Advanced Power Electronics and HTS Technology for SMES: Demonstration Results

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Abstract
Superconducting magnetic energy storage (SMES) has evolved from its application origins of load leveling, in the early 1970s, to include power quality for utility, industrial, commercial and military applications. It has also shown promise as an energy source for pulsed power applications such as electromagnetic guns and electromagnetic aircraft launchers (EMAL), as well as for vital loads when power distribution systems are temporarily down. These new applications demand more efficient, compact, high performance power electronics and advanced superconducting SMES technology. This paper addresses these issues and describes tests of an advanced power electronics system developed at the Center for Power Electronics Systems (CPES) at Virginia Tech with a high temperature superconducting (HTS) magnet at the Naval Research Lab (NRL). These two systems were operated together successfully and demonstration results are presented.

Introduction

Recently there has been a technology development push for an all-electric aircraft carrier. A major change in an all-electric ship is the replacement of the steam catapult with an EMAL system. Along with EMAL, the ship would also convert all of its hydraulic and pneumatic actuators to electrical actuators and replace hydraulic aircraft arresting gear with an electromagnetic arrester capable of recovering energy. It would likely incorporate an advanced electrical defense system and electrically powered weaponry [1]. These new capabilities as well as the incorporation of more advanced controls and navigation equipment will require a means of energy storage to smooth transients on the distribution system and maintain clean, reliable power. Stringent requirements exist for naval shipboard equipment and these systems must be made compact and efficient as well as reliable. HTS technology allows substantial simplification and reduction in cryogenic support requirements for SMES, as well as improved thermal stability compared to low temperature superconductors (LTS). In addition, advanced power electronics can have significant impact on efficiency, size and weight of a power conditioning system (PCS).

SMES magnets can be implemented using conventional liquid-helium cooled, LTS. However, HTS may offer several potential advantages in SMES applications over LTS [2]. In particular, HTS SMES magnets can be cooled with cryocoolers operating at around 25 K instead of liquid helium or cryocoolers operating inefficiently at 10 K. At the higher temperatures, specific heats of materials are higher so that a given heat load causes less of a temperature rise. Consequently, the high heat loads accompanying fast current ramping and AC harmonics are more manageable with HTS than with LTS. This can be important for potential Navy SMES applications with requirements for rapid delivery of stored energy, for example, EMAL and ordnance handling systems.

American Superconductor Corporation (ASC) and Gesellschaft fur Innovative Energieumwandlund und Speicherugn (EUS) [2] demonstrated the first significant HTS SMES system, a 5 kJ system, operating at 25 K in 1996. In the present work, we describe a demonstration of HTS SMES using an 85 kJ magnet, also built by American Superconductor.

The majority of research and development in PCS technology for SMES has been driven by utility applications. Due to the high power levels involved with these applications, the majority of systems employ gate turn-off (GTO) thyristors and silicon controlled rectifier (SCR) devices. Consequently, very little work has been done on SMES for medium power (several megawatts). By implementing state of the art power electronics, medium power systems can be designed based on available insulated gate bipolar transistors (IGBT). There a[1]re several basic advantages of IGBTs compared to the GTO and SCR. First, the IGBT eliminates the need for snubber circuitry which often

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contain bulky passive components. Secondly, the use of IGBTs enables the switching frequency to be increased and in turn improves the dynamic performance of the system and reduces the size of the filter components. A scaled down SMES PCS was developed at CPES based on IGBT technology. These advantages were realized and a more compact, efficient system was developed.

PCS Overview

A 250 kW PCS for SMES applications was developed at CPES and demonstrated using the HTS 85 kJ magnet at NRL. The PCS consists of a three phase, three-level voltage source converter (VSC) for the utility/load to DC-link interface and a bi-directional DC/DC converter (chopper) as the magnet interface. The PCS schematic is shown in Figure 1. The main switch is the Powerex 400 A, 1200 V module. The maximum DC-link voltage is 1800 V with a current rating of 150 A.

Both the VSC and chopper employ zero-current transition (ZCT) pulse width modulation. ZCT alleviates bulky inefficient snubber components, reduces device stresses and simplifies thermal management. In addition, soft switching allows the switching frequency to be increased [4]. The switching frequency of the VSC and chopper is

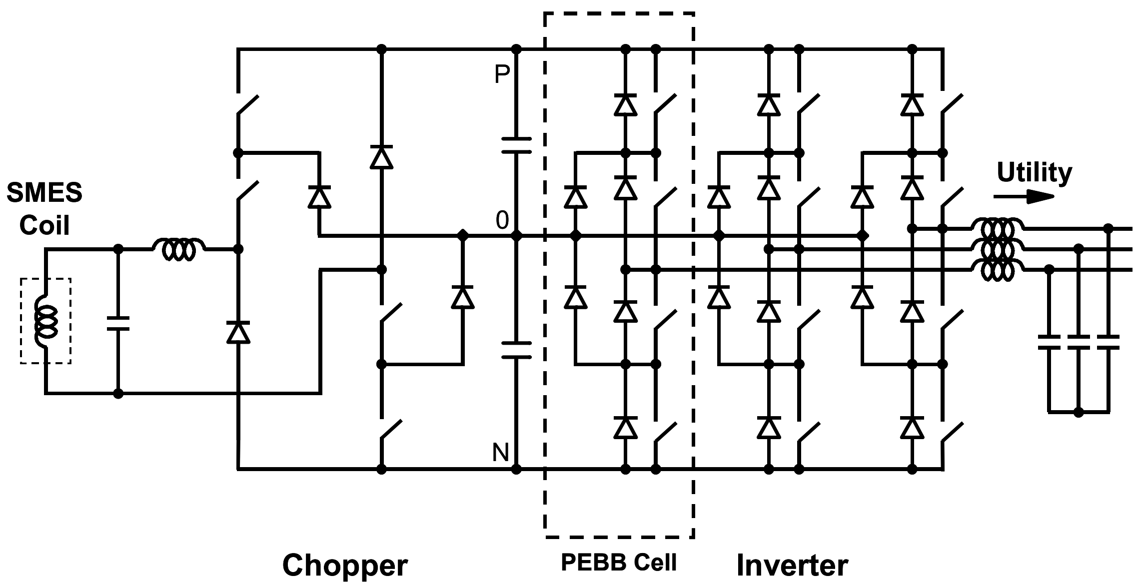

Figure 1. SMES PCS circuit diagram.

20 kHz. This increased switching frequency results in an improvement in controller bandwidth and in turn improves overall system dynamics. With this improved dynamic performance passive components on the DC-link and magnet are significantly reduced while maintaining the ability to quickly respond to line fluctuations before sensitive equipment is effected. This reduction in passive component size is possible because they are designed based on voltage ripple requirements and not energy storage. DC-link capacitance for this system is only 1400 µF, capacitance across the magnet is 50 µF and input inductor values are 600 µH while input capacitance is completely eliminated.

The three-level topology provides for a higher voltage rating relative to the two-level topology. Since only one device is switched every switching cycle with only half the DC-link voltage, the inductor current ripple is reduced and switching losses are decreased by approximately 50 percent [4]. Three-level technology also eliminates the voltage sharing problems that plague series connected devices.

HTS Magnet Overview

The high field, warm-bore, conduction-cooled HTS magnet at NRL was built by American Superconductor in 1997 [2]. Fifteen kilometers of BSCCO 2223 powder-in-tube tape is used in 34 double-pancake coils. Peak magnetic field of 7.25 Tesla is obtained in a 5 cm diameter bore at a current of 121 Amps. The field/current coefficient is 0.06 T/A.

The operating temperature of the coils is 20-25 K. The cooling is achieved with a pair of single-stage Gifford-McMahon cryocoolers. One Leybold RGS-120T cryocooler cools the magnet coils with 30 W cooling power at 25 K. A separate cryocooler cools the thermal shield and current leads to 45 K. At this point we note that the thermal design of the magnet was not intended for the very fast ramp rates described below, but primarily for thermal stability at sustained peak field operation and for current ramp rates around 0.5 A/sec. Characterization of the magnet thermal response performed previously [2] indicated that it should be capable of ramping safely for at least one cycle at 20 A/sec. The experiments described below were planned for a current ramp rate less than this, around 13 A/sec.

The inductance of the magnet is 12 H. At peak current of 121 A, 85 kJ of energy would be stored. For the demonstrations described in this paper, maximum current of only 100 A was used to ensure that thermal runaway could not occur. At this current, maximum energy capacity is 60 kJ.

The magnet described above was delivered to NRL in 1998. It was constructed with HTS tape manufactured in mid-1997, with an engineering critical current density at 77 K and self-field of 8500 A/cm^2. Production tapes at present achieve at least 13,500 A/cm^2, [2] so that the same magnet if built with the current generation of wire could (assuming corresponding increases in critical field) achieve at least twice the total energy capacity as the current magnet.

Demonstration System Operation

A demonstration was completed to illustrate the potential advantages of SMES in naval applications. Three basic operations had to be demonstrated successfully in order to show that SMES can meet the unique requirements of the all-electric ship. They are power quality, pulsed power and control of vital (motor) loads.

There are six basic modes of operation; magnet charge, utility discharge, hold, standby, pulsed load and vital load. A functional block diagram of these modes and the demonstration system setup is shown in Figure 2.

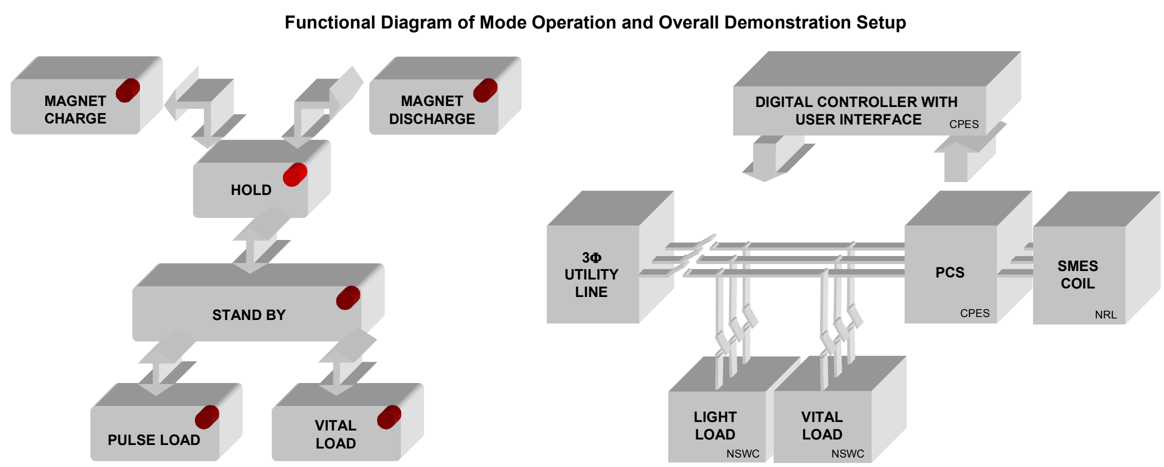

Figure 2. Mode transition diagram and overall demonstration setup.

The charge mode charges the magnet to a specified current level. A constant voltage is applied across the coil and the current is ramped linearly. As the current in the coil reaches the predetermined limit, the system automatically transitions into the hold mode. In this mode current freewheels through the chopper and a small voltage is applied to the coil to compensate for the voltage drop across the semiconductor devices and the current leads. The system remains in this mode until the magnet is ready to be discharged. From the hold mode the system can enter into the discharge mode or the standby mode. The utility discharge mode provides constant power from the magnet to the utility. This demonstrates the systems ability to be used for utility stabilization and conditioning and maintain the grid during temporary outages. The standby mode disconnects the utility from the system in preparation to connect one of the other two loads. In the standby mode the current freewheels in the chopper and losses in the semiconductor devices and leads are compensated using energy in the magnet. From the standby mode the system can be connected to the light bank to demonstrate a pulsed load or connected to the motor to demonstrate a vital load. The pulsed load consists of three two-kilowatt stadium lights. Energy is transferred in short pulses of approximately 3 seconds each. Three different motor operations are demonstrated; soft start to full speed, soft start to half speed and a quick start to full speed. These scenarios demonstrate different possible conditions that could arise onboard a naval ship.

Demonstration Results

For the SMES test runs, the power supply supplied with the magnet was simply disconnected at the magnet terminals and replaced with the above mentioned PCS. The magnet instrumentation, for monitoring coil voltages, temperatures and magnetic field in the bore, was retained. The current in the coils was calculated from the measured field in the magnet bore and the terminal voltage was calculated from the coil voltage drops. Stored energy was calculated as $\frac{1}{2} L I^2$, using the known inductance of 12 H.

Figure 3 a and b shows history of the stored energy, and coil temperature when a constant energy storage of 25 kJ is maintained in the magnet by the PCS for about ten minutes. There is a continuous temperature rise of about 0.004 K/s in this state, due to losses resulting from the harmonic content of the PCS as it maintains constant current. Since the temperature rise rate is roughly linear, and is not reaching a steady state, the losses are exceeding the cooling capacity of the cryocooler. The cooling rate at 25 K of the uncharged magnet is about 0.0035 K/s. We can therefore estimate that the losses corresponding to the 0.004 K/s temperature rise are about twice the cooling capacity of the cryocooler, or about 60 W. The current corresponding to 25 kJ stored energy is only about 65 A, which is well within the stability range of the HTS coils, therefore the losses are imposed by the AC harmonic content of the PCS. Such AC losses are generally due to eddy currents. There also is a spike in the coil temperature upon discharge of the magnet. This is typical and the temperature rise associated with the spike recovers quickly. However, the temperature spike at the cryocooler is much smaller and spread out in time, implying that this transient heat load is localized in some small region of the coils or their supports and dissipates into the coil structure quickly.

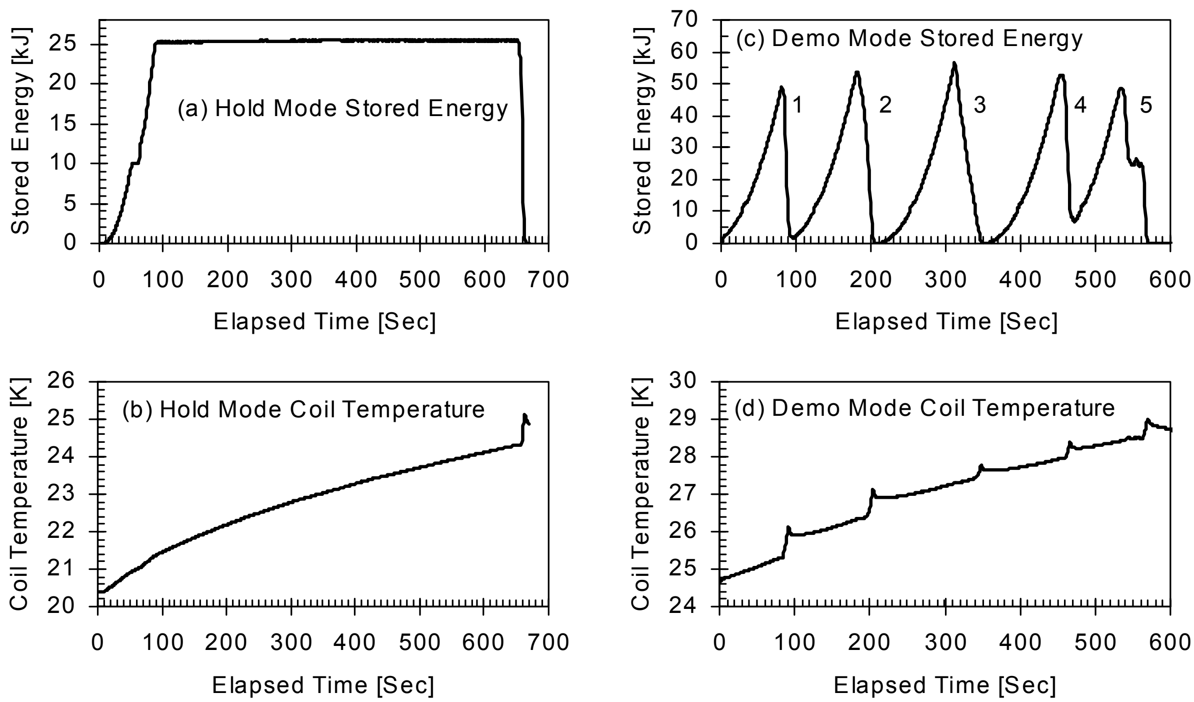

Figure 3. History of energy stored in the magnet and the coil temperature for hold mode and the demonstration mode. The demonstrations indicated in (c) are labeled as follows: 1- motor quick start to full speed, 2-motor soft start to full speed, 3-motor quick start to half speed, 4- high intensity lamps, and 5-power fed back to utility, followed by high intensity lamps.

Figure 3, c and d shows the history of the stored energy, coil temperature and coil voltage for a series of five different short-term SMES demonstrations. The first three events are the different operations of a motor, the fourth event is operation of stadium lights and the last event, energy is fed to the building power utility. There is a temperature rise of 0.0065 K/s during the charging of the magnet at a rate of 1 A/s, and a coil temperature transient of 0.4 to 0.8 K during discharge at rates of 7 to 15 A/s. The cooling rate at 25K for an uncharged magnet is about -0.0035 K/s for the cryocooling of 30 W cooling power, so we estimate that the losses during 1 A/s charging are on the order of three times the cooling capacity, or about 90 W. Charging time of 100 s means 9 kJ losses to store 65 kJ of energy. The advantage is the rapid discharge of the stored energy that is possible. The entire 65 kJ of energy can be dumped in less than 10 seconds with only a small, quickly dissipated transient temperature rise in the magnet coils.

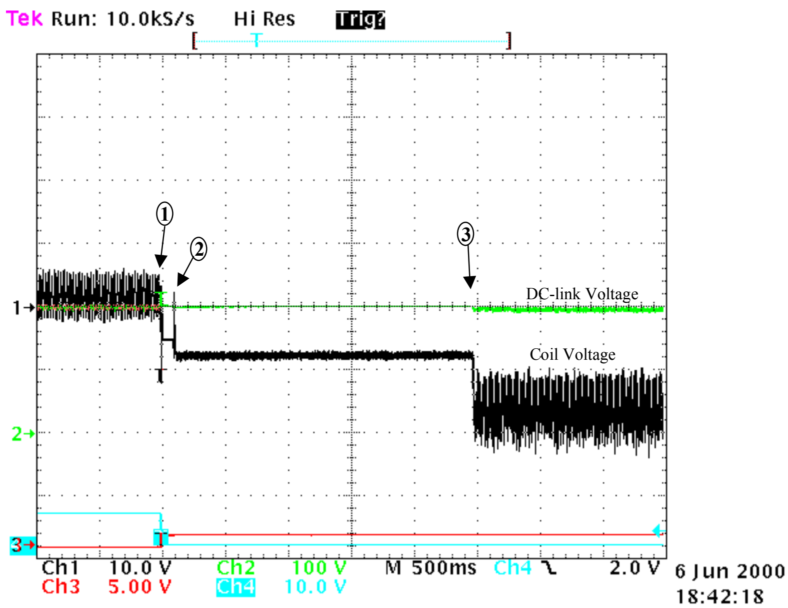

Figure 4. DC-link voltage and coil voltage waveform.

Figure 4 is of a hold – standby – discharge transition. Until point 1 the system is in the hold mode, with an average voltage of approximately 4V, maintaining a constant coil current. At this point the command to enter the standby mode is received by the chopper and VSC and the utility disconnected. Initially only the VSC transitions to standby and the chopper disables its bi-directional capabilities. The coil voltage drops to approximately –5 V as the coil current free-wheels through the chopper. At point 2 the chopper enters the standby mode, maintaining the DC-link voltage and compensating for converter losses with the energy in the magnet. This consequently produces a voltage of approximately –8 V across the magnet. This continues for 2.4 s when the system enters the pulse mode and the coil voltage is further decreased to provide the needed power on the DC-link to power the lighting load. All of these transitions are accomplished with no noticeable change in DC-link voltage and no undesirable transients.

Conclusions

We have successfully demonstrated HTS SMES at peak energy storage capacity of up to 65 kJ and stored power delivery rates in excess of 5 kW. The thermal recovery rate of the particular magnet used for the demonstrations is sufficient for about 6 to 8 rapid sequential full charge/discharge cycles at 1 A/s charge and 10 A/s discharge rates without exceeding the temperature operating limits of the conductors. Thereafter, the magnet requires about an hour for the temperature to recover. This system should be capable of sustaining continuous charge/discharge cycles at these ramp rates of about one every ten minutes if allowed to recover thermally to 25 K between each cycle. Continuous rapid charge/discharge cycling with no recover interval would require at least tripling the coil cooling rate.

The PCS was successfully interfaced with the HTS magnet and demonstrate all modes of operation. It was able to demonstrate bi-directional power flow, as is needed in a SMES system, while illustrating its versatility to supply different loads under various conditions.

A significant increase in temperature occurred while maintaining 25 kJ of energy storage for 10 minutes. During this time the PCS was operating in the hold mode. It was found, and can be seen in Figure 4, that there is significant voltage ripple on the output of the PCS during the hold mode. The frequency of this ripple is approximately 50 Hz. The cause of this ripple has not been investigated at this time. When transitioning into the hold mode the chopper employs a different modulation scheme, because of duty cycle limitations, were both positive and negative voltages are applied to obtain a small average value. Hysterisis control is used during this time and it is suspected that discontinuity points in the unique control scheme are responsible for this ripple.

Acknowledgements
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