

# A 100 MJ SMES Demonstration at FSU-CAPS

Cesar A. Luongo, *Member, IEEE*, Thomas Baldwin, *Member, IEEE*, Paulo Ribeiro, *Senior Member, IEEE*, and Charles M. Weber

**Abstract**—The Center for Advanced Power Systems (CAPS) at Florida State University (FSU) was recently established to pursue research and education in power engineering. Development and demonstration of superconducting technologies is one of the cornerstones of the CAPS program. Important aspects of the program are the test of superconducting equipment at power levels up to 5 MW, and the creation of a reconfigurable network that will support pulsed power testing. A 100 MJ SMES system is being completed at BWX Technologies for integration to the CAPS test facility, to allow pulsed power operation of the testbed. The SMES coil, scheduled for completion in 2003, is based on cable-in-conduit technology and NbTi superconductor. The full system (including cryostat and power converter) will be integrated at CAPS and be operational in late 2004.

**Index Terms**—SMES, superconducting cables.

## I. INTRODUCTION

THE CENTER for Advanced Power Systems (CAPS) has recently been established at Florida State University to pursue research and education in power engineering. A major component of the CAPS program involves work on applied superconductivity, from materials characterization and development, to superconducting power equipment design and test. Technologies of interest to CAPS are superconducting cables, transformers, motors, and energy storage (SMES).

CAPS, as an outgrowth of the National High Magnetic Field Laboratory (NHMFL), is building a new facility in Tallahassee, Florida, to house the new program. The facility will accommodate offices, space for research and educational activities, and a high-bay building connected to the local utility substation for hardware testing, including superconducting power equipment. A testbed is being planned around an experimental variable-frequency AC bus, and a variable-voltage DC bus, plus the power electronics and switching to control them. The testbed, rated at 5 MW, will also include a real-time digital simulator allowing for “hardware-in-the-loop” (HIL) testing under realistic conditions. An important feature of the facility will be the ability to simulate pulsed power conditions up to the rating of the testbed, the network will include energy storage in the form of a 100 MJ

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C. A. Luongo is with the Center for Advanced Power Systems, Florida State University and also with the FAMU-FSU College of Engineering, Mechanical Engineering Department, Tallahassee, FL 32310 USA (e-mail: luongo@magnet.fsu.edu).

T. Baldwin is with the Center for Advanced Power Systems and also with the FAMU-FSU College of Engineering, Electrical Engineering Department, Tallahassee, FL 32310 USA (e-mail: baldwin@magnet.fsu.edu).

P. Ribeiro is with the Department of Electrical Engineering, Calvin College, Grand Rapids, MI USA and is also with CAPS, Florida State University, FL USA (e-mail: pribeiro@calvin.edu).

C. M. Weber is with BWX Technologies, Lynchburg, VA 24506 USA.

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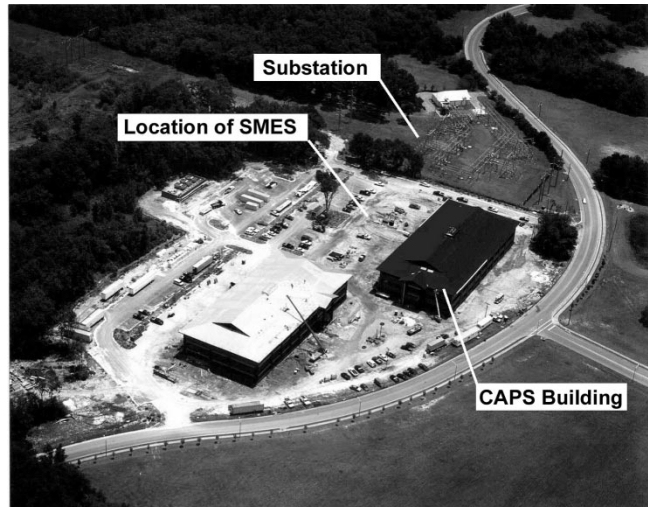


Fig. 1. CAPS facilities under construction next to the Levy St. substation, showing the future location of the SMES.

SMES that will serve not only as a pulsed power supply during tests, but also as a field demonstration of SMES technology at a scale not achieved before and meaningful for both military and utility applications [1], [2].

The 100 MJ SMES coil being installed at CAPS is the result of a multi-year development program led by BWX Technologies, of Lynchburg, Virginia. The system was originally geared to demonstrate the feasibility of adding energy storage to an existing FACTS device [3]–[7]. In 2001 the focus of this program shifted to becoming part of the CAPS testbed as an ideal way of demonstrating the operational capabilities of SMES under controlled conditions.

## II. NEW RD&D PROGRAM IN APPLIED SUPERCONDUCTIVITY

### A. Center for Advanced Power Systems (CAPS)

The creation of CAPS stems from a desire to establish an educational and research program in power engineering (both within Electrical and Mechanical Engineering) in response to the shortage of engineers on a broad swath of industries that require expertise in areas such as electricity generation, transmission, and distribution, power equipment design, controls, power system analysis and simulation, etc. As CAPS develops a new program to educate the power engineers of the future, applied superconductivity will play a major role within the activities of the new center.

A long-term objective for CAPS is to integrate a number of superconducting technologies to its facilities and adjacent substation. The site offers an ideal location for the development and demonstration of new superconducting power technologies (i.e.,

SMES, motors, cables, transformers, etc.). The following synergisms make CAPS a good choice to host the SMES demonstration:

- 1) Core mission to develop superconducting technologies for naval and utility application, thus leveraging funding for dual use technologies
- 2) Proximity to world-class expertise in superconductivity and cryogenics at the NHMFL
- 3) A well-instrumented substation, load, and CAPS facility, plus a very supportive local utility (Tallahassee Electric)
- 4) Access to faculty and students that can carry out special projects or research to evaluate the prototypes.

*B. The CAPS Testbed*

CAPS is developing an equipment testbed facility that will be coupled to real-time simulation capability. The testbed will be flexible and will have the capability to test equipment up to about 5 MW of capacity.

The core of the facility will be a test stand for low RPM motor drives. Two dynamometers connected together on a single shaft serve as torque load for the drive (converter plus machine) under test. The latter is powered either directly from the utility grid, or via a variable speed drive (to be implemented at a later stage). This second option will provide the flexibility to control the AC bus voltage dynamically, thus simulating the actual situation as it would appear on the grid or an electric ship.

By incorporating a real time simulator (RTS) into the controls of the test bed, a unique test system emerges which allows for hardware-in-the-loop (HIL) testing of motor drives. In particular, the RTS will be capable of simulating the ship’s electric power system (generators, distribution system, etc.) and the propulsion dynamics (speed-torque relationship of the propeller) simultaneously and in real-time. The simulator will therefore control the dynamometers and the converters feeding the AC experimental bus. The control will be done in such a way, that the drive motor under test “sees” the same torque load as in “real life” while it is powered from an AC bus that reacts to load changes like the on board distribution system would.

The capabilities of the proposed testbed reach beyond the task of just motor testing. In the final stage of expansion, the test bed will also feature:

- dedicated DC experimental bus (0 to 2 kV, 1 MW)
- 100 MJ SMES device (to be used either for power conditioning of the AC experimental bus, the utility bus, or serving as a source for pulse power loads).
- 2 sets of gas turbines (generators), 2.5 MW each
- auxiliary 13 kV bus.

Multiple possibilities of interconnecting these subsystems will ensure the highest level of flexibility for the testbed (e.g., the SMES may be either support the DC experimental bus, or can be connected to the local utility grid). Fig. 2 shows an illustration of the extended testbed, the one-line diagram of the testbed shows the SMES configured in such a way as to provide protection to the CAPS facility and the NHMFL operations. The testbed and the SMES demonstration are connected to two 115 kV transmission lines serving the City of Tallahassee.

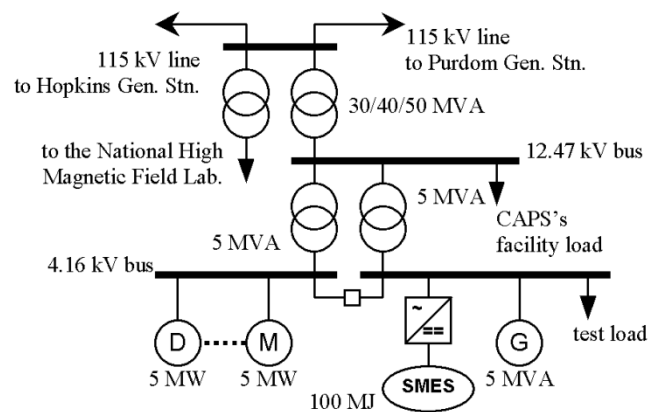


Fig. 2. Simplified diagram of the SMES experimental testbed.

The SMES demonstration consists of connecting the 100 MJ superconducting magnet to a four-quadrant 5 MW converter and chopper. This configuration is adequate for confirmatory testing of all SMES operating modes. The transmission enhancement portion of the demonstrations includes studies with the Tallahassee Electric Department to evaluate SMES benefits. The neighboring facilities, Center for Advanced Power Systems and the National High Magnetic Field Laboratory, are excellent candidates for Power Quality and Power Factor correction demonstrations. The NHMFL and CAPS housekeeping load averages 3 to 5 MW with an additional 40 MW of interruptible load.

The initial phase of the testbed (RTS plus motor test stand) will be operational in 2003, with the SMES implementation planned for 2004, and subsequent testbed enhancements to follow beginning in 2005.

*C. Power Systems Real Time Simulator*

CAPS has purchased a real-time simulator from RTDS Technologies Inc., of Winnipeg, Manitoba. The RTDS DSP-based parallel computer is an integrated hardware-software solution to the power-system simulation problem, providing a user interface based on Manitoba Hydro’s PSCAD/EMTDC and extensive facilities for interfacing with external hardware via both analog and digital I/O [8]. The system purchased by CAPS, to be commissioned in late 2002, will have sufficient computational capacity to simulate in real time a power system with half a dozen machines and several converters modeled at the switching level, or a large utility system. This capability will be employed initially to develop HIL strategies for motor testing; the experience gained will then be employed in developing realistic tests of the SMES, such as by simulating a utility system to be stabilized by SMES through the experimental AC bus.

*D. SMES and FACTS*

SMES, when combined with a FACTS controller, offers a new technology solution to provide increased transfer capability and reliability for transmission lines. When transmission level power system disturbances take place generators do not

always respond fast enough to avoid wide spread frequency and voltage stability problems. These instabilities can lead to frequency and voltage fluctuations capable of damaging equipment, brownouts, load shedding or blackouts. Stored energy (real power) in combination with reactive power can offer a low cost, multi-functional solution not currently available. If 10 s to 100 s of megawatts of real power were available (for injection or absorption) then frequency, voltage and phase angle could be controlled more effectively using the entire 360° of the PQ plane. This four-quadrant operation capability can offer an alternative to the costly and complex power circulation options currently available.

The high speed switching devices required for this type of control is already in operation today. The two key areas of investigation and demonstration are the fabrication and operation of superconducting magnets built specifically to operate at transmission system voltage levels and to tolerate the AC losses caused by the rapid discharge and recharge of the magnet. The second key area is controls. There has been sufficient evaluation by researchers of the use of real and reactive power in transmission system stabilization to provide confidence that this type operation is possible and beneficial.

The SMES demonstration proposed by CAPS provides the opportunity to validate this potentially valuable tool in assuring transmission system reliability and performance improvement. This capability of SMES may offer the greatest economic benefit because of its potential to increase power transfer and stability of the supply system.

#### *E. Development and Demonstration of Superconducting Power Equipment*

Some of the specific research programs that will use the SMES facility to run tests and experiments are:

- 1) *SMES controls and power converter technology.* Develop robust control strategies for managing high-power SMES systems, and investigate possible topologies for power converters optimized for SMES (voltage vs. current-source converters)
- 2) *Magnet/Power Converter Interactions.* Study the interaction between high frequency switching in the power converter (e.g., chopper) and the superconducting magnet. Assess impact of these interactions on AC losses, insulation rating (over voltages), and pulsed power response. This program is both computational and experimental
- 3) *Protection of large superconducting magnets.* This research aims at developing computational tools to better simulate quench and protection schemes in large superconducting magnets (e.g., SMES)
- 4) *Modeling of energy storage and network stability.* Develop computer models of energy storage devices (incl. controls) to incorporate to other CAPS programs in network architecture and simulation
- 5) *Power quality and Network stabilization.* Conduct demonstration experiments of the capabilities of SMES to enhance power quality and network stability

CAPS will also engage in the development and demonstration of other superconducting power technologies. A proposed

Superconducting Substation will be added to the testbed, including the use of superconducting transformers. HTS transformers have reduced size and weight requirements, lower losses, and oil-free benefits. Modern cryocooler technologies provide cooling without liquid coolants and less maintenance. Using medium voltage distribution loads will require distribution transformers in the 2–4 MVA range.

In addition to these more conventional attributes, the HTS transformer has the potential of having significant system benefits [9], [10]. These benefits come from reducing the short circuit current in the system and lower transformer impedance. The HTS wire has current limiting capability. This can reduce the interrupting ratings of circuit breakers and in some cases, permit the use of mesh networks for a tightly coupled power system. The lower transformer impedance will improve voltage regulation and stability; and increase real and reactive power availability to the power system.

The program outlined above serves as a technology demonstrator for the utility industry, but is also an excellent platform for research and teaching in power engineering.

### III. SMES DEMONSTRATION

For the last 8 years BWX Technologies has been developing SMES for application in the utility industry (spinning reserve and transmission stability). The program, supported by DOE, has also received support from BWXT and EPRI. In its last phase, the program was geared toward building a demonstration 100 MJ SMES magnet to be installed at an existing FACTS device substation to enhance transmission. The purpose of this project was to demonstrate the capabilities of SMES to stabilize high-voltage transmission grids. Installation of the SMES has been suspended and the DOE program is being phased out. However, since the magnet is being manufactured, BWXT and CAPS have entered into an agreement to continue the SMES demonstration program. CAPS will host the SMES at its facilities being built at Florida State University adjacent to the National High Magnetic Field Laboratory (NHMFL). The CAPS installations are located next to the Levy substation of Tallahassee Electric and will provide a testbed not only to SMES, but to other technologies of interest to both the Navy and the utility industry.

#### *A. Background of SMES System*

The SMES coil for this project is in the final manufacturing phase. Completion is expected by middle of 2003. This system can provide 100MW peak and  $\pm 50$  MW oscillatory power with 100 MJ of stored energy. The base line for the coil design is a cable-in-conduit conductor (CICC), with rated voltage of 24 kV, and operating at nominal temperature of 4.5 K. The 24 kV voltage was driven/determined by an intermediate transmission system application which did not realize.

In the process of optimizing the design of the SMES coil for a power utility application, designers have started with the duty cycle in which the coil exchanges energy with the electric grid. The transmission stability application, which requires the coil to rapidly and cyclically discharge and absorb power, was a major

TABLE I  
SUMMARY OF BWXT SMES CHARACTERISTICS/PARAMETERS

Parameter	Value
Coil Configuration	Solenoid
Rated Current	4,000 A
Rated Voltage (terminal-to-terminal)	24,000 V
Peak Power	96 MW
Stored Energy @ Rated Current – 4,000 A	86 MJ
Stored Energy @ 4,300 Amperes	100 MJ
Max. Power Exchange (@ 0.2-3 Hz, 15 sec. exp. decay at 5 sec )	+/- 50
Winding Type	Pancake
No. Pancakes	88
No. Double Pancake	44
Winding turns per layer (pancake)	20
Total No. Turns	1,760
Inductance	10.8
Bmax, @ Rated Current	4.03
Conductor – Cable-In-Conduit, Nb-Ti	CICC
Cu/SC Ratio	2.9
Cu RRR, minimum	70
No. SC strands per cable	180
No. Cu strands per cable	30
Total No. strands per cable	210
Strand Critical Cur. nominal at 4.2K, 5T	129 A
Strand Critical Cur. Density	2750 A/mm <sup>2</sup>
Operating Current/Critical Current	17 %
Helium Inlet Temperature at 5 bar, max.	4.6 K
Helium flow capacity	15 g/sec

challenge since the operation results in high AC losses. Typical frequencies in which significant amounts of energy are exchanged with the electrical grid are in the range of 0.2 to 3 Hz. In addition, low frequency pulsed demands and higher frequency duty cycles are also required. The high AC losses drive the design toward the CICC approach that minimizes the conductor mass subjected to eddy currents. Cost limitations also drove the energy requirement from an initial 1800 MJ, for short-term spinning reserve application, to a dynamic stability application requiring no more than 100 MJ.

*B. Description of Magnet System*

The general functional characteristics and parameters of the BWXT SMES coil are shown in Table I. Fig. 3 shows in detail the CICC configuration approach from the wire to the cable stages, conductor sheath and coil dimensions. Winding of the solenoid is done as double pancakes (total of 44), which are then assembled in modules for impregnation (total of 11 modules).

*C. Status of Magnet Fabrication*

Figs. 4–6 show the coil assembly and winding at the BWXT plant in Lynchburg, Virginia. The complete coil is scheduled to be shipped to CAPS in the middle of 2003 and the entire SMES system should be in operation by 2004.

During the design, development and qualification phases of the SMES program, numerous tests have been performed on the various components and subsystems. Representative hardware used for the actual SMES magnet was fabricated using materials and methods that were developed for production. All of the novel features and performance parameters have been successfully tested and exceed design and specification requirements.

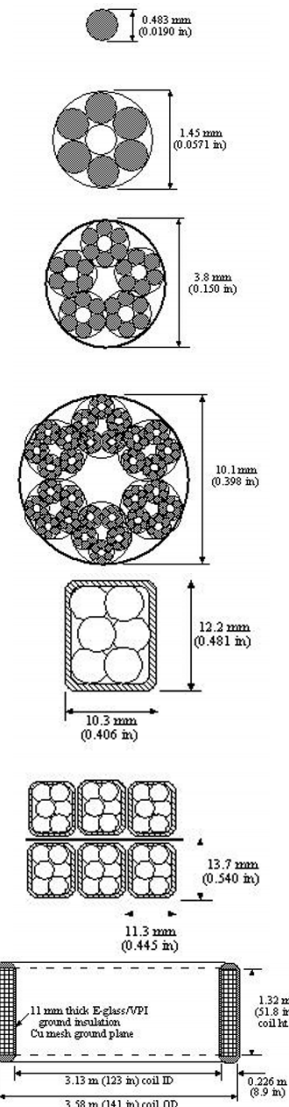


Fig. 3. SMES coil configuration and dimensions—wire, cable stages, cable sheath and coil dimensions.



Fig. 4. SMES CICC fabrication line and coil assembly.

The major test categories are structural, superconductivity and stability, and insulation. All of the materials used in the construction have been tested for their mechanical properties. A 4 × 5 conductor array with ground wall insulation mockup was fabricated and tested. This mockup was thermally cycled to LN2

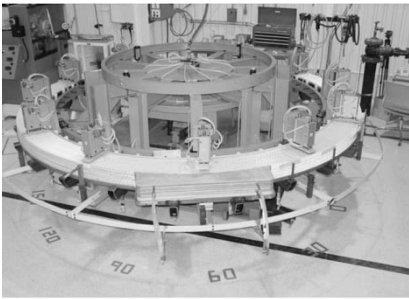


Fig. 5. Insulated CICC coil module in winding fixture.

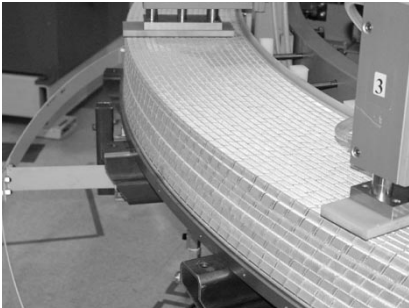


Fig. 6. Close-up of coil winding.

temperatures three times and mechanically loaded to full operational stress, cyclically loaded to five times the design life and then voltage withstand tested to failure.

Cracking in epoxy-rich regions was observed for this end of life insulation testing. The voltage breakdown obtained greatly exceeded the test and design values. The minimum turn to turn breakdown voltage obtained was 30 kV. The minimum turn to ground breakdown voltage obtained was 96 kV. Again, these values are after full-life applied stresses. Adjacent conductors have been tested for voltage withstand in air without epoxy and have demonstrated 68 kV voltage withstand. Another proof of concept system insulation test was completed for the first phase. This “Proof Test” consisted of all the components, except the coil, that is exposed to electrical power contact for the SMES magnet system; which includes the high voltage current leads, the lead bus and terminals, the splices and splice box assembly, the helium isolators, the voltage taps and instrumentation wires and vacuum feed-throughs and system ground screens.

The entire circuit/hardware was thermally cycled to LN<sub>2</sub> temperatures three times and voltage withstand tested in vacuum. The system withstood 25 kV, at which point a breakdown occurred. The failure was traced to one of the voltage tap wires at about 10 feet from the splice box and the failure was in the wire FEP insulation. Thus, to date, the entire electrical/insulation system has demonstrated 25 kV withstand potential. The failed instrumentation line is being removed and the remaining hardware will be further tested to failure, which is expected to be at a much higher value.

The superconducting conductor and arrangements have also been tested and qualified for this cyclic system operation. Each strand length has been tested for critical current during wire manufacturing. All the conductor strands have exceeded the specification requirements. Additionally, strand samples have been removed from processed cable-in-conduit

conductor (CICC) and tested to determine if the CICC manufacturing process resulted in any degradation in strand critical current—no degradation has been observed. A test article consisting of two 1-meter lengths of CICC with an intercoil splice connection on one end and two bus splice connections on the other end was fabricated and tested at LHe temperatures (4 K) in magnetic fields of varying strength and rate. The AC losses of the conductor have been measured and the stability of the conductor and both types of splices assessed. From these operational tests adequate margin and stability of all the components has been obtained with temperature margins of about two times the design margin. A stable, low loss CICC conductor has been achieved. The AC loss exponent value,  $n\tau$ , obtained in various samples in various ramping magnetic fields, up to 1.6 T/s, was 7–13 ms. The design value for  $n\tau$  to meet the  $\pm 50$  MW at 0.2 to 3 Hz power exchange is 50 ms. Again, good margin has been achieved for the superconductor and the splices which should enable the system to exceed specification requirements.

The important and critical features of the SMES magnet system have been tested using representative hardware and all results to date have demonstrated substantial margin to design requirements. It should be noted that due to limitations in the power electronics rating of the CAPS facility, the coil will not be subjected to more than 10% of the design terminal voltage, so ample margin is available.

The cumulative effect of good thermal insulation to minimize heat load on refrigerator, mechanical structure to cope with the electromagnetic forces and strong insulation to withstand the high voltage stresses makes this SMES coil a valuable demonstration for pulsed power applications.

#### D. Installation of SMES System at CAPS and Integration to Testbed

The SMES coil will be fully fabricated at BWXT in Lynchburg, VA, and transported in one piece to CAPS in Tallahassee, FL (a wide load weighing 30 tons). Shipping is expected for the summer of 2003. Installation of the coil at CAPS will involve the following steps:

- Foundation and bottom of the vacuum vessel inside temporary enclosure
- Setting coil on vacuum vessel bottom
- Splicing of pancake-to-pancake terminations, and welding of headers and electrical breaks at each helium port
- Completion of the helium circuit and connection to the refrigeration system
- Installation of the thermal shield system and installation and welding of the vacuum vessel top
- Bottoming up the vessel with the current lead assembly, connection to the coil, and completion of shield system
- Connection to power converter and CAPS testbed
- Commissioning tests and start-up.

These tasks will take about a year from coil delivery so that full operation of the SMES system is expected for the summer of 2004.

#### IV. SUMMARY

The Center for Advanced Power Systems (CAPS) at Florida State University has embarked on the development of a new power engineering program including a major emphasis on applied superconductivity. An important component of the CAPS facility will be a 100 MJ SMES system that has been fully designed, and is now undergoing final fabrication and component testing. The full system is expected to be operational in 2004. The SMES system will be not only a demonstration of utility and military application at a scale not achieved before, but also the centerpiece of an educational and research program in power engineering, power systems controls and superconductivity.

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