SUPERCONDUCTING INDUCTIVE COILS

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Contents

Summary

Superconducting Magnetic Energy Storage (SMES) systems have coils that are placed inside powerful coolants to keep them near absolute zero temperature so that they become superconductive. At this state, the conductors have almost zero resistance, and therefore, large amounts of power can be stored in the magnetic fields of the coils. Therefore, SMES systems can be used to store energy when the demand is less than the production, and then this stored energy can be released if there is demand for it. This is especially important to make good use of diurnal energy sources like solar energy.

SMES systems can also be used to increase the stability and power quality of power transmission lines. SMES systems for energy storage applications are cost effective only at very large power levels. However, as the power level gets large, the physical size of the coils also becomes very large. Therefore, there are only conceptual designs for large power levels at the moment, but there are several research projects around the world with increasing power levels for SMES systems. It is expected that, with increasing use of high temperature superconducting materials, and continuing deregulation processes in energy systems especially in the USA and Europe, SMES systems will find considerably wider application areas, both for energy storage and other power quality issues.

1. Introduction

Superconducting Inductive Coils combine superconductivity and magnetic energy storage concepts to store electrical energy. Another widely used term for these coils is Superconducting Magnetic Energy Storage (SMES) coils.

The main purpose of using SMES devices is to store electrical energy in the magnetic field of a large coil so that it can be used whenever it is needed. They are mainly used to supply large, repetitive power pulses, and for load leveling applications. They can also be used in power systems in order to increase the power quality.

SMES systems basically consist of a large coil, AC/DC converters and cooling units. The conductors used in the coil are superconductors, and therefore powerful cooling units need to be employed to maintain the superconductivity feature of the conductors. AC/DC converters convert the available AC voltage into DC form which is required for energy storage. By proper control, the AC/DC converters invert the stored DC energy into AC form so that it can be utilized.

Energy systems of the U.S.A. and Europe have been going through a deregulation process. Now it is possible for third parties to buy the electrical energy from the generating companies and sell it. This open market also causes in concerns for energy storing and power quality issues, and SMES systems with their possible application areas and promising future seem to be a good solution.

2. Principle of Operation

The energy (E_L) stored in the magnetic field of an inductor is proportional to its inductance (L) and to the square of the current flowing through its windings (I).

$$E_L = \frac{1}{2} LI^2 . \qquad (1)$$

It is obvious that if large currents flow through the windings of an inductor, significant amount of energy can be stored in its magnetic field. However, even the best conductors have some resistance. Since the electrical power loss is proportional to the resistance and to the square of the current, large currents also mean large power losses. Therefore, storing large amount of energy with high efficiency is not possible unless superconductors are used in the windings of the coils.

Some materials become superconducting at very low temperatures. Most widely used superconductors are some alloys of niobium. However, maintaining superconductivity requires efficient cooling of the conductors and the medium. Therefore, superconducting coils are immersed in some liquefied gas (usually helium).

SMES coils are feasible at high power levels. At these levels the operating currents are measured in several kiloamperes, and the field level can be as high as 8 T. There occur very big forces associated with these current and field levels, and therefore the whole SMES system needs to be supported well. Bigger systems are placed underground to ease the problem.

3. Importance of Energy Storage

Energy storage can reduce the time and rate mismatch between energy supply and energy demand. Finding new, efficient, and cheap ways to store energy is as vital as finding new sources of energy. Energy can be generated and stored when the demand is low, and this stored energy can be used when there is a demand for it.

There are different types of mismatches between the energy supply and the demand for it. For example, energy supply may be variable (such as solar energy), while the demand is constant. In this case, the excess energy during the daytime is stored and used in the evening. Sometimes, both supply and demand may be varying. For example, there may be very low demand when the energy is available (day time), and demand may increase substantially when the energy is not available. In this case, almost all of the generated energy needs to be stored. In some regions, solar energy is available only during summers. In this case, a larger amount of energy needs to be stored during the high energy season to be used in the other seasons. Sometimes, the energy supply is constant, but there might be high energy demands for short amount of times. In this case, amount of stored energy is lower, but the rate at which demand needs to be met is very high.

Storing energy also helps reducing pollution and the cost of production. Also, stored energy is better suited for transportation to very long distances.

4. A Brief History of Superconductivity and SMES Systems

Superconductivity was first discovered by H. K. Onnes in 1911. However, application of superconductors in the area of electric power systems had to wait until the late 1960s. In 1969, M. Ferrier proposed using SMES for load leveling. In 1970s, some universities (such as University of Wisconsin-Madison) and laboratories (such as Los Alamos National Laboratory- LANL) initiated research projects in the area. These research projects revealed that the current technology was adequate for the application. Initially, large size magnets were found to be more cost effective than the small ones. Also, the solenoid magnets turned out to be the most proper geometry for SMES coils.

Initially, Nb_3-Sn was used as the superconducting material. Later, Nb-Ti replaced it as it is a cheaper material. Also, the operation temperature was determined to be 1.8 ^oK on the basis of stable operation and reduced amount of material.

Today, there are several big research projects to develop small and mid-size SMES systems in the U.S.A, Europe and Japan. Some of these projects are only defense oriented while most of them are for civilian purposes. There is also a lot of research to exploit advantages of using SMES in power systems for power quality concerns.

5. General Structure of SMES Systems

The components of a typical SMES system are shown in the block diagram of Figure 1. The coil takes its energy through a converter which employs solid state switches to control the energy flow.

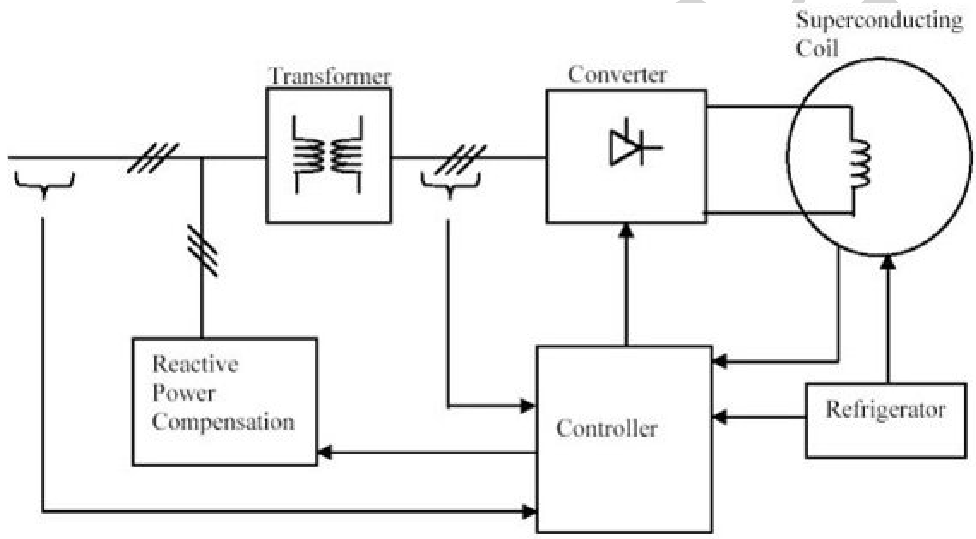

Figure 1:. Components of a Typical SMES System

Since the energy storage capacity of an inductor is related to the magnitude of its current, very large currents in the order of tens of kiloamps flow through it. However, this level of current is not possible in power systems; thus a transformer is used to convert high voltage low current into low voltage high current.

The SMES coil is an inductive load for the power system and therefore a reactive power compensation unit is necessary to provide the required capacitive energy.

The size of the SMES coil depends upon the energy storage requirement and coil geometry. Since superconducting property starts only at very low temperatures, the coil should be immersed in liquid helium at around 1.8 ^oK. Since around this temperature the viscosity of the liquid is virtually lost, liquid helium at this state is called to be a super fluid.

Helium has the property of existing as a gas or as a liquid at the operating temperature. Therefore, it is used as the cooling substance in the refrigerator of the SMES systems.

Refrigerator adjusts the temperature of the coolant. Since the conversion that takes place during storage and recovery processes is only from one form of electricity to another (AC to DC or DC to AC), and there is no conversion of energy from one form to another (such as electromechanical or electrochemical), the efficiency of the SMES system is very high. The largest energy consumption occurs at the refrigerator part.

The current passes from the converter side, which is at higher temperature, to the coil, which is at very low temperature, through special current leads. The heat that is conveyed to the coil through these leads is absorbed by the helium bath.
The whole SMES system is kept underground, inside a cavern, to provide the necessary support against the large radial forces. Inside the cavern there is a cryostat that consists of a vacuum vessel and a helium vessel. The superconducting coil is placed in the helium vessel. The helium vessel also contains the liquid helium. Figure 2 shows a cut-out view of a typical SMES system. The struts seen in the figure are made up of low thermal conductivity material and provide support from the floor and the walls of the cavern.

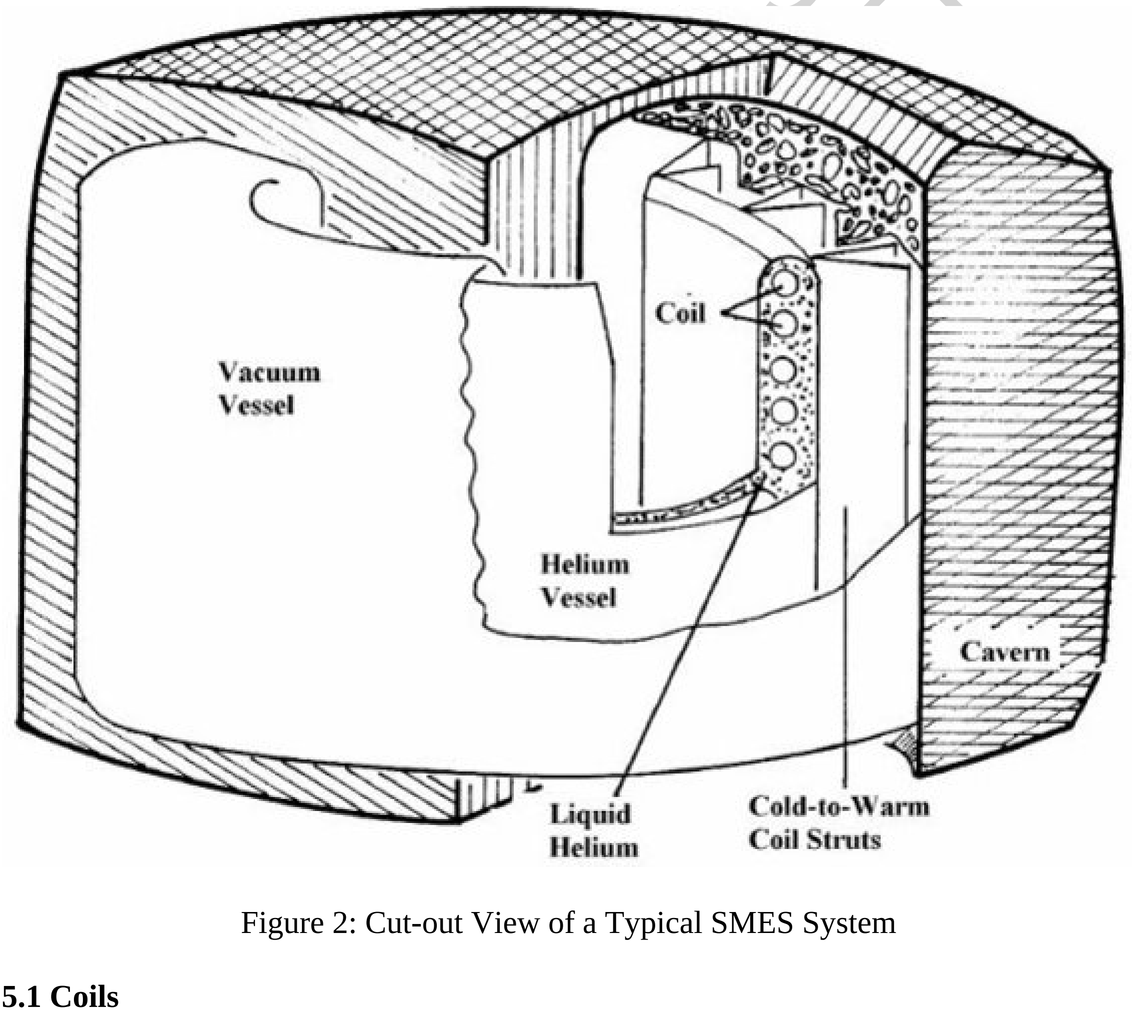

Figure 2: Cut-out View of a Typical SMES System

5.1 Coils

Coils can be classified as small, intermediate and large sized coils. However, what is meant with small, intermediate or large size differs continuously as the technology improves. Instead, a different approach is used in determining the size classification of

the coils. Large coils have diameters that are sufficiently large that makes their economics relatively insensitive to overall current density. Also, their stored energy is so large to necessitate the use of fully stabilized conductors. On the other hand, current densities of small size coils are very low, and there is no need to use stabilized conductors. Intermediate sized coils are of course in between the small and large sized coils. The energy storage is high enough to require some form of protection against overheating and over voltage. The size on the other hand is small enough to take advantage of high current densities. Whether it is necessary to use stabilized coils depend on if there are alternative ways to assure safe operation without stabilized coils.
In power system applications, diameter ranges of large coils and small coils are 1 to 5 m and less than 10 cm, respectively. However, for the SMES systems with a storage capacity of a few GWh may have diameters up to a km or more, and a height of a few tens of meters. These are the systems that need to be placed underground to overcome the large radial forces.

In large coils, usually Nb-Ti copper composite conductors are used, and coil structure is generally pancake type. The purpose of using copper is to provide stabilization. Aluminum can also be used for the same purpose. Although aluminum is more advantageous than copper, it should be in pure form, and therefore has little physical strength that makes it unsuitable for the application.

Small coils generally employ Nb-Ti or Ni_2Sn_3 conductors. Since Nb-Sn is a brittle material, it can be handled only as very thin layers, thus it is constructed with a special technique in the form of ribbon.

In the intermediate size coils, usually stabilized, but small cross-section conductors are used. The current density is therefore usually high.

5.2 Conductors

Superconductors can be classified broadly as type I and type II. Type I materials (such as lead or tin) have high current densities but very limited available cross section areas. Therefore, their current carrying capacity is very small, and they can not be used in SMES systems.

Type II materials (such as Nb_3Sn, Nb-Ti, V_3Ga) have very high field values and high current carrying capacities. Therefore, these materials are suitable to use in superconducting magnets. However, there are other requirements that must be met to use a type II material in a magnet. A superconductor can not keep its superconductivity unless its temperature, field and current values are below certain levels. It should also be noted that these values are interrelated.

With the continuing advancements in superconductor technology, it is now possible to use high temperature superconductors in SMES systems. The transition temperature of these conductors is around 60 to 80 ^{o}K. Coils using high temperature superconductors can be used by liquid nitrogen which is far cheaper than helium. However, the performance of these new materials (YBCO, BSCCO and TBCCO) is not yet at a level to allow their use in electrical power applications.

Superconductor wires have thousands of strands of superconductors. These strands are supported by copper or aluminum. These materials are called stabilizers since they help maintain superconductivity when the conductors experience large heat pulses. A typical conductor assembly for 200 kA is seen in Figure 3.

NbTi-Cu multifilament conductors stabilized with pure Al and reinforced by high strength Al alloys may have current levels between 100 kA and 300 kA, below 5 T field values. Figure 4 shows two different conductor configurations proposed for 100 kA. The purpose of this type of design is to overcome the anticipated large axial and radial forces.

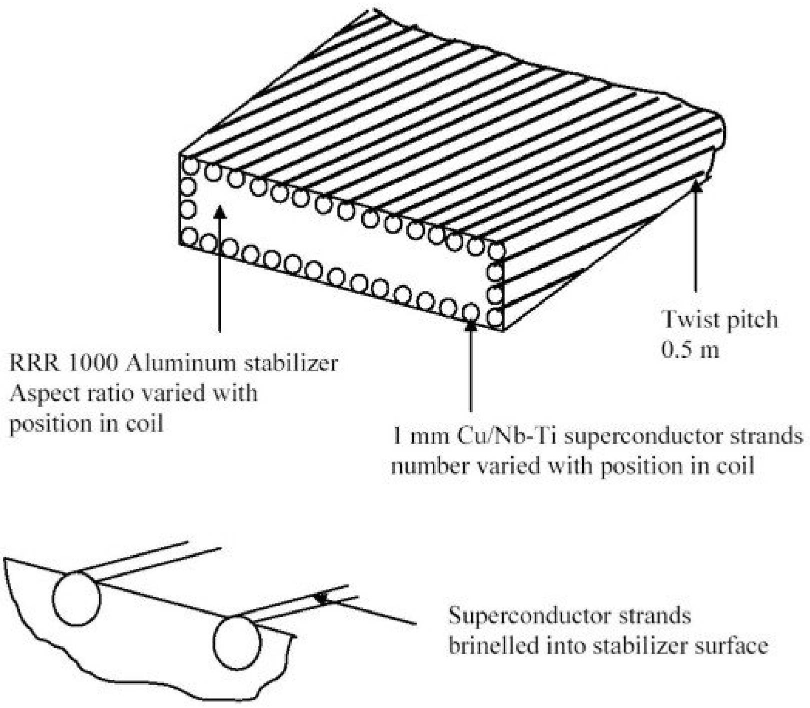

Figure 3: A Typical Conductor Assembly for 200 kA

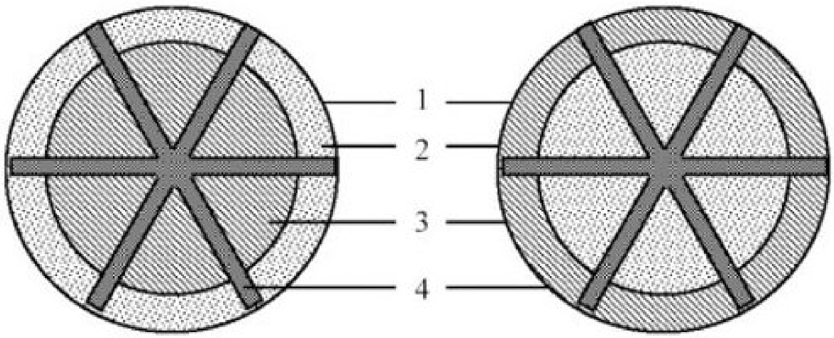

Figure 4: Two Different Conductor Configurations Proposed for 100 kA; 1: casing (Al alloy (+ insulation), 2: NbTi filaments in Cu-matrix, 3: high purity Al (stabilizer), 4: reinforcing structure (Al alloy)

Wires are kept in temperature between 1.5 and 4.5 ^{o}K. In order to keep the coil in the desired temperature range, it is either immersed in liquid helium, or liquid is pumped through the conductors. In either case, conductor and helium are kept inside a vacuum jacket, radiation shields, liquid nitrogen shield (usually) and another vacuum shield.

5.3 Cryogenic Considerations

Superconducting coils must be operated below their transition temperature. A typical temperature is the liquid helium temperature at atmospheric pressure, 4.2 ^{o}K. Nb-Sn can be operated at 14 ^{o}K although its transition temperature is 18 ^{o}K. If the highest heat transfer coefficient is desired, then the operation needs to be below the lambda point of helium, which is 2.2 ^{o}K. In this case, double cryostat is generally used. Conduction cooling and gas cooling techniques are also utilized. There are also some proposals that are worth mentioning. One proposal is to use hollow conductors and let the super critical helium flow in them.

Cryostats are usually made of stainless steel. There are three ways of heat leeks in cryostats: radiation, conduction through the support tube of the cryostat and coil, and electrical leads. Electrical leads are an important issue in the design of SMES systems.

Depending on the use cycle of the SMES coil, the magnet may be let to warm up completely when not in use, or may be allowed to warm up only to 20^{o}K.

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Bibliography

Baumann, P. D. (1992); *Energy Conservation and Environmental Benefits That May Be Realized From Superconducting Magnetic Energy Storage*, IEEE Trans. on Energy Conversion, vol.7, no.2, pp.253-259, June 1992. [This paper discusses the environmental effects of SMES systems, and gives a design example.]

Cerulli, J.,(1999) *Operational experience with a superconducting magnetic energy storage device at Brookhaven National Laboratory, New York*; Proceedings of the 1999 Winter Meeting of IEEE Power Engineering Society. v 2, p 1247-1251,1999.

Cultu, M (1988): *Superconducting Magnetic Energy Storage*; Proceedings of Advance Study Institute on Energy Storage Systems: Fundamentals and Applications; June 27- July 8, 1988, Izmir Turkey; [This work covers many aspects of SMES systems in detail].

Ehsani M. and R. L. Kustom (1988): *Converter Circuits for Superconductive Magnetic Energy Storage*, TEES Monograph Series, 1988. [This book covers all the converter circuits that are used with SMES systems in detail].

Karasik, V., Dixon, K., Weber, C., Batchelder, B., Campbell, G., and Riberio, P.(1999): *SMES For Power Utility Applications: A Review of Technical and Cost Considerations*, IEEE Transactions on Applied

Superconductivity, vol. 9, no.2, June 1999. [This paper provides an overview of power utility applications of SMES systems].

Krischel, D.(2000): *Industrial Applications of Superconducting Magnet Technology in Europe*, IEEE Trans. On Appl. Supercond. Vol. 10, no.1, pp.697-702, March 2000. [This paper discusses the current status of SMES technology in Europe].

Mann, T. L., Zeigler, J. C., Young, T. R.; *Opportunities for Superconductivity in the Electric Power Industry*, IEEE Trans. on Appl. Supercond., vol.7, no.2, pp. 239-245, June 1997. [This paper discusses the current situation and the future of SMES system applications for power systems].

Melhorn, C. J., Braz, A., Hofmann, P., Mauro, R. J.(1997): *An Evaluation of Energy Storage Techniques for Improving Ride-Through Capability for Sensitive Customers on Underground Networks*, IEEE Tran. on. Ind. Appl. Vol. 33, no.4, pp. 1083-1095, July/August 1997. [This paper discusses different energy storage techniques]

Schoettler, R.; Coney, R.G.(1999): *Commercial application experiences with SMES*, Power Engineering Journal, v 13, n 3, pp 149-152, 1999. [This paper describes a protection application of SMES system].

Tam, K.S., Kumar, P.(1990): *Impact of Superconductive Magnetic Energy Storage on Electric Power Transmission*, IEEE Trans. on Energy Conversion, vol.5, no.3, pp.510-509, September 1990. [This paper has useful information especially in the discussion part].

Ullrich, George W. (1995): *Summary of the DNA SMES development program*, IEEE Transactions on Applied Superconductivity, v 5, n 2, pp 416-421, Jun 1995. [This paper gives a brief account of government supported SMES programs in the USA].

Biographical Sketches

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