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LOCKHEED MARTIN

CRADA Final Report for
CRADA ORNL92-0074
(EPRI RP3087-18)

**Power Applications of
High-Temperature Superconductivity:
Variable Speed Motors, Current Switches,
and Energy Storage for End Use**

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ABSTRACT

The objective of this project is to conduct joint research and development activities related to certain electric power applications of high-temperature superconductivity (HTS). The new superconductors may allow development of an energy-efficient switch to control current to variable speed motors, superconducting magnetic energy storage (SMES) systems, and other power conversion equipment. Motor types that were considered include induction, permanent magnet, and superconducting ac motors. Because it is impractical to experimentally alter certain key design elements in radial-gap motors, experiments were conducted on an axial field superconducting motor prototype using 4 NbTi magnets. Superconducting magnetic energy storage technology with 0.25 - 5 kWh stored energy was studied as a viable solution to short duration voltage sag problems on the customer side of the electric meter. The technical performance characteristics of the device were assembled, along with competing technologies such as active power line conditioners with storage, battery-based uninterruptable power supplies, and supercapacitors, and the market potential for SMES was defined. Four reports were prepared summarizing the results of the project.

PROJECT OBJECTIVES

1. To produce a report on inverter topologies that would employ superconducting and advanced semiconductor switches and that would drive variable speed motors. Motor types to be considered include induction, permanent magnet (PM), and superconducting ac motors. Determine switch characteristics as a function of motor type. Develop frequency and temperature effects data base for the magnetic materials used in an adjustable speed drive (ASD).
2. To produce a report of the performance of an axial air gap ac superconducting motor and to measure the ac and dc magnetic field effects and vibration effects due to operation of the ASD.
3. To produce a report on the evaluation of end-use SMES as a viable option in meeting utility customer needs for enhanced power quality compared to alternate stored energy systems and to prioritize and recommend the next steps for technology development.

The objectives of the CRADA were generally met as set forth in the statement of work and as discussed in joint meetings and teleconferences.

CRADA benefits to the DOE Superconductivity Program and to EPRI: Both EPRI and ORNL obtained valuable information concerning power applications of HTS.

The development of a HTS-based power electronics switch would enable the development of variable speed motor controllers that are more energy efficient than those presently available. The semiconductor devices currently used in these motor controllers dissipate as heat approximately \$300 million in electricity per year. The potential market for energy-efficient controllers is indicated by the amount of electricity consumed by motors in the commercial and industrial sector—more than 1×10^{12} kWh, or 64% of the total U.S. electrical production. The development of such “conservation” technology fits within the mission of the HTS program while EPRI and its member utilities benefit from access to a technology that could result in tremendous savings in the production of electricity. Also, since power quality has become a critical issue to U.S. competitiveness, the joint evaluation of SMES for end-use applications provides benefit to the DOE and EPRI program offices charged with studying such energy applications.

PROJECT SUMMARY

The following reports emanating from this CRADA summarize the work accomplished. The abstract from each report is also provided.

1. J. M. Bailey, "Motor Models and Transient Analyses for HTSc Switch-Based Adjustable Speed Applications: Phase II," Final Report No. EPRI RP 3087-16, University of Tennessee, Knoxville, Tennessee, February 1994.

Abstract

This report describes the topologies for control systems for axial-gap superconducting and permanent-magnet (PM) motors, including the actively controlled resonant dc link, inverter, vector controller, and adjacent state current regulator (in this report called adjacent zero-state current regulator).

Further, design configurations are presented for double stator 100-500 hp rotors with trapezoidal back EMF and with sinusoidal back EMF simulation results. These PM motors consist of two stators and one rotor. The rotor has magnets on both sides and the stators are connected in series. The motor models and adjacent zero-state current regulators are incorporated into a modular PC SIMNON-based package. Since these studies are to be used to investigate fast-switching, high-temperature superconducting components in adjustable speed drives, performance curves of present day drives are included.

2. R. J. Ferraro and B. W. McConnell, "Understanding SMES Technology, Applications, and Economics for End Use Workshop," Report ORNL/Sub/88-SM362/1, June 1993.

Executive Summary

Principle Objectives: As electric service power quality equipment rapidly expands in usage nationally, utilities and their customers need a better understanding of new technologies entering the marketplace. The EPRI/ORNL project, "Assessment of Small Superconducting Magnetic Energy Storage (SMES) for Power Quality Enhancement," was to build its findings from present SMES activities. The major objective of the project was to determine the state of the art and to what extent existing SMES is a viable option in meeting utility and customer needs for enhanced power quality, and to evaluate the impact of high temperature superconductors (77 K and 20-35 K) on SMES applications. A secondary objective was to define and to analyze existing SMES performance characteristics with competitive stored energy systems and active power conditioning technologies.

Approach: ORNL and Ferraro, Oliver & Associates (FOA) constructed a network of industry contacts and research consultants that were used to collect, update, and

analyze on-going SMES research and development and marketing activities in industries, utilities, and equipment manufacturers. These resources were utilized to assemble performance characteristics on existing SMES and other comparative technologies. By ORNL and FOA participation in SMES workshops, conferences, and technology transfer events, future EPRI and ORNL roles would be determined.

Results achieved:

- Compiled summary of key people and organizations in existing SMES.

DOE's SMES Utility Interest Group meeting in Buffalo, New York, on June 7-9, 1992, and their SMES Utility/Industry Applications Workshop in Milwaukee, Wisconsin, on September 2-3, 1992, were important inputs into providing this EPRI/ORNL/FOA project access to key SMES research and development contacts and information resources. These DOE meetings were conducted in an open forum for discussions on the strategic outlook and SMES operating concerns of the electric utility industry and others. Through these events, this project was able to identify over 320 people interested in existing SMES activities. SMES research and development and marketing efforts were reviewed with potential commercial/industrial end users, government, component and system equipment manufacturers, professional services organizations, universities, utilities, EPRI, Edison Electric Institute, and various trade associations. Many of these individuals are listed in Appendix B and their constructive feedback provided the foundation for this report's work.

- Developed technology performance and cost matrices of existing SMES to alternate stored energy systems.

Figure 1-1 lists some salient comparisons between potential storage technologies and small SMES for a nominal 1-MW capability. Only storage component costs are shown because it is assumed that the "balance of plant" equipment costs are similar for similar applications. On a dollars/kilowatt (\$/kW) basis, it seems that batteries in 0-30 second applications have a clear cost advantage @\$25/kW with electrolytic capacitors being a strong competitor in the 0-5 second range @\$60/kW. Small SMES, larger batteries, and flywheels have higher costs @\$240-300/kW. On a dollars/kilowatt-hour (\$/kWh) basis, large batteries in the 30 seconds - 15 minutes and flywheels have the distinct cost advantage over the other storage devices, at \$60/kWh and \$75/kWh, respectively. Small batteries, electrolytic capacitors, and small SMES have significantly higher \$/kWh costs. It is interesting to note that while not shown in Fig. 1-1, the classic motor-generator (MG) set offers sag protection for 0-30 seconds but is burdened with high operating and maintenance costs, and potential underfrequency problems. What these data and information show is the importance of end users knowing their specific power quality application needs.

	Energy stored (kWh)	Duration (seconds)	(\$/kW)	(\$/kWh)	Key benefits/problems
Small SMES	0.25	0-2	250	1.5 M	High power-low energy density, fast response, lower maintenance
Batteries ^[1] 0-30 seconds	0-8	0-30	25	3000	Low cost, reliability may be an issue, maintenance can be a problem for some users
Batteries ^[2] 30 seconds-15 min	8-4000	30-900	240	60	Low cost, reliability may be an issue, maintenance can be a problem
Electrolytic capacitors 0-5 seconds	0-1.4	0-5	60	43 K	Relatively low cost, no refrigeration, reliability high, low energy density
Flywheel	8-4000	30-900	250-300	75	Very high potential, modular, standby losses must be reduced, power electronics may be different

Notes: ^[1]Battery design similar to standard starting, lighting, and ignition (SLI) automotive applications.
^[2]Battery design similar to industrial grade and uninterruptible power supply energy storage (UPS) applications.

Fig. 1-1. Potential storage technologies comparisons for power quality.
(Storage capital costs only)

Figure 1-2 summarizes battery, capacitor, low temperature superconductor, and flywheel stored energy system technologies for specific electric service protection times from 0.1 to 1000 seconds. Seventy to one hundred percent voltage sags are listed with the estimated prices for each stored energy system candidate that might be utilized to mitigate the electric service voltage sag. While batteries are available that cover all the listed protection times, capacitors and low temperature superconducting (LTS) storage systems only seem practical for protection durations up to about 5 seconds. Flywheel stored energy system costs are preliminary estimates but appear favorable. The key question for the capital cost of flywheel energy storage is the MG/power electronics costs. It is also clear that advanced flywheel systems are potentially competitive with batteries for periods longer than one minute. For periods of 0-6 seconds, flywheel technology applied to standard MG sets could reduce or eliminate the underfrequency problem associated with such MG sets. MG sets must be series connected (on line) and O&M costs are therefore higher than a comparable SLI or electrolytic capacitor system; however, protection against other power quality problems is also provided by a properly applied MG set.

In comparing stored energy systems which are off-line (standby or shunt configured), the standby losses must be taken into account. Standby losses are highest for the MG set (80 kW for 1 MVA rating). On-line stored energy systems add the O&M cost for on-line inverter operation.

Total price comparisons for each storage technology system for the electric service protection times listed in Fig. 1-2 indicate that present battery and capacitor technologies have more than a two-to-one price advantage over LTS

systems. Flywheel system prices become extremely competitive with battery storage systems for electric service protection times above 30 seconds.

Electric service protection time (seconds)	Voltage sag below nominal voltage (percentage)	Stored energy system technology (\$K)				Power electronics interface system (\$K)	System installation costs (\$K)	Total price for electric service protection per storage technology (\$K)			
		Battery	Capacitor	LTS	Flywheel			Battery	Capacitor	LTS	Flywheel
0.1	70	6	30	200	90	100	20	126	150	320	210
1.0	96	6	30	200	90	100	20	126	150	320	210
2.0	99	6	30	300	90	110	20	136	160	430	220
5.0	100	6	60	500	100	115	20	141	195	635	235
10.0	100	6	-	-	100	120	20	146	-	-	240
20.0	100	6	-	-	100	130	25	161	-	-	255
60.0	100	140	-	-	100	150	70	360	-	-	310
100.0	100	140	-	-	180	150	70	360	-	-	400
120.0	100	150	-	-	180	160	90	400	-	-	430
300.0	100	183	-	-	180	180	100	463	-	-	460
600.0	100	210	-	-	180	190	150	550	-	-	520
1000.0	100	240	-	-	220	200	220	660	-	-	640

Fig. 1-2. Technology performance and capital cost matrix.

Assumptions:

1. All prices are in \$/kVA.
 2. Installation costs are considered the same for 0-10 seconds.
 3. Beyond 10 seconds, only batteries are presently available and installation costs are 25-50% of capital costs including facility engineering costs.
 4. Power electronics costs are duty rated for the electric service protection time plus a "few" seconds.
 5. 1-MVA system @power factor = 0.8 @inverter efficiency of 95%, shunt operation.
 6. Power electronics equipment configurations are considered to be similar for each technology.
- Organized and conducted the EPRI/ORNL December 2-3, 1992, Atlanta, Georgia, workshop entitled "Understanding SMES Technology, Applications, and End Use."

A significant portion of the field and research experience with stored energy systems and load equipment were developed from industry experts invited to

present selected topics at the EPRI/ ORNL workshop. The workshop strategy included gathering the most current and comprehensive data on previously demonstrated stored energy system equipment and installation knowledge. Using the workshop as a forum, combined with a post-workshop SMES applications survey, unique insights to SMES technology issues and needs were documented. Principle findings of these SMES activities showed:

- There is still a need to better document and communicate the unique benefits, costs, and other relevant performance features for SMES storage technology compared to other stored energy technologies.
- "Examples" of the cost elements for each storage technology with approximate value to specific end users are virtually nonexistent. Credible costs/benefits and justifications outlining the step-by-step thinking process need to be accomplished.
- Power electronics component costs of all candidate technologies are not well defined. Power electronics equipment and associated cost breakdowns need to be more clearly defined in the context of various end-use application scenarios.
- Enhancing end-use electric load compatibility with the electric service begins with developing objective data on what causes the disturbances and how susceptible each electric load is to that electric service disturbance. This situation dictates that there is a need for accomplishing these tests, and using the resulting data to make equipment application tradeoffs.
- To exploit small SMES for improved end-use electric service enhancement, a number of questions still need to be answered: a) Is small SMES unique enough to compete with traditional and advanced active power conditioning technologies? b) What are the required performance characteristics of SMES from an end-user's perspective? c) Can the present system costs be made more attractive by applying power electronic devices and packaging advances? d) What incremental improvements would high temperature superconductors make in this application? and e) Does small SMES have a role on the utility side of the meter?
- Tailored small SMES and alternative technology demonstrations can provide the practical insights and data needed to prove claimed advantages for specific storage equipment systems. Just under 50% of workshop survey respondents indicated tailored demonstrations had a high degree of importance to them. Approximately 25 respondents suggested they had more than a casual interest in cost sharing or providing in-kind services as part of niche demonstrations.

Recommendations based on results:

This project's work provided many opportunities for open discussions with key people and organizations on both the strategic and tactical energy storage needs of potential end users. By developing storage technologies performance and capital cost matrices on existing SMES to competitive alternative stored energy systems, the data and information provide technology guidance when the end users have defined their power quality problem. In addition, perhaps the aforementioned EPRI/ORNL December 1992 workshop findings suggest the more urgent near-term actions for consideration. The following recommendations flow directly from the overall project's work.

- A. Industrial power quality surveys are one form to pursue better insights into applying stored energy technologies to mitigate electric service problems. But, do we really know whether "voltage sags and momentary interruptions" are real issues? Will the potential "technology buyer" know the cost of each power quality event versus cost of hardware to justify his actions? Are there presently enough storage technology application guidelines to identify aggressive end users with power quality concerns to get involved? It is not clear from this project's work that the answers to these questions are imminent.

Therefore, it is recommended that a number of end-user industrial surveys be conducted through utility market services personnel. Through small focus group meetings with end users and technical advisors with direct experience in the diverse stored energy systems, the barriers would be identified that may impede end-user participation in power quality mitigation concepts. In this way, technology cost justifications, reliability information, applications, and research and development issues can be realistically addressed up front.

- B. Working with select EPRI member utilities, different commercial/industrial end users can be identified to develop electric service profiles that require power quality enhancement and establish the power quality enhancement(s) potential of applying various stored energy systems. This process can be used to develop a list of applications for utilities and their customers. Specific advantages/disadvantages in each selected end-use application can be analyzed and compared to traditional power quality mitigation equipment approaches. Whether new SMES, SLI batteries, electrolytic capacitor, or flywheel technologies are capable of significantly cutting customer reports of power quality problems beyond "sags and power interruptions" can then be evaluated.

Therefore, it is recommended that a series of informal roundtable meetings be arranged with utilities, their customers, and equipment manufacturers to

identify niche demonstrations for SLI batteries and/or electrolytic capacitors, small SMES, and flywheel technologies that will be designed to gather the much needed market research into whether there is enough interest in cost-shared hardware and data collection activities. These informal meetings should be designed to collect feedback on the overall demonstration(s) purpose, objectives, costs, and expected results. Preliminary "hardware" sketches/outline can be discussed with select utility market/ energy services personnel. This approach would identify those parties with sincere interest and commitments to proceed with the niche demonstrations.

- C. As sensitive electronic loads proliferate in residential, commercial, and industrial applications, electric service disturbances can result in lost revenues and lost productivity. The ability of various loads to withstand the present electric environment while continuing to perform their intended function without significant upset is a major part of the power quality issue. Many electrical loads are in fact "disturbance generators" and can have a detrimental effect on the electric power source, which in turn could "transmit" the problem to other sensitive loads. To this end, we must better understand the electric services and electronic load compatibility issues and how to deal with them.

Different types of electricity users require different levels of precisely shaped electric service depending on how well the configurations of their electrically operated equipment compare to the electric service's operating "envelope." Electric devices, such as process controllers, computers, relays, and adjustable speed drives (ASDs) have different sensitivities to various electric service voltage changes that can cause "sporadic operation." When disparities between the electric service and these customer loads occur, there are many methods and mitigation equipment available to eliminate or reduce the impact of these disparities. Protective devices range from providing minimal protection to those that construct a new electric service for critical loads. The cost-effectiveness of interface equipment depends on the number and the nature of power quality-related upsets expected.

Therefore, it is recommended that end-user electric load equipment response characteristics be established over a range of likely electric service conditions. This first step should become the basis in evaluating the end-user's need for any electric power conditioning interface system. Electrically operated load equipment sensitivities to electric service aberrations should be gathered in a controlled laboratory environment. When this information is coupled with customer productivity loss estimates collected from a specific site, then cost justifications for dealing with "less than perfect electric service" can become meaningful.

3. J. W. McKeever et al., "Operation of a Test Bed Axial-Gap Brushless DC Rotor with a Superconducting Stator," *Adv. Cryog. Eng.*, Vol. 39, pp. 941-948, 1994.

Abstract

A variable-speed axial-gap motor with a stator consisting of the four liquid helium cooled superconducting electromagnets (two pole pairs) was built and proof tested up to 608 rpm in November 1990 as a tool for joint industry-laboratory evaluation of coils fabricated from high-temperature oxide superconductors. A second rotor was fabricated with improved material, winding configuration, and wire type, and the drive system was modified to eliminate current spiking. The modified motor was characterized to design speed, 188 rad/s (1800 rpm), to acquire a performance baseline for future comparison with that of HTS wire. As it becomes commercially available, HTS wire will replace the low-temperature electromagnet wire in a stator modified to control wire temperatures between 4 K and 77 K.

Measurements of the superconducting electromagnetic field and locked rotor torque as functions of cryocurrent and dc current through two phases of the motor, respectively, provided data to estimate power that could be developed by the rotor. Back emf and parasitic mechanical and electromagnetic drag torques were measured as functions of angular velocity to calculate actual rotor power developed and to quantify losses, which reduce the motor's efficiency. A detailed measurement of motor power at design speed confirmed the developed power equation. When subsequently operated at the 33-A maximum available rotor current, the motor delivered 15.3 kW (20.5 hp) to the load.

In a final test, the cryostat was operated at 2500 A, 200 A below its critical current. At rotor design current of 60 A and 2500 A stator current, the extrapolated developed power would be 44.2 kW (59.2 hp) with 94% efficiency.

4. L. J. Talarico and J. W. McKeever, "Survey of Cryogenic Semiconductor Devices," ORNL/TM-13173, Oak Ridge National Laboratory, April 1996.

Summary

Improved reliability and electronic performance can be achieved in a system operated at cryogenic temperatures because of the reduction in mechanical insult and in disruptive effects of thermal energy on electronic devices. Continuing discoveries of new superconductors with ever increasing values of T_c above that of liquid nitrogen temperature (LNT) have provided incentive for developing semiconductor electronic systems that may also operate in the superconductor's liquid nitrogen bath. Because of the interest in HTS devices, liquid nitrogen is the cryogen of choice and LNT is the temperature on which this review is focused.

The purpose of this survey is to locate and assemble published information comparing the room temperature (298 K), performance of commercially available conventional and hybrid semiconductor devices with their performance at LNT (77 K), to help establish their candidacy as cryogenic electronic devices specifically for use at LNT.

The approach to gathering information for this survey included the following activities. Periodicals and proceedings were searched for information on the behavior of semiconductor devices at LNT. Telephone calls were made to representatives of semiconductor industries, to semiconductor subcontractors, to university faculty members prominent for their research in the area of cryogenic semiconductors, and to representatives of the National Aeronautics and Space Administration (NASA) and NASA subcontractors. The sources and contacts are listed with their responses in the introduction, and a list of references appears at the end of the survey.

Information on the devices is organized under the following classes: diode, bipolar junction transition (BJT), field-effect transistor, and combined technology. Devices under the BJT class are the BJT, thyristor, gate turnoff thyristor, for which no articles were found, metal-oxide semiconductor field-effect transistor (MOSFET) controlled thyristor, and insulated gate bipolar transistor. Devices under the field-effect transistor class are the junction field effect transistor and MOSFET. Devices under the combined technology class are the complementary metal-oxide semiconductors.

Design parameters were sparsely distributed in the literature surveyed. A conclusion of this survey is that parameters needed to design cryogenic electronic circuits must now be measured by the designer or subcontracted to one of the universities. Private industries, which have little incentive to release design data for which they have paid, will keep data that they have measured for internal use. If sufficient market demand exists for cryogenic electronic devices, then the industrial vendor will have reason to provide the data.

With few exceptions, the commercial market does not design bipolar or field-effect transistors for cryogenic operation. Until recently, nearly all active semiconductor devices being used and considered for cold electronics belonged to the field-effect transistor class. The results of this survey indicate that the BJT class is now also included because its technology has evolved sufficiently for BJT devices to have acceptable current gain and breakdown voltage at LNT.

CONCLUSIONS

There were no inventions made or reported during the term of the CRADA and no direct commercialization possibilities resulting from the project.

The main objectives of this cooperative agreement were met. Four reports containing information valuable to the sponsors and their stakeholders were generated and broadly disseminated. No further collaboration is planned.

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