Modular Transportable Superconducting Magnetic Energy Systems

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Abstract-Design and cost studies were performed for the magnet components of mid-size (1-5 MWh), cold supported SMES systems using alternative configurations. The configurations studied included solenoid magnets, which required onsite assembly of the magnet system, and toroid and racetrack configurations which consisted of factory assembled modules. For each configuration, design concepts and cost information were developed for the major features of the magnet system including the conductor, electrical insulation, and structure. These studies showed that for mid-size systems, the costs of solenoid and toroid magnet configurations are comparable and that the specific configuration to be used for a given application should be based upon customer requirements such as limiting stray fields or minimizing risks in development or construction.

INTRODUCTION

Designs for superconducting magnetic energy storage systems have been under development for several decades as a means for providing efficient electric energy storage. Potential applications for these systems have ranged from small systems, similar in size to current laboratory magnets, providing power quality control to massive systems designed for diurnal load leveling capable of storing several thousand megawatt-hours. Until recently, the major focus for large scale design studies has been on low aspect ratio solenoids that have depended upon earth (or warm) support systems to react the radial Lorentz loads. This was because it has long been advocated that large-scale SMES can only be economical with earth (or warm) support [1]. This belief has driven the design of large scale systems and demonstrating earth supported systems was considered essential for engineering test models intended to demonstrate SMES technologies. However, recent cost studies have shown that the economical cross-over point for cold and warm supported designs is much higher than previously believed and that cold supported designs will be less expensive than warm supported designs for any application likely to be built in the foreseeable future. These cost studies have been based upon systems incorporating design and technology advancements made by Martin Marietta during the SMES-ETM program and have been confirmed using both parametric studies and point designs of systems designed for energy storage capabilities from 1 to 1,000 MWh [2].

The realization that demonstrating earth supported systems is not necessary, greatly increases the design flexibility and opportunities for cost savings on mid-size (1-5 MWh) SMES systems. For systems in this size range, magnet costs are driven more by fabrication and assembly operations than by material costs. Therefore, designs which can minimize labor costs and construction schedules through the use of standardized, factory assembled modules have the potential to become competitive with systems that are assembled in-situ. Design and cost studies were performed for the magnet components of mid-size (1-5 MWh), cold supported SMES systems using three alternative configurations. The configurations studied included solenoid magnets, which required on-site assembly of the magnet system, and toroid and racetrack configurations which consisted of factory assembled modules.

DESIGN REQUIREMENTS

The requirements for the SMES magnet system were based upon the data generated and lessons learned from the SMES-ETM program and from input from potential customers in the government and electric utility industry. These requirements were divided into two categories, system requirements and coil pack requirements. The system requirements included general system level objectives necessary to ensure that the design met technology and cost objectives. These requirements included demonstrating critical technologies for SMES, minimizing costs and risks, and developing a system that provides siting flexibility.

The coil pack requirements were more specific and included design criteria and constraints developed during the SMES-ETM program that directly affected the design of the magnet components. These requirements included the use of a high current (100 kA) cable-in-conduit conductor operating at 1.8 K and the use of a coil pack design which is self supporting and which is capable of absorbing the stored energy during an energy dump.

CONFIGURATION OPTIONS

The configurations studied included solenoid magnets, which required on-site assembly of the magnet system, and toroid and racetrack configurations which consisted of factory assembled modules. For each configuration, preliminary designs were prepared for various size coils ranging from 1 to 10 MWh of energy storage capability. A comparison between these configurations for a 1 MWh system is shown in Figure 1.

Solenoid Coil Description The solenoid coil pack consists of a two radial layer, helically wound coil as shown in Figure 2. The major components of the coil pack assembly include the conductor, dump shunt, and electrical insulation system. The dump shunt consists of an aluminum extrusion which provides the thermal mass necessary to absorb the stored energy during an energy dump and also provides the structural support for the axial and radial Lorentz loads. For a mid-size SMES, the cross-sectional area of the dump shunt is governed by the width required to install bolts at the field assembly joints. This results in the structure being oversized between joints so that structural stresses are relatively low. The area required for thermal mass purposes is lower than that required for structural purposes so there is a large thermal margin in the system as well.

The electrical insulation system serves to electrically insulate the conductor turns from each other and the ground. The primary insulation consists of a layer of Kapton tape wrapped around the assembled conductor and dump shunt. A layer of pre-impregnated fiberglass tape is wrapped over the Kapton to protect the Kapton from tears or abrasion. An outer case, consisting of precured and formed fiberglass components, serves to hold the layers of the coil pack together and also provides additional redundancy for electrical insulation purposes.

Each of the major components (conductor, dump shunt, and electrical insulation segments) is fabricated offsite and assembled into the coil onsite using field assembly joints and splices. This minimizes material usage but results in extensive onsite labor and inspection procedures.

Toroid Coil Description The toroid coil pack consists of 36 oval shaped modules approximately 14 feet wide by 47 feet long arranged in a circular configuration as shown in Figure 3. Each module consists of 16 conductor turns arranged in two layers. The primary electrical insulation consists of a layer of Kapton tape wrapped around the conductor turns. A layer of fiberglass tape is wrapped over the Kapton to protect the Kapton from tears or abrasion. This assembly is then vacuum pressure impregnated to form the conductor assembly.

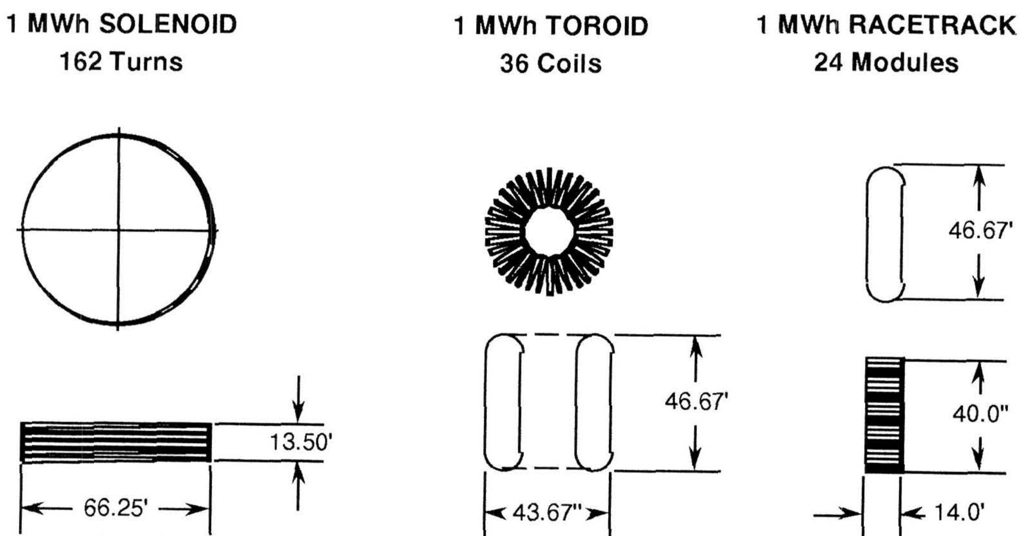

Figure 1. Configuration Options.

This conductor assembly is then placed into a structural case. The case consists of inner and outer leg segments. The inner leg case wall is designed to be wedged together with adjacent modules to form a bucking cylinder to react the inward Lorentz loads from the toroid. Tension straps running from the inner leg to the outer leg are used to react the outward Lorentz loads on the outer leg.

Each module is designed to be fabricated in a factory and then shipped to the site. Fabricating modules in the factory provides for a cleaner and more controlled environment for conductor and insulation fabrication, allows for the use of rate tooling and trained and experienced technicians, and improves quality assurance, including the capability for testing of the completed modules prior to shipping, when compared to the field assembly operations required for the solenoid.

Race Track Coil Description The race track coil pack consists of 24 racetrack modules approximately 14 feet wide by 47 feet long stacked on top of each other as shown in Figure 4. These modules are similar to the modules used for the toroid with modifications to the case walls to react the different Lorentz Loads.

COIL COMPARISON SUMMARY

The design studies demonstrated that all of the configuration operations were technically viable and were capable of satisfying the design requirements of demonstrating critical technologies for SMES, minimizing costs and risks, and developing a system that provides siting flexibility.

The critical superconducting magnet technologies for cost effective large SMES systems include high current cable-in-conduit conductors, 1.8 K helium operation, high voltage electrical insulation, and quench protection systems capable of handling the large amounts of stored energy. All of the configurations studied demonstrate these technologies. The major differences are in the design of the structure required to react the loading conditions which are unique to each configuration. However, the structural behavior of the materials and design configurations are well understood and are predictable using currently available technologies.

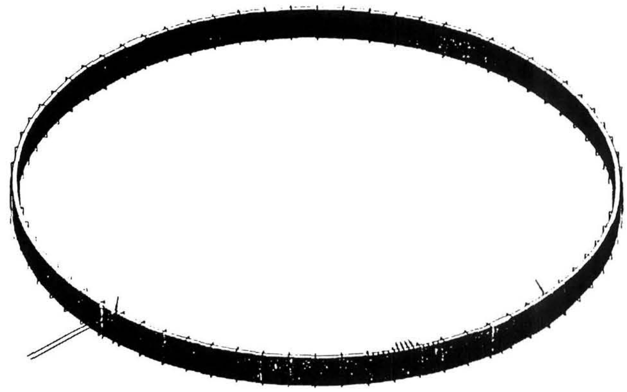

Figure 2. Solenoid Coil Configuration.

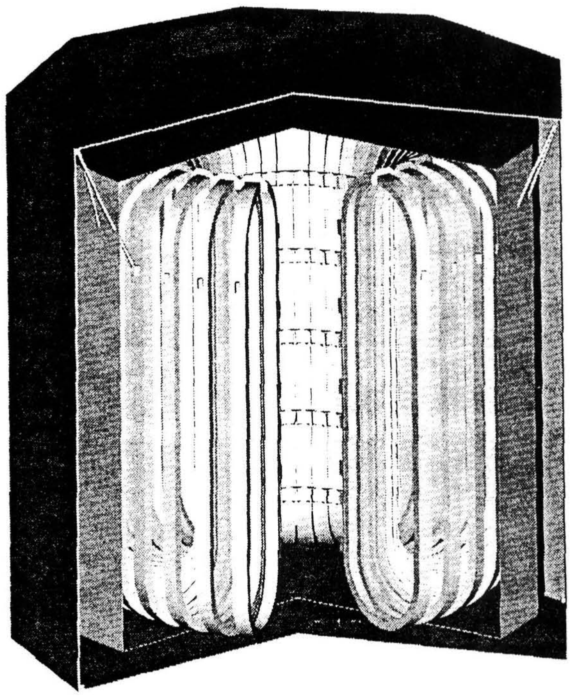

Figure 3. Toroid Coil Configuration.

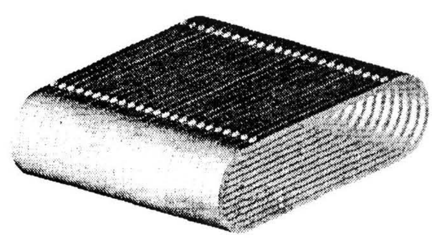

Figure 4. Race Track Coil Configuration.

Although the risks for any configuration are considered to be reasonable, the toroid and race track configurations offer advantages in several key areas. The first advantage is in technology demonstration. For a solenoid system, technology demonstration is limited to the component level and system verification requires a full scale unit. For a modular system, technology demonstration can be performed on full scale modules allowing critical design and manufacturing technologies to be fully verified before committing to a full-up system. The toroid magnets also utilize technologies which are common to other ongoing large superconducting magnet programs such as ITER and TPX. Developments in coil winding and electrical insulation technologies could be shared with those programs. The final difference in risk minimization is in the repairability of a production unit. The repair of a faulty section of a solenoid would require the removal and replacement of a large section which is essentially integral with adjacent components. The toroid and racetrack designs are based upon interchangeable modules which are only connected at a few carefully selected field assembly points

All of the configurations offer considerable siting flexibility in that they are free standing systems that do not require special soil conditions to react the magnetic loads. The major differences are in the stray field effects due to the magnet configurations. The solenoid and race track generate a field that requires a circle approximately 230 feet in radius before the 10 gauss limit is reached. the toroid generates almost no stray field and the 10 gauss limit is contained within the vacuum vessel.

The results of an analysis of the direct manufacturing costs of the different coil configurations are shown in Table 1. The costs ranged from $6.4M for the solenoid to $14.1M for the toroid. Additional analysis, which includes the effects of the reduced onsite construction time for the race track and solenoid and incorporates learning curve effects for multiple SMES units, is in the process of being performed. This analysis is expected to show that the total system cost difference is less than that shown when only magnet manufacturing costs are included. When compared to the total system cost, which is in the range of $60M-$70M, the differences in the costs between the solenoid and toroid magnets should not be the major factor in choosing the magnet configuration.

Table 1. 1 MWh Coil Cost Comparison.

	Solenoid	Solenoid RaceTrack	Toroid
Field Labor			
Cost	$1.4 M	$0.2 M	$0.3 M
Time	12 mo	3 mo	3 mo
Factory Labor	-	$2.0 M	$3.2 M
Material	$3.1 M	$6.1 M	$ 7.0 M
Conductor			
Cost	$1.9 M	$2.3 M	$ 3.6 M
Length	33,400'	40,600'	60,900'
TOTAL	$6.4 M	$10.6 M	$14.1 M

CONCLUSIONS

The study concluded that transportable, modular coils can be cost effective when considered as part of an ongoing business for SMES devices around 1 MWh. They are also effective in incrementally demonstrating the technologies required in larger scale devices. They offer the possibility of a lower risk demonstration device due to the ability to test single modules individually at cryogenic temperatures, prior to the entire array.

On the other hand, truck transportable modules are not particularly cost effective for constructing devices larger than 5 MWh, unless the transportation limits can be significantly increased by either exceeding normal truck/rail sizes or by limiting applications to barge accessible locations.

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REFERENCES

1 Verga, R.L., "SMES and other large-scale SDI cryogenic applications", Adv. Cryo. Eng., 1990, 35A.

2 Rix, C., et al, "A Self-Supporting Superconducting Magnetic Energy System (SMES) Concept", presented at the 15th International Cryogenic Engineering Conference.