotor modules to get sizes for specific markets. The first products are addressing markets for discharge durations from 0.5 second to 1 minute, with most between 1 to 20 seconds. They made this selection because the products are cost competitive at that level. As the ESS Program discovered for batteries, Trinity has found that discussing $/kW or $/kWh is difficult (at best) because those methods of determining costs are not orthogonal treatments of the cost components. For example, the $/kW for a 50kW inverter is the same as the $/kW for a 300kW inverter, but the cost of the controller is not the same; the cost of the controller dominates the total cost. Instead, Trinity considers power components, energy components, and balance of plant (BOP) as three separate cost components. Power components include the inverter, controller, permanent magnets, and stator. The composite part of the rotor is the only energy component. The BOP is everything else: hub, bearings, containment, sensors, vacuum system, cooling system, enclosure, mounting, structural elements, bearing mounts, non-power wiring, even the nuts and bolts. The BOP dominates cost in a short-discharge (several seconds) system. Power electronics in a DC system are less than 1/3 of total cost and in an AC system are only slightly greater than 1/3 of the total system cost. In short-discharge systems, the rotor contributes less than 10% of the total system cost. Just as battery-based energy storage systems seem to become noneconomical for applications over two hours in duration, Trinity has found that composite flywheels become noneconomical for applications between one and three minutes; the carbon fiber cost drives the total cost to unacceptable levels in this range.

Instead of less than 10% of total system cost (as in the short-duration discharge systems), the cost of the carbon fiber in a five-minute system would probably exceed 50% of the total system cost. For a one- to two-hour system, the carbon fiber cost would completely dominate the system cost. Therefore, the five-minute system will be cost-effective only if market demand drives high-volume sales that drop the carbon fiber cost substantially. Trinity has the technical capability to make a five-minute system and even a 25-kWh system with PV that can do one- to two-hour discharges, but do not expect the carbon fiber costs to drop enough to make the products economically feasible. The one- to two-hour system, in particular, is a long-term development goal. Right now other applications for carbon fibers are driving cost (pressure vessels and infrastructure applications), and the sales volume is insufficient to lower the costs for composite flywheels that use carbon fibers.

Bender estimates that the barriers to FES products are about equal parts technical obstacles, market development, and capitalization. Trinity has been doing its work by equity financing. All of the work with Lawrence Livermore has been funds-in to the lab. Trinity believes that private companies are facing some high risk R&D obstacles that they are unlikely to handle without federal assistance; the first-order issue is bearings. The second-order issue is a coordinated life program and criteria for safe operation standards from the beginning of life. While Trinity believes that an industry-wide system-level approach to safety is necessary, Bender's experience with utility and automotive technical managers suggests that end-users may be overlooking that need. In general, the technical managers that have looked at Trinity products, the people who are usually very careful to have and adhere to codes, "don't care (if the product is developed under some standard code) and assume it's safe." Even without this customer-pull for standards, Trinity is actively pursuing them (white paper on web-site: www.trinityflywheel.com).

While several developers view rotor production speed as a high priority for R&D, Trinity sees it as a third-order issue. Trinity sees carbon material cost as the real limit since the rotor-manufacturing process is scalable by simultaneously making several rotors on the same mandrel. The issue is a chicken-and-egg problem: material cost will come down if the market volume is high; the market volume will be high if the benefit/cost is good and the products are available when demand occurs; availability will depend on manufacturing volume. Therefore, initial R&D should focus on things other than increasing manufacturing speed, and developers should keep watching for viable ways to increase production volume so that they are prepared for any sudden demand and market window of opportunity.

Trinity has conducted a number of market studies over the last five years to identify niches for their products. The first set of short duration products is the result of the carbon-cost limitation and the results of the market studies. Trinity believes that real market-pull is the force that is motivating the tremendous interest that Trinity is witnessing on the part of potential end-users in evaluation systems.

10.3.9 University of Texas Center for Electromechanics

The University of Texas at Austin
J.J. Pickle Research Campus
Mail Code #R7000
Austin, TX 78712
January 6, 1998

Discussion Participants:

Dr. Steven P. Nichols, P.E., Acting Director

John H. Price, Research Associate
Ted Aanstoos, P.E., Research Engineer
John Pappas, Research Engineer Associate

UT-CEM is one of 84 research units managed by the University of Texas at Austin. Its annual budget has been relatively stable from $10 million to $15 million over the past ten years. However, starting five years ago UT-CEM's funding base has become much more diversified. Previously, 90% of the funding came from the DoD.

UT-CEM's early work in electromechanics centered on the development of pulsed rotating power supplies and electric guns for the DoD. An electric gun uses pulses of electric current to accelerate an armature that drives a payload. Among other advantages, an electric gun's exit velocity is not limited by the thermodynamic velocity of an explosive charge. UT-CEM's efforts in stationary and mobile FESS have benefited significantly from their expertise in high-power, high energy pulsed rotating machines.

Currently, in a project jointly funded by DARPA and the Federal Railroad Administration, UT-CEM is developing a 600 MJ, 3 MW prototype flywheel to be used as the energy storage component of a hybrid electric power system for a locomotive. The first integrated flywheel system is scheduled to be available in 2000. Also, working in partnership with EPRI and Texas Utilities, UT-CEM plans a study of utility applications for composite flywheels.

UT-CEM is involved in a teaming arrangement with AlliedSignal. AlliedSignal is supplying the motor component of the locomotive flywheel system, and has helped UT-CEM develop a concept for a microturbine/flywheel hybrid system. The flywheel rotor and the turbine share the same shaft, and the flywheel provides inertia for the microturbine. Also, UT-CEM is working with AlliedSignal to organize a for-profit R&D consortium to advance flywheel technology for aerospace applications. Prospective participants in the consortium include AlliedSignal, Boeing, and TRW.

UT-CEM's approach to technology development is to take "big steps," that is, to build something that is much larger and more advanced than anything else that exists. The big step approach has three stages. First, UT-CEM uses analytical tools to extrapolate a design from what is known about a technology. Next, they build and test components. Finally, using models and the results of component testing, they build a prototype. This philosophy is exemplified in the 3 MW flywheel, which will be an order of magnitude larger than any existing single-rotor composite flywheel.

A significant accomplishment of UT-CEM is the development of the rotor component for the 3 MW locomotive flywheel. The rotor is 2 feet in diameter and 2 feet high. It spins at 45,000 rpm with a tip speed of 968 meters per second (tip speed is the linear velocity of material at the periphery of the rotor). The flywheel system is able to discharge at a rate of 3 MW for two and a half minutes. The rotor is made up of layers of "pre-impregnated" composite material separated by thin layers of glass that inhibit crack propagation and break up eddy currents caused by magnetic fields.

In order to get the most energy per unit of composite material, the inner diameter of the composite rim is relatively large (the material near the outer edge of a disk has a higher velocity and holds more kinetic energy). Thus, a key component is the arbor that connects the inner surface of the rotor to the flywheel shaft. The arbor design is made more difficult because the composite rotor inner diameter expands roughly 1/4 inch between idle and 45,000 rpm. UT-CEM has developed a proprietary conical arbor structure that is lightweight and able to expand and contract with the rotor.

The composite is fabricated in several individual annular sections that are press-fit together. UT-CEM subcontracts the composite winding, but they develop their own materials and closely monitor the fabrication process. The annular components are pressed together onsite. An important advancement in rotor construction is designing the rotor so that the inner windings do not rely wholly on the outer windings for strength. If an outer winding fails, the circumferential force on the winding below it will increase, but not above its design strength. In that way individual winding failures will not cause a domino effect.

Safety is a key issue in flywheel development. Early predictions that a composite flywheel could be designed so that it fails with no shrapnel danger (that is, feather burst) have not yet been realized. Another early approach to safety was to build a containment system that can withstand the worst-case failure. This requires an estimate of the highest possible external force that can result from a failure, and UT-CEM has developed significant competency in this area. Argonne National Laboratory first investigated the basic principles.

There are two categories of flywheel systems failures: rotor failure and loose rotor. A rotor failure causes external forces an order of magnitude greater than a loose rotor event, because 90% of the rotor's kinetic energy is dissipated by friction. In a rotor failure, the magnitude of the external force depends on how many pieces the rotor breaks into initially; the worst case would be a few big chunks, because they would land against the outer shell with the most force.

The force of a worst-case rotor failure is strong enough that containment systems designed for it are too heavy for vehicular and aerospace applications. In utility applications, a flywheel could be buried to contain a failure, but this may not be cost-effective because it requires a high degree of site-specific engineering for each deployment. As a result, composite flywheel developers have begun to develop a database of rotor failure analysis data. Developers are attempting to identify a target operating speed for a specific rotor at which there is an acceptably low level of failure risk based on statistical analysis of the data, as is done for jet engine and electric power turbines. Under this approach the containment system is designed to protect against a loose rotor event only. NASA is leading this effort, and UT-CEM plans to incorporate the results in future designs.

UT-CEM's current methodology for developing a rotor at specific operating speeds is as follows. Individual rotor ring components are hydrostatistically tested to determine their burst pressure. Based on the burst pressure of the individual rings, a burst rpm of the fully assembled rotor is calculated. Currently, the operating rpm is set two standard deviations below the burst rpm (that is, 2 sigma). The UT-CEM goal is to improve composite performance to where the current operating rpm is six standard deviations from the burst rpm, thereby increasing the margin.

UT-CEM recently conducted failure test of a composite flywheel that produced some interesting results. They spun a rotor assembly up and exploded a charge near the bottom face of the rotor on the inside of the flywheel container. The charge was designed to cause a rotor failure, and it did cause the rotor to crack. However, the crack only propagated about a third of the rotor length. The bottom third of the rotor fell away from the top. The containment vessel had a screw lid construction designed to absorb energy from a loose rotor event. Because of the nature of the rotor failure, the screw turned the wrong way and the top of the rotor containment vessel unscrewed and came off. From these results, one can conclude that the rotor is robust and is likely to withstand an external event (for example, earthquake, explosion, forklift runs into the assembly) without failing catastrophically. Another conclusion is that the screw construction of the containment vessel must be reconsidered.

In cooperation with EPRI and Texas Utilities, UT-CEM plans a study of commercial opportunities for composite flywheels in the utility sector. Texas Utilities is especially interested in power quality because of the large number of silicon chip manufacturers and other high-tech customers in its service territory. Phase 1 of the study will focus on design trade offs, system requirements, manufacturing, and the electrical interface. An initial effort will be to chart the performance characteristics of the various energy storage/power quality options (for example, batteries, steel flywheels) and identify areas where composite flywheels have an advantage.

Key objectives of the Phase 1 effort will be to determine the specifications of a utility sector composite flywheel product, quantify the size of its potential market, estimate a target sales price and a manufacturing partner. The objective of Phase 2 is to build and test a prototype, and the objective of Phase 3 is to deploy a unit at a customer site to satisfy a real-world need.

10.3.10 Urenco, Limited

Capenhurst, Chester
Chesire, CH1 6ER
0151.473.4504
June 14, 1998

Discussion Participants:

C. D. Tarrant, New Products Manager

Urenco has 25 years of experience building centrifuges for uranium enrichment. Over the years they have perfected centrifuge designs and manufacturing processes to the point where their centrifuges can operate for over 10 years without interruption. As a result, power disruptions have become the primary cause of lost production. Several years ago the staff at Urenco began exploring options for protecting the facility against power disruptions. Flywheel-based energy storage seemed like a natural choice for Urenco, because it presented an opportunity for them to utilize their expertise in centrifuge design and manufacture.

Four years ago Urenco began developing a flywheel-based energy storage systems, and today they are on the verge of launching a commercial flywheel product for power quality applications. Their plan is to build and demonstrate units that protect their uranium enrichment facility, and then to begin selling units to outside customers. Urenco is considering a partnership with Siemens, a manufacturer of power electronics equipment, to enhance their commercial product line. Their PIROUETTE system is designed to provide 120 kW of power for up to 28 seconds. The rotor is constructed from carbon and glass fiber. Its outer diameter is roughly 300 mm and the inner diameter is 170 mm.

A critically important characteristic of the Urenco system is the high degree of balance they are able to achieve in their rotor windings without post-mandrel machining. This is a benefit from their experience in manufacturing centrifuges, and is based on proprietary techniques. The high degree of balance enables Urenco to use a low stiffness bearing assembly consisting of a passive magnetic bearing at the top of the rotor and low-loss pivot bearings at the bottom.

The rotor is tall and thin (that is, low d/l ratio) compared to other designs. Urenco claims their rotor will bend before it breaks apart and thus fail safely. During a bend failure, the rotor skids along the inner wall of the containment vessel safely dissipating its kinetic energy. The shaft is designed to absorb energy during a failure as well. Urenco has conducted varied failure tests and has not had a rotor escape the containment system.

On the inside of the rotor is a layer of magnetic powder loaded composite materials made of glass fibers embedded with powdered permanent magnet material. Urenco is able to achieve precise patterns of magnetic material and uniform fields within magnetic regions. Two sections of the rotor are magnetized, one part to serve as the stators of a permanent magnet motor/generator and the other as the magnet portion of a magnetic levitation assembly.

Urenco has measured the idling losses in their flywheel system to be 1.74 kW or 1.5% of the protected load (120 kW). The mechanical friction losses are minor compared to the losses from motor/generator and power electronics (for example, hysteresis, eddy currents, and switching).

10.3.11 U.S. Flywheel Systems

1125 Business Center Circle
Newbury Park, CA 91320
April 1, 1998

Discussion Participants:

Jack Bitterly, Chief Scientist
Steve Bitterly, Program Manager
Henry V. Chase, President

Jack and Steve Bitterly founded U.S. Flywheel, Inc., in the 1970s when the federal government was funding energy-related R&D in response to the Oil Producing and Export Countries (OPEC) oil crisis. At that time, the commercial viability of flywheels was limited primarily because the ancillary equipment was not ready (for example, controls, motors, bearings). The Bitterlys eventually stopped working in flywheels when the federal funding ceased, but started again with American Flywheel Systems in July 1990 through a contract with the U.S. Army to develop a person-worn energy system. The Bitterlys eventually left American Flywheel Systems, and in November 1993, reactivated USFS with funding from actor Kevin Costner.

In 1993, USFS designed and built a one-of-a-kind winding machine that achieves what the company calls “unprecedented control,” over the composite rotor fabrication process. As an indication of the degree of process control, 86% of the volume of a USFS rotor is fiber material; the maximum possible is 93%. Because of the tight packing of the composite fibers, the rotors are inherently uniform. Little balancing is required, and the center of gravity does not shift significantly as the rotation speed increases. Tight control is maintained over the resin composition as well.

The performance of carbon fibers has improved substantially in recent years. In the mid-1980s Kevlar was preferable to carbon for flywheel applications, but carbon has since surpassed it. The development of advanced carbon fiber materials with even higher tensile strengths could further improve flywheel performance. Notable areas of development are nanotube and fullerene structures. Also, the tensile strength of glass fibers can be improved 40% by cooling the rotor to roughly 150 K.

USFS has spun a composite rotor to 42,000 rpm using conventional mechanical bearings. The company's focus is on developing control mechanisms for levitated magnetic bearings. One approach is to move from a proportional integral derivative (PID) controller to state space control algorithm. This requires full characterization of the system, but provides more robust controls. USFS hopes to be able to demonstrate safe operation in the supercritical regime (that is, non-rigid) with their advanced bearings. A practical problem that USFS has recently solved is getting a noise-free sensor reading on the rotor location, providing accurate information to the magnet control algorithm.

In current magnetic control systems developed by USFS, a 42-pound rotor requires 2 to 5 W of parasitic load. USFS hopes to reduce that to one watt by reducing inefficiencies in the power electronic controls. The radial magnets have a capacity equal to 1.5 times the primary levitation force. The bearings are designed to control the rotor's center of rotation to within one 1/1000th of an inch. All levitated flywheel systems contain a touch-down bearing system that must be able to survive several touch-down incidents over the useful life of a flywheel system (for example, 30 years). USFS recognizes the development of cost-effective, robust touch-down bearings as a key area of development with a high degree of technical risk.

For applications with long-duration electric discharges, the motor efficiency becomes important because the energy lost through inefficiency is rejected into the flywheel as heat. The heat can be taken out of the system by chilled water or other means, but this is an added expense (advanced heat removal concepts are being evaluated). USFS has developed an advanced motor design. It has a continuous rating of 18 kW and is roughly the size of a coffee cup. The motor can generate up to 50 kW for short bursts of time.

USFS prototype flywheel systems contain more than 100 sensors providing both control of the system operation and safety monitoring. With respect to controls, the sensors limit the system response time (not the actuators) and so faster sensors are desired. The development of fiber optic connectors will greatly reduce the bulk of wires necessary to run the system.

Rotor failures can be categorized as radial (a crack from the middle of the rotor out to the edge) or hoop (a crack along the middle of the rotor that forms a concentric circle with the rotor circumference). A circumferential failure can cause a catastrophic event in which large chunks of rotor material fly out against the containment vessel. A radial failure is usually benign, causing only a small shift in the rotor's center of balance. USFS designs their rotors to fail radially before a circumferential failure occurs. The flywheel system contains instrumentation that closely monitors the rotor's center of rotation, so the controller can detect a radially failure and respond to it before the rotor breaks apart. USFS closely monitors the expansion of a rotor during spin-up to evaluate the uniformity and strength of the rotor. They are perfecting the analysis of this information as a means of non-destructive testing of a rotor.

USFS is participating in a DARPA-funded flywheel life-cycle testing program. The goal of the program is to test the strength of composite rotors over several years of service. USFS recently built testing facilities that are capable of spinning a rotor for long periods of time without interruption, and anticipates initiating the testing soon.

A flywheel system powered by a photovoltaic array at the USFS facility produced enough power to spin up the rotor and discharge enough energy to run a vacuum cleaner on flywheel power. The power to the vacuum seemed uniform as the rotor spun down.

USFS is focusing on R&D, and at this time is not trying to commercialize a flywheel energy system. They are interested a partnership with a firm that is focused on manufacturing and sales, but have found no matches yet. An important first step in commercializing flywheels is to identify a standard system size. As system size is increased, the unit cost would come down, but the system would become too big for certain niche applications. Small modular units can be combined to meet larger loads, but at some point this is not effective, either a cost or a maintenance perspective. Perhaps three to four standard sizes could cover most applications. An initial size should be small enough so that one person can lift and handle the system, thus simplifying the manufacturing process.

Near-term applications for flywheels include portable power systems (for example, person-worn army units, wheelchairs, landmine-clearing robots), locomotive power systems, pulse power for electric train stations, and replacements for lead-acid batteries in cold or hot environments.

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10.5 Contacts

10.5.1 SMES System Manufacturers and Researchers

Advanced Cryo Magnetics, Inc
Jeffrey Bilton
619-536-1400
7390 Trade Street
San Diego, CA 92121
Found through data search

American Superconductor
Michael Gravely
916-725-7271
2114 Eagle Drive
Middleton, WI 53562-2550
Active Study Participant

Intermagnetics General
A. Kamal Kalafala
518-782-1122
450 Old Niskayuna Road
P.O. Box 461
Latham, NY 12110-0461
Active Study Participant

Lawrence Livermore National Laboratory
Keith I. Thomassen
510-422-9815
P.O. Box 5511, L-637
Livermore, CA 94550
Active Study Participant

Lawrence Livermore National Laboratory
Richard Post
925-422-9853
7000 East Ave
Livermore, CA 94550
Active Study Participant

10.5.2 SMES Component Manufacturers

Ability Engineering Technology
Mike Morgan
708-331-0025
16140 Vincennes Ave
Rt. 6 & Vincennes Ave
South Holland, IL 60473
Found through data search

Advanced Cerametrics Inc.
Jonathan D. French
609-397-2900
P.O. Box 128
Lambertville, NJ 08530
Found through data search

American Magnetics, Inc.
Paul Arakawa
615-482-1056
PO Box 2509
Oak Ridge, TN 37831
Found through data search

APD Cryogenics
610-791-6700
1833 Vultee Street
Allentown, PA 18103-4783
Found through data search

Cryomagnetics, Inc.
423-482-9551
Oak Ridge, TN 37830
Found through data search

Cryomech
Peter Gifford
315-455-2555
113 Falso Drive
Syracuse, NY 13211
Found through data search

IGC Advanced Superconductors
203-753-5215
1875 Thomaston Ave
Waterbury, CT 06707
Found through data search

Leybold Cryogenics North America
Evan Sohm
603-595-3270
25 Sagamore Park Road
Hudson, NH 03051
Found through data search

Magnet Applications
Mike Panacek
800-437-8890
415 Sargon Way
Horsham, PA 19044
Found through data search

New England Techni-Coil Inc.
603-569-3100
Center Tuftonboro, NH 03816
Found through data search
Focus1: Coils
Focus2: Magnets

Oxford Superconducting Technology
Dr. Hong
908-541-1300
600 Milik St.
Carteret, NJ 07008-0429
Found through data search

Superconductive Components, Inc.
J. R. Gaines
614-486-0261
1145 Chesapeake Avenue
Columbus, OH 43212
Found through data search

Superconix, Inc.
612-222-0046
Lake Elmo, MN 55042
Found through data search

10.5.3 Cryogenics Manufacturers

Andonian Cryogenics, Inc.
Martin Andonian
800-446-3533
90 Hatch St.
New Bedford, MA 23745
Found through data search

BOC Gases
Caroline Lawson
908-464-8100
Murray Hill, NJ 07974
Found through data search

Boreas Cryocoolers
508-670-7200
Found through data search

Cryofab, Inc
908-686-3636
Kenilworth, NJ 07033
Found through data search

Cryo Industries of America, Inc
Kelcie Sven
603-893-2060
11 Industrial Way
Atkinson, NH 03811-2195
Found through data search

Cryomagnetics, Inc.
423-482-9551
Oak Ridge, TN 37830
Found through data search

Cryomech, Inc
315-455-2555
Syracuse, NY 13211
Found through data search

International Cryogenics, Inc
Donna Jung
317-297-4777
4040 Championship Drive
Indianapolis, IN 46268
Found through data search

Pope Scientific, Inc.
Dean Segull
414-251-9300
Menomonee Falls, WI 53052-0495
Found through data search

Superconductor Technologies, Inc.
805-683-8527
460-F Ward Drive
Santa Barbara, CA 93111-2358
Found through data search

10.5.4 Flywheel System Manufacturers and Researchers

Active Power
Bill Kainer
512-491-3154
11525 Stonehollow Drive
Suite 135
Austin, TX 78758
Active Study Participant

Active Power
Jim Balthazar
512-491-3131`
11525 Stonehollow Drive
Suite 135
Austin, TX 78758
Active Study Participant

Acumentrics
Gary Mook
617-461-8251
14 Southwest Park
Westwood, MA 02090-1548
Found through data search

American Flywheel Systems
John Coyner
423-933-1045
241 Koa Drive
Kodak, TN, 37764
Found through data search

Beacon Power
Bill Stanton
781-938-9400
6 Gill Street
Woburn Industrial Park
Woburn, MA 01801-1721
Active Study Participant

Beacon Power
Dick Hockney
781-938-9400
6 Gill Street
Woburn Industrial Park
Woburn, MA 01801-1721
Active Study Participant

Boeing
Alan D. Boutilier
206-773-9776
Information, Space & Defense Programs
P.O. Box 3999
MS 73-09
Seattle, WA 98124-2499
Active Study Participant

Boeing
Michael Strasik
425-234-2863
Information, Space & Defense Programs
P.O. Box 3999
MS 73-09
Seattle, WA 98124-2499
Active Study Participant

Boeing
Sam B. Wright
253-773-5688
Boeing Defense & Space Group
P.O. Box 3999
MS 64-09
Seattle, WA 98124-2499
Active Study Participant

Flywheel Energy Systems, Inc.
Ralph Flanagan
190 Stafford Road West
Unit 108
Nepean, Ontario K2H 9G3
Canada
Found through data search

Lawrence Livermore National Laboratory
J. Ray Smith
925-422-7802
P.O. Box 808, L-641
Livermore, CA 94551
Active Study Participant

Lawrence Livermore National Laboratory
Dr. Richard Post
925-422-7802
P.O. Box 808, L-641
Livermore, CA 94551
Active Study Participant

Mechanical Technology Inc.
Joe Tecza
948-1 Albany Shaker Road
Latham, NY 12110
Found through data search

Penn State Applied Research Laboratory
Charles E. Bakis
814-865-3178
227 Hammond Building
Pennsylvania State University
University Park, PA 16802

Satcon Technologies
Gary Colello
617-349-0820
161 First St.
Cambridge, MA 02142
Found through data search

Thortek
Douglas Thorpe
423-573-8183
P.O. Box 20363
Knoxville, TN 37940-1363
Found through data search

Trinity Flywheel Batteries
Michael Bowler
415-362-0643
10 Lombard St.
Suite 410
San Francisco, CA 94111
Active Study Participant

Trinity Flywheel Power
Donald A. Bender
925-455-7990
6724-D Preston Avenue
Livermore, CA 94550
Active Study Participant

Trinity Flywheel Power
John Eastwood
415-362-0643
10 Lombard Street
Suite 410
San Francisco, CA 94111
Active Study Participant

Unique Mobility, Inc.
Joseph Olbermann
303-278-2002
425 Corporate Circle
Golden, CO 80210
Found through data search

United Technologies
Dr. Thomas Grudowski
411 Silver Lane
East Hartford, CT 06101
Found through data search

U.S. Flywheel Systems
Henry V. Chase
805-375-8433
1125 Business Center Circle
Newbury Park, CA 91320
Active Study Participant

U.S. Flywheel Systems
Jack Bitterly
805-375-8433
Laguna Hills, CA
Active Study Participant

U.S. Flywheel Systems
Steve Bitterly
Laguna Hills, CA
Active Study Participant

World Flywheel Consortium, Inc.
Edward Stone
610-889-9088
225A Plank Avenue
Paoli, PA 19301-1726
Found through data search

10.5.5 Flywheel Component Manufacturers and Researchers

Austin Scientific Co.
Margie Templeton
512-441-6893
4114 Todd Lane
Austin, TX 78744
Found through data search

Barden Corporation
Al Wysocki
800-243-1060
200 Park Avenue
Danbury, CT 06813
Found through data search

Barden Corporation
Brenda Ashley
800-243-1060
200 Park Avenue
Danbury, CT 06813
Found through data search

Boeing
Alan D. Boutilier
206-773-9776
Information, Space & Defense Programs
P.O. Box 3999
MS 73-09
Seattle, WA 98124-2499
Active Study Participant

Boeing
Michael Strasik
425-234-2863
Information, Space & Defense Programs
P.O. Box 3999
MS 73-09
Seattle, WA 98124-2499
Active Study Participant

Boeing
Sam B. Wright
253-773-5688
Boeing Defense & Space Group
P.O. Box 3999
MS 64-09
Seattle, WA 98124-2499
Active Study Participant

Flywheel Power Institute
Donald Finn
908-604-6692
121 Northfield Rd.
Millington, NJ 07946-1353
Found through data search

Glacier RPB Inc.
Mike Swann
860-536-1881
12 Roosevelt Avenue
Mystic, CT 06355-2809
Found through data search

Intech Bearing, Inc.
William Steven Kroll
800-327-7424
1993 Tellepsen St.
Houston, TX 77023
Found through data search

Lawrence Livermore National Laboratory
Richard Post
925-422-9853
7000 East Ave
Livermore, CA 94550
Active Study Participant

Magnetic Moments
Brad Paden
805-683-9659
Goleta, CA 93117
Found through data search

Penn State Applied Research Laboratory
Charles E. Bakis
814-865-3178
227 Hammond Building
Pennsylvania State University
University Park, PA 16802

Revolve Technologies Inc.
Rolf Wenzel
403-232-9292
707 10th Avenue, SW
Suite 300
Calgary, AB T2R0B3
Canada
Found through data search

RMB Miniature Bearings, Inc.
Tom Rudziensky
800-552-0541
29 Executive Pkwy
Ridgewood, NJ 07456
Found through data search

SatCon Technology Corp.
Greg Stoltz
617-349-0938
161 First St.
Cambridge, MA 02142-1221
Found through data search

Synchrony Inc.
Victor Iannello
540-989-1541
7777 Bent Mountain Rd.
Roanoke, VA 24018
Found through data search

Toray Composites of America
Ann Graham
253-846-1777
19002 50th Avenue East
Tacoma, WA 98446
Found through data search

Toray Composites of America
Earl Benton
253-846-1777
19002 50th Avenue East
Tacoma, WA 98446
Found through data search

10.5.6 Composites Manufacturers

C-K Composites, Inc.
412-547-4581
Mount Pleasant, PA 15666
Found through data search

Toray Composites of America
Ann Graham
253-846-1777
19002 50th Avenue East
Tacoma, WA 98446
Found through data search

Toray Composites of America
Earl Benton
253-846-1777
19002 50th Avenue East
Tacoma, WA 98446
Found through data search

10.5.7 Power Conversion Systems Manufacturers

Abacus Controls, Inc.
908-526-6010
Somerville, NJ 08876
Found through data search

Advanced Energy Systems
Dr. Robert Wills, P.E.
603-654-9322
Riverview Mill
PO Box 262
Wilton, NH 03086
Found through data search

Alternative Power Tech
John Berdner
916-478-6645
870 Gold Flat Rd.
Nevada City, CA 95959
Found through data search

Atlas Energy Systems
800-832-8527
713 W Duarte Rd
Bldg G299
Arcadia, CA 91007
Found through data search

Camden Transformer Co.
609-825-4900
Millville, NJ 08332-4031
Found through data search

Computer Power, Inc.
800-526-5088
High Bridge, NJ 08829-1707
Found through data search

Cyberex, Inc.
800-921-9391
Mentor, OH 44060-5327
Found through data search

Dynapower Corp.
800-292-6792
South Burlington, VT 05407-9210
Found through data search

Exide Electronics
John Breckenridge
919-870-3114
8609 Six Forks Rd
Raleigh, NC 27615
Found through data search

Liebert Corp.
Robert J. Miller
714-457-3711
9650 Jeronimo Rd.
Irvine, CA 92618
Found through data search

Neeltran, Inc.
800-245-0061
New Milford, CT 06776
Found through data search

New World Power Technology Co.
Clint Coleman
One North Wind Rd
PO Box 999
Waitsfield, VT 05673-0999
Found through data search

NWL Transformers
800-448-1269
Bordentown, NJ 08505
Found through data search

Omnion Power Engineering Corp.
Hans Meyer
414-642-7200
2010 Energy Dr.
East Troy, WI 53120
Found through data search

PDI
John B. Kammeter
800-225-4838
510 Eastpark Court
Suite 150
Sandston, VA 23150
Found through data search

Philtek Power Corp.
800-727-4877
Blaine, WA 98230
Found through data search

Silicon Power Corp.
Roberto M. Andraca
610-251-7364
175 Great Valley Parkway
Malvern, PA 19355
Found through data search

Softswitching Tech.
Deepak Divon
608-836-6552
2224 Evergreen Rd., #6
Middleton, WI 53562
Found through data search

StatPower Technologies Corp.
604-420-1585
Burnaby, BC V5A 4V8
Canada
Found through data search

SuperPower, Inc.
800-422-7697
Arden Hills, MN 55126-6198
Found through data search

TRACE Engineering Corp.
Mike Behnke
510-455-3269
PO Box 5049
Livermore, CA 94551-5049
Found through data search

Westinghouse Electric Corp
T.C. Matty
410-993-2696
PO Box 1693
MS111
Baltimore, MD 21203
Found through data search

ZZZAP Power
800-682-2677
Champlain, NY 12919
Found through data search

10.5.8 Controls and Monitors Manufacturers

Drive Control Systems
800-323-0504
Minnetonka, MN 55343-9108
Found through data search

Omega Engineering, Inc.
800-826-6342
Stamford, CT 06907
Found through data search

Sierracin/Magnedyne
800-663-4051
Vista, CA 92083
Found through data search

10.5.9 UPS Manufacturers

Abacus Controls, Inc.
908-526-6010
Somerville, NJ 08876
Found through data search

Atlas Energy Systems
800-832-8527
713 W Duarte Rd
Bldg G299
Arcadia, CA 91007
Found through data search

Neeltran, Inc.
800-245-0061
New Milford, CT 06776
Found through data search

NWL Transformers
800-448-1269
Bordentown, NJ 08505
Found through data search

Piller, Inc.
Bradley S. Walter
914-355-5445
R.D. No. 4
Box 194
Middletown, NY 10940-9518
Found through data search

Power Technologies, Inc.
360-435-9530
Arlington, WA 98223-8763
Found through data search

Precise Power Corp.
800-780-3515
Bradenton, FL 34206-9547
Found through data search

TSI Power Corp.
770-263-6063
Norcross, GA 30071-1803
Found through data search

10.6 Glossary

The following glossary defines some of the nomenclature necessary to discuss SMES, FES, and CAES technologies. The listings are alphabetic. Definitions are specialized within the context of SMES, FES, and CAES.

AC (alternating current) — an electrical current that varies in amplitude sinusoidally. An electrical system with alternating current also has alternating voltage, and the term, AC, refers to both alternating current and voltage in most general discussions of electricity.

AC losses — (1) in an electrical system that carries alternating current, the energy that is lost when impedance of the system causes heating of the components; (2) in a SMES coil, the energy that is lost in microscopic areas where the coil material loses its superconducting properties.

Adiabatic — a thermodynamic process in which no heat escapes the system under consideration.

Bus — a set of two or more electric conductors that serve as common connections between two or more load circuits and a source.

Capacitor — two conductors (such as parallel metal plates) insulated from each other by a dielectric. The device stores electrical energy as electrons collect on one of the plates, blocks the flow of direct current, and permits the flow of alternating current in a way that depends on the strength of the dielectric and on the frequency of the current.

Carnot cycle — a theoretical thermodynamic cycle that is made up of reversible processes. The first step of the process is a constant-temperature expansion of gas. The second step is heat transfer from the gas to a low-temperature "reservoir" with a continued expansion. The third step is compression of the gas at constant temperature, and the fourth step is heat transfer from a high-temperature, "reservoir" to the gas. The Carnot cycle has 100% efficiency and is the basis for the development of real thermodynamic devices such as cryostats.

Closed-cycle refrigeration — thermodynamic cycle in which the fluid does not enter or leave the system, but is used over and over again.

Critical current (and critical current density) — the amount of current (and amount of current per unit of area of superconductor) at which an abrupt change in the conductive behavior of superconducting material occurs. See current density.

Critical magnetic field — the field below which a superconductive material is superconducting and above which the material is normal, at a specified temperature and in the absence of current.

Critical temperature — in superconductors, the temperature above which the substance is no longer superconducting.

Cryogenics — the production and maintenance of very low temperatures, and the study of phenomena at these temperatures.

Cryostat — an apparatus used to provide low-temperature environments in which operations may be carried out under controlled cryogenic conditions.

Current density — the current per unit cross-sectional area of a conductor.

dI/dt — the rate at which the current in the coil changes.

DC (direct current) — electrical current with a constant value that equals the voltage in the circuit divided by the resistance of the circuit.

Enthalpy — the sum of the internal energy of a system plus the product of the system's volume and the pressure exerted on the system by its surroundings.

Entropy — a function of the state of a thermodynamic system whose change in any differential reversible process is equal to the heat absorbed by the system from its surroundings divided by the absolute temperature of the system.

Free electron — an electron that is not constrained to remain in a particular atom and is, therefore, able to move in matter or in a vacuum when acted upon by external electric or magnetic fields.

Flux pinning — a property of superconducting materials in which microscopic flaws allow magnetic field lines to penetrate the otherwise magnetically impermeable interior of the superconductor. Once established through a flaw, the magnetic field is anchored through that location and will move only if a greater force overcomes the "pinning" effect.

Gate-turnoff SCR — a silicon-controlled rectifier that can be turned off by applying a current to its gate; used largely for direct-current switching because turnoff can be achieved in a fraction of a microsecond.

Harmonics — unavoidable frequencies in AC and voltage that are multiples of the fundamental frequency. Harmonics are undesirable because they cause heating in electrical devices and do not produce work.

Heat exchanger — any device, such as an automobile radiator, that transfers heat from one fluid to another or to the environment. In cryogenic systems, heat exchangers are used to pre-cool cryogenic fluids.

Hooke's law — an empirical relationship that states that stresses that are below the yield strength of a solid material are proportional to strain in the material. The proportionality constant for the relation is known as Young's modulus.

I^2R — energy loss by creating heat as current (I) passes through a material with resistance (R); even though R in a superconductor is low, it is not zero, and "AC losses" in microscopic local areas do occur.

IGBT — insulated gate bipolar transistor. Solid-state switch that can switch at speeds of about 50 kHz and has a power capacity of about 1 MW.

Impedance — the total opposition that a circuit presents to an alternating current. Impedance is the ratio of the maximum AC voltage to the maximum AC and includes both the resistive and the reactive parts of the circuit's opposition to current flow.

Inductance — the ability of a change in current in one circuit to stimulate current flow of free electrons in a neighboring circuit.

Inversion temperature — the temperature at which the Joule-Thomson effect of a gas changes sign.

Inverter — a device for converting direct current into alternating current; it may be electromechanical, as in a vibrator or synchronous inverter, or it may be electronic.

Isobaric — a thermodynamic process that occurs at constant pressure.

Isothermal — a thermodynamic process that occurs at constant temperature.

Joule-Thomson expansion — the adiabatic, irreversible expansion of a fluid flowing through a porous plug or partially opened valve.

Levitation (magnetic levitation) — causing a magnetic object to "float" in air through the attractive or repulsive force of a magnetic field on the object.

Life-cycle costs — over its service life, the total costs of a piece of equipment incurred in the purchase, operation, and maintenance of that equipment.

Lorentz force — the force exerted on a charged particle by electric and magnetic fields in which it moves. In a superconducting coil, Lorentz forces in electrons moving through the coil create a tendency for the coil to expand.

Magnetic permeability — the ability of a substance (including vacuum for the purposes of this definition) to allow a magnetic field to pass through it unattenuated.

MCTs — (MOS-controlled thyristor) a solid-state electronic switch that uses metal-oxide semiconductor technology to switch a frequency of about 20 kHz and a power of 1.5 MW.

Meissner effect — the expulsion of magnetic flux from the interior of a piece of superconducting material as the material undergoes the transition to the superconducting phase.

MOSFET — a metal oxide semiconductor field-effect transistor, which is a transistor with an electronic gate that is insulated from the semiconductor substrate by a thin layer of silicon dioxide.

Operation and maintenance costs — the costs for a piece of equipment incurred through operating the equipment and performing regular service maintenance on it.

Photovoltaic arrays — a collection of photovoltaic cells that are devices capable of collecting energy from sunlight and converting it to electricity through the interaction of photons from the sunlight with electrons in the semiconductor material from which the cell is made.

Rectifier — a nonlinear circuit component that ideally allows current to flow in one direction unimpeded but allows no current to flow in the other direction. In real rectifiers, a small amount of current flows in the opposite direction, but the device is still useful as a way to convert AC power to DC power.

Reactance — the tendency of a material to resist the flow of and change the sinusoidal nature of AC electricity.

Renewables — generation resources that do not consume fossil fuels or use nuclear reactions to make electricity. Renewables include, but are not limited to, photovoltaic generation, wind generation, geothermal generation, and hydroelectric generation.

Resistance — the tendency of a material to oppose the flow of DC electricity.

Resistivity — a measure of resistance of a material.

Semiconductor — a material in which electrons are neither as free as in metals (conductors) nor bound as in ceramics (insulators). As a result, semiconductors conduct electricity only under special conditions.

Silicon-controlled rectifier — (SCR) a semiconductor rectifier that can be controlled.

Solenoid — a tubular coil of wire.

Solid-state switch — a switch that uses a semiconductor technology to allow current to flow or impede current flow in a circuit.

Superconducting magnet — an electromagnet whose coils are made of superconducting materials with a high transition temperature and extremely high critical field, such as niobium tin.

Superconductivity — a property of materials in which their electrical resistivity nearly vanishes at temperatures near absolute zero.

Strain — deformation in a solid material.

Stress — the effect of a force on a cross-section of a solid material.

Throttling — an adiabatic irreversible process in which a gas expands by passing from one chamber to another chamber, which is at a lower pressure than the first chamber

Thyristor — a specialized electronic switch based on the transistor that has especially high-speed triggering action or switching speed.

Toroid — a donut-shaped coil of wire.

Touch-down (touch-down bearings) — physical contact between levitated flywheel rotor shaft and bearings that allow its rotation; bearings designed to withstand the loss of levitation or other failure conditions.

Type I superconductor — a superconductor for which there is a single critical magnetic field; magnetic flux is completely excluded from the interior of the material at field strengths below this critical field, while at field strengths above this critical field, magnetic flux penetrates the superconductor completely, and it reverts to the normal state.

Type II superconductor — a superconductor for which there are two critical magnetic fields; magnetic flux is completely excluded from the interior of the material only at field strengths below this smaller critical field, and at field strengths between the two critical fields. the magnetic flux consists of flux vortices in the form of filaments embedded in the superconducting material.

Ultimate tensile strength — the stress that causes a solid material to fracture.

Vapor-compression cycle — a refrigeration cycle that circulates refrigerant through a machine that allows for vaporization of liquid refrigerant as it passes through an expansion valve, cools its surroundings, and then compresses the refrigerant vapor to liquid.

Yield strength — the stress that creates permanent deformation in a solid material.

Young's modulus — a constant of proportionality that relates stress and strain in a solid material; a measure of material; stiffness.

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11. Relevant Patents

The following abstracts describe patents relevant to the topics of this report.

11.1 SMES Patents

United States Patent: 5,495,221
Post, February 27, 1996

Dynamically Stable Magnetic Suspension/Bearing System

A magnetic bearing system contains magnetic subsystems that act together to support a rotating element in a state of dynamic equilibrium. However, owing to the limitations imposed by Earnshaw's Theorem, the magnetic bearing systems to be described do not possess a stable equilibrium at zero rotational speed. Therefore, mechanical stabilizers are provided, in each case, to hold the suspended system in equilibrium until its speed has exceeded a low critical speed where dynamic effects take over, permitting the achievement of a stable equilibrium for the rotating object. A state of stable equilibrium is achieved above a critical speed by use of a collection of passive elements using permanent magnets to provide their magnetomotive excitation. The magnetic forces exerted by these elements, when taken together, levitate the rotating object in equilibrium against external forces, such as the force of gravity or forces arising from accelerations. At the same time, this equilibrium is made stable against displacements of the rotating object from its equilibrium position by using combinations of elements that possess force derivatives of such magnitudes and signs that they can satisfy the conditions required for a rotating body to be stably supported by a magnetic bearing system over a finite range of those displacements.

Inventor: Post, Richard F. (Walnut Creek, California)
Assignee: The Regents of the University of California (Oakland, California)

11.2 Flywheel Patents

United States Patent: 5,816,114
Gregoire, et al., October 6, 1998

High Speed Flywheel

A method of operating a flywheel includes the provision of a central shaft defining an axis of rotation; providing disk-shaped hub joining drivingly with both the shaft and with a rim portion; the hub has a shape when the flywheel is at rest, which is of a shallow dihedral geometry. That is, the hub is cone-shaped when the flywheel is at rest. As the rotational speed of the flywheel is increased from the at-rest speed toward and then to a design operating speed for the flywheel, this hub progressively flattens out until it becomes flat and extends radially between the shaft and the hub at the design speed for the flywheel. Thus, the flattening of the hub with increasing rotational speed for the flywheel moves the rim portion axially in response to centrifugal force.

Inventors: Gregoire, Daniel J. (Thousand Oaks, California); Harvey, Robin J. (Thousand Oaks, California)
Assignee: Hughes Electronics Corporation (El Segundo, California)

United States Patent: 5,778,736
Maass, et al., July 14, 1998

Spiral Woven Composite Flywheel Rim

A fiber-reinforced composite flywheel for energy storage has a plurality of disks in the form of a coil produced from continuous hoop and radial fibers, each disk having a mix of fiber types in the hoop direction, relatively strong fibers disposed about an inner section of the disk, an intermediate section of the disk composed of relatively strong and relatively less strong fibers, and an outer portion having a mix of fibers with fewer relatively strong fibers. A fiber-reinforced composite flywheel, alternatively or in addition, has a higher volume of radial fibers disposed about the intermediate section of the disk, to increase radial strength in a banded area of the disk subject to increased radial stress. Preferably, the disk is composed with a three-dimensional orthogonal weave architecture that allows the fibers to shear during weaving to provide minimum distortion of the spiral-woven disk. Constructing a spiral-woven composite flywheel disk in accordance with the invention optimizes stress and strength properties to increase operating speed and energy storage capacity at minimum cost.

Inventors: Maass, David (New Haven, Connecticut); Hoon, Douglas M. (Guilford, Connecticut)
Assignee: DOW-United Technologies Composite Products, Inc. (Wallingford, Connecticut)

United States Patent: 5,778,735
Groves, et al., July 14, 1998

Interlayer Toughening of Fiber Composite Flywheel Rotors

An interlayer toughening mechanism to mitigate the growth of damage in fiber composite flywheel rotors for long application. The interlayer toughening mechanism may contain one or more tough layers made of high-elongation fibers, high-strength fibers arranged in a woven pattern at a range from 0 to 90 degrees to the rotor axis, and bound by a ductile matrix material that adheres to and is compatible with the materials used for the bulk of the rotor. The number and spacing of the tough interlayers is a function of the design requirements and expected lifetime of the rotor. The mechanism has particular application in uninterruptible power supplies, electrical power grid reservoirs, and compulsators for electric guns, as well as electromechanical batteries for vehicles.

Inventors: Groves, Scott E. (Brentwood, California); Deteresa, Steven J. (Livermore, California)
Assignee: Regents of the University of California (Oakland, California)

United States Patent: 5,775,176
Bender, et al., July 7, 1998

Separators for Flywheel Rotors

A separator forms a connection between the rotors of a concentric rotor assembly. This separator allows for the relatively free expansion of outer rotors away from inner rotors while providing a connection between the rotors that is strong enough to prevent disassembly. The rotors' assembly includes at least two rotors referred to as inner and outer flywheel rings or rotors. This combination of inner flywheel ring, separator, and outer flywheel ring may be nested to include an arbitrary number of concentric rings. The separators may be a segmented or a continuous ring that abuts the ends of the inner rotor and the inner bore of the outer rotor. It is supported against centrifugal loads by the outer rotor and is affixed to the outer rotor. The separator is allowed to slide with respect to the inner rotor. It is made of a material that has a modulus of elasticity that is lower than that of the rotors.

Inventors: Bender, Donald A. (Dublin, California); Kuklo, Thomas C. (Oakdale, California)
Assignee: Regents of the University of California (Oakland, California)

United States Patent: 5,767,591
Pinkerton, June 16, 1998

Method and Apparatus for Providing Startup Power to a Genset-backed UPS

A UPS provides improved reliability by supplying temporary standby power to a critical load and start-up power to a backup power source from a single energy storage system. In the preferred embodiment, an FES device that produces three-phase AC voltage is used to provide temporary power to a critical load while a backup power supply, such as a diesel generator set (Genset), is accelerated to full speed. The start-up power for the Genset is also provided from the FES device through a circuit that converts the AC voltage at one level to DC voltage at a lower level (for example, 12 or 24 V). Therefore, backup power will be provided from the Genset unless a catastrophic failure occurs in the Genset itself.

Inventor: Pinkerton, Joseph F. (Austin, Texas)
Assignee: Active Power, Inc. (Austin, Texas)

United States Patent: 5,758,549
Deteresa, et al., June 2, 1998

Interface Structure for Hub and Mass Attachment in Flywheel Rotors

An interface structure for hub and mass attachment in flywheel rotors. The interface structure efficiently transmits high radial compression forces and withstands both large circumferential elongation and local stresses generated by mass-loading and hub attachments. The interface structure is composed of high-strength fiber, such as glass and carbon, woven into an angle pattern that is about 45 degrees with respect to the rotor axis. The woven fiber is bonded by a ductile matrix material that is compatible with and adheres to the rotor material. This woven fiber is able to elongate in the circumferential direction to match the rotor growth during spinning.

Inventors: Deteresa, Steven J. (Livermore, California); Groves, Scott E. (Brentwood, California)
Assignee: Regents of the University of California (Oakland, California)

United States Patent: 5,747,426
Abboud, May 5, 1998

High-Performance Magnetic Bearing Systems Using High-Temperature Superconductors

A magnetic bearing apparatus and a method for providing at least one stabilizing force in a magnetic bearing structure with a superconducting magnetic assembly [and a magnetic assembly,] by providing a superconducting magnetic member in the superconducting magnetic assembly with a plurality of domains and arranging said superconducting magnetic member such that at least one domain has a domain C-axis vector alignment angularly disposed relative to a reference axis of the magnetic member in the magnetic assembly.

Inventor: Abboud, Robert G. (Barrington Hills, Illinois)
Assignee: Commonwealth Research Corporation (Chicago, Illinois)

United States Patent: 5,731,645
Clifton, et al., March 24, 1998

Integrated Motor/Generator/Flywheel Utilizing a Solid Steel Rotor

A flywheel energy conversion device provides highly efficient conversion between kinetic and electrical energy. The flywheel produces increased output by providing armature coils in an air gap formed about the flywheel (both radial and axial embodiments are described). In preferred embodiments, field coils of a magnetic circuit are energized with DC drive current that creates a homopolar flux within a rotating solid rotor with teeth cut from a flat disk. The total reluctance of the magnetic circuit and total flux remain substantially constant as the rotor rotates. The flux may travel radially outward and exit the flat disk through the teeth passing across an armature air gap. Air gap armature coils are preferably utilized in which the changing flux density (due to the rotating teeth) induces an output voltage in the coils. The flux is diffused before returning to the rotor in one of several ways so that core losses are effectively reduced, thereby enabling the flywheel to operate efficiently at high frequencies.

Inventors: Clifton, David B. (Leader, Texas); Pinkerton, Joseph F. (Austin, Texas); Andrews, James A. (Austin, Texas); Little, Scott R. (Austin, Texas)
Assignee: Magnetic Bearing Technologies, Inc. (Austin, Texas)

United States Patent: 5,729,903
Bitterly, et al., March 24, 1998

Methods of Making an Anisotropic Flywheel

Flywheel-based energy storage devices are provided along with methods for their use and fabrication. The devices have the capacity to store electric energy and kinetic energy and to generate electric energy from the stored kinetic energy. Preferred devices contain a pair of counter-rotating anisotropic flywheels that are designed to rapidly rotate within an evacuated housing. The flywheels contain a lightweight hub and a circumferentially wound fiber rim. The hub and rim are fabricated from materials with high tensile strength and are connected to a system of novel tube assemblies positioned around the hub and parallel to the axis of rotation. The flywheels are principally supported by magnetic bearings and are further stabilized during rotation by a self-restoring liquid-bearing system.

Inventors: Bitterly, Jack G. (Woodland Hill, California); Bitterly, Steven E. (Agoura, California).
Assignee: American Flywheel Systems, Inc. (Bellevue, Washington)

United States Patent: 5,717,263
Cox, February 10, 1998

Rotors

A rotor containing a cylindrical structure including a portion made from a fibre reinforced composite wherein magnetic filler within the matrix of the composite and wherein the loading of the magnetic filler material varies through the matrix whereby the average mass per unit volume of the structure decreases with distance radially from the axis of the structure. As a result, strain matching across the rotor can be achieved even when the rotor is spinning at high speed, such as when used in an FES and conversion apparatus.

Inventor: Cox, Terence Martin (Warrington, Great Britain)
Assignee: British Nuclear Fuels PLC (Great Britain)

United States Patent: 5,710,469
Ries, January 20, 1998

Magnetic Bearing Element for a Rotor Shaft Using High-t_c Superconducting Materials

A magnetic bearing element contains a first bearing part attached to a shaft and a second fixed-position bearing part surrounding the first bearing part. One of the bearing parts contains an arrangement of a plurality of alternatively polarized permanent magnetic elements between which there are ferromagnetic elements, and the other bearing part contains a superconducting structure. This superconducting structure should have grains made of high-T_c superconducting material, whose respective grain size is larger than the thickness of each of the permanent magnetic elements. In addition, the rotor shaft should be made of a nonmagnetic material. The rotor shaft may contain the bearing part with permanent magnetic elements or the structure with the high-T_c superconducting material.

Inventor: Ries, Guenter (Erlangen, Germany)
Assignee: Siemens Aktiengesellschaft (Munchen, Germany)

United States Patent: 5,708,312
Rosen, et al., January 13, 1998

Magnetic Bearing System Including a Control System for a Flywheel and Method for Operating Same

The magnetic bearing system including a control system for a flywheel used for energy storage and high surge power in vehicular applications includes first and second radial force generators disposed in the first plane perpendicular to the rotation axis of the rotor, the first and second force generators including only electromagnets, third and fourth radial force generators disposed in a second plane perpendicular to the rotation axis of the rotor, the third and fourth force generators including only electromagnets, and upper and lower axial force generators each containing an electromagnet and a permanent magnet. According to one aspect of the bearing system, each of the force generators includes control circuitry having simple and complex lead networks so as to permit the force generators to rapidly respond to vehicular transients while maintaining a desired bearing stiffness. The bearing system also includes upper and lower touchdown ball bearings that are engaged only when the first through fourth radial force generators are unable to maintain the rotor in a predetermined cylindrical volume within the flywheel. A method for controlling the bearing system is also described.

Inventors: Rosen, Harold A. (Santa Monica, California); Khalizadeh, Claude (Newbury Park, California); Pano, Scott B. (Torrance, California); Kubicky, Joseph J. (Woodland Hills, California); Rubin, Seymour N. (Los Angeles, California)
Assignee: Rosen Motors, L.P. (Woodland Hills, California)

United States Patent: 5,614,777
Bitterly, et al., March 25, 1997

Flywheel-Based Energy Storage System

A compact energy storage system includes a high-speed rotating flywheel and an integral motor/generator unit. The rotating components are contained within a vacuum enclosure to minimize windage losses. The flywheel rotor has a unique axial profile to both maximize the *energy* density of the flywheel and to maximize the volumetric efficiency of the entire system. The rotor is configured with hollowed-out regions at each axial end to accommodate magnetic bearing assemblies. The integral motor/generator is disposed on a tail shaft of the flywheel rotor, outboard of the magnetic bearing assembly. The motor/generator stator is mounted on a translation carriage for axial movement. During normal operation, the stator is in operative alignment with a rotor on the flywheel shaft. However, when neither motor nor generator operation is required, the stator is extended to an axial position where it is effectively decoupled from the rotor. A magnetic shield surrounding the rotor confines the lines of magnetic flux to minimize eddy currents, and thereby minimize parasitic *energy* losses that would otherwise slow the flywheel during idle periods.

Inventors: Bitterly, Jack G. (Woodland Hills, California); Bitterly, Steven E. (Agoura, California)
Assignee: U.S. Flywheel Systems (Newbury Park, California)

United States Patent: 5,640,887
Hull, et al., June 24, 1997

Low-loss, High-speed, High-t_c Superconducting Bearings

An FES device including an iron structure disposed for rotation adjacent a stationary superconductor material structure and a stationary permanent magnet. The stationary permanent magnet levitates the iron structure while the superconductor structure can stabilize the rotating iron structure.

Inventors: Hull, John R. (Hinsdale, Illinois); Mulcahy, Thomas M. (Western Springs, Illinois); Uherka, Kenneth L. (Frankfort, Illinois)
Assignee: University of Chicago (Chicago, Illinois)

United States Patent: 5,695,584
Gregoire, December 9, 1997

Method of Manufacturing a Flywheel Having Reduced Radial Stress

A high-speed flywheel includes a composite rim supported for rotation around a central axis that is perpendicular to the plane of the rim. The rim includes at least a pair of rim portions or regions of differing elastic modulus in the circumferential direction of the material forming the rim. Moreover, a radially outer portion of the rim has a higher elastic modulus in the circumferential direction, while a radially inner portion of the rim has a lower elastic modulus in the circumferential direction. This variation of circumferential elastic modulus is achieved by a selected radial variation of the angle of the fiber reinforcement material relative to the circumferential direction of the rim. A result is that the radially inner portion of the rim transfers radial force to the outer portion, with a resulting lower radial stress in the radially inner portion of the flywheel rim. An improved speed of operation and greater energy storage for the flywheel is achieved.

Inventor: Gregoire, Daniel J. (Thousand Oaks, California)
Assignee: Hughes Aircraft Company (Los Angeles, California)

United States Patent: 5,656,870
Turnbull, August 12, 1997

Current Control for Superconducting Magnetic Energy Storage System

A superconducting magnetic energy storage system for applying power to a load includes a superconducting magnet, with an inductor that is supplied with current from a source that may be preset to a desired value of current, and a feedback loop which is responsive to a sensed current adjusts the source to provide the desired current. Energy from the superconducting magnet is transferred from a series of pulses of current from the magnet to a first capacitor for charging the capacitor to a desired voltage greater than the voltage at the superconducting magnet. A further transfer of energy from a series of pulses of current results in a charging of a second capacitor to a voltage lower than the voltage of the first capacitor. The second capacitor feeds the load. A switch disposed in a current recirculation path through the magnet is operated cyclically to divert increments of current from the magnet to the first capacitor, and a second switch is operated cyclically to provide pulses of current from the first capacitor to the second capacitor. A diode is disposed in the current path between the magnet and the first capacitor. An inductor is disposed in the current path between the first capacitor and the second capacitor. This arrangement of the components provides for an efficient transfer of power from the magnet to the load.

Inventor: Turnbull, Fred Gerdes (Scotia, New York)
Assignee: Intermagnetics General Corporation (Latham, New York)

United States Patent: 5,682,304
Shteynberg, October 28, 1997

Superconductive Electromagnetic Energy Storage Apparatus and a Method for Storing Electromagnetic Energy

A superconductive system for receiving electromagnetic energy from an outside source, storing electromagnetic energy in two interacting forms of DC and AC electric current, and delivering electromagnetic energy to an outside load wherein the electromagnetic energy is charged into and discharged from the superconductive storing system exclusively from inductive coupling links. The electromagnetic energy is stored as DC current in high-capacity superconductive coils with each coil connected into a superconductive permanent closed loop circuit. The energy is then used to support electromagnetic oscillation in a superconductive oscillating circuit where it is stored in low capacity superconductive coils as AC current. The superconducting oscillating circuit is then used to provide power to an outside source.

Inventor: Shteynberg, Mark (15527 45th Pl. West, Lynnwood, Washington 98037).
Assignee: None Listed

United States Patent: 5,798,678
Manlief, et al., August 25, 1998

Superconducting Wind-and-React-Coils and Methods of Manufacturer

A process for manufacturing superconducting magnetic coils from strain-tolerant, superconducting multifilament composite conductors is described. The method involves winding the precursor to a multifilament composite conductor and an insulating material or its precursor around a mandrel in order to form a coil, and then exposing the coil to high temperatures and an oxidizing environment. The insulating material or its precursor is chosen to permit exposure of the superconductor precursor filaments to the oxidizing environment and to encase the matrix-forming material enclosing the filaments, which is reversibly weakened during processing.

Inventors: Manlief, Michael D. (Westborough, Massachusetts); Riley, Jr., Gilbert N. (Marlborough, Massachusetts); Voccio, John (Sommerville, Massachusetts); Rodenbush, Anthony J. (Marlborough, Massachusetts)
Assignee: American Superconductor Corporation (Westborough, Massachusetts)