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SUPERCONDUCTIVE ENERGY STORAGE FOR DIURNAL USE BY ELECTRIC UTILITIES

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ABSTRACT

A summary report of a five-year study of superconductive energy storage for electric utility systems is presented. Conceptual designs over that period have all been for one layer solenoids of aluminum-NbTi composite conductors cooled to 1.8 K in superfluid helium. The solenoids are mounted underground in bedrock in one or more tunnels. The two preferred designs in 1980 are: a 15 tunnel solenoid arranged in a circular pattern and a large radius single tunnel solenoid. The electrical energy storage efficiency in all cases is 95 to 96%.

Introduction

Superconductive energy storage studies at Wisconsin were last reported to ASC at Oakbrook in 1975 [1]. At that time we had settled on composite conductors of NbTi plus aluminum, 1.8 K pool cooling, single layer high current solenoids and structure provided by in-situ bedrock. Three phase Graetz bridge circuits were designed for the ac-dc conversion interface between dc current in a storage magnet and three phase ac current in the electric utility network.

The solid rectangular monolithic conductor and its dewar were rippled along the circumference to reduce cooldown motion in the radial direction from about 20 cm unrippled to 0.4 cm rippled. The ripple radius was typically 1 meter. Struts of fiberglass epoxy were optimized as to length and cooling stations in order to best transfer forces from the low temperature turns to the room temperature rock face. Scaling laws were developed to extrapolate similar aspect ratio magnets to other sizes for different stored energies, magnetic fields and heat leak through the struts.

Over the years better design, component improvements and engineering optimization have led to the series of storage cost estimates shown in Table 1 for three tunnel units.

Table 1

Storage Costs for 10^4 MWh Discharge Daily, Including Amortized Capital and Operating and Maintenance Costs

Year	Costs* mills/kWh	Comment
1970	117.0	steel structure, copper conductor
1974	31.4	rock structure, aluminum conductor
1976	21.7	optimized design, rectangular conductor
1978	22.3	round conductor, fiberglass polyester struts

*Cost estimates have been extrapolated to 1978 dollars

The cost of energy from superconducting magnetic energy storage consist of the amortized storage unit capital cost and O & M costs (Table 1), plus the purchase cost of energy to place into storage. Since I-C unit storage efficiencies are about 96%, the incremental value of energy delivered from storage is only 4% higher than the incremental cost of buying energy to charge an I-C unit. There is considerable available charging capacity in the incremental cost range of 15-30 mills/kWh. Thus I-C storage is a competitor to the more expensive intermediate generators by providing power in the 30-50 mills/kWh range.

In comparison to other storage units only I-C superconductive storage is 96% efficient. Compressed air storage burning fuel is the lowest in efficiency at 42% while advanced batteries may become the best of the rest at 70-80% efficiency. Pumped hydrostorage is traditionally 66% efficient. Not only does efficiency affect the cost of delivered energy but also the size of a storage unit. One of the main points in the A.D. Little study of SMES by B.M. Winer and J. Nicol is that less efficient storage units need to be much larger in order to provide energy without premature depletion [2].

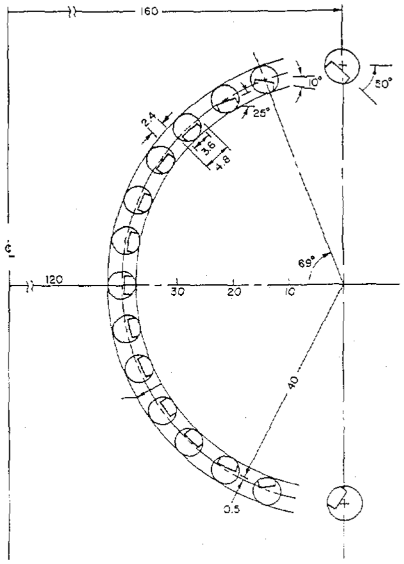

Fig. 1 Cross Section of 15 Tunnel 1000 MWh Energy Storage Solenoid. Dimensions in meters.

Design

The design of the Wisconsin superconductive energy storage unit has emphasized demonstration unit size of 1000 MWh discharge capabilities. Recent work has been directed toward a new design which reduces the need for axial structure in the unit [3,4]. A sketch of this design is shown in Fig. 1. There are 15 tunnels arranged in a circular pattern. The resultant forces are primarily radially directed outward along the 40 m radii. The orientation of the forces normal to the rock structure greatly reduces the shear loading and the need for axial structure. The use of many tunnels reduces the accumulation of

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axial forces by transferring these forces more frequently.

Table 2

Fifteen Tunnel Solenoid

Energy Stored	1186 MWh
Major Radius	120 m
Minor Radius	40 m
Total Turns	554
Turns per Central Tunnel	36
Turns per End Tunnel	43
Current per Turn	300,000 A
Central Average Field	2.5 T
Maximum Field	4.2 T
Total Normal Force	$8.8\text{x}10^{10}$N
Total Tangential Force	$1.7\text{x}10^{9}$N
Normal Strut Material*	$0.79\text{x}10^{6}$Kg
Tangential Cold Structure*	$1.2\text{x}10^{6}$Kg
Tangential Strut Material*	$0.03\text{x}10^{6}$Kg
Extra Safety Structure*	$2.0\text{x}10^{6}$ Kg

*Material is polyester fiberglass used at $1.9\text{x}10^{8}$ N/m^2 (27,000 psi)

The central tunnels would have their turns wound perpendicular to the minor radius. The two tunnels at ±69° would have the turns inclined at about 10° from horizontal. The end tunnels at ±90° are 20% larger in diameter with 20% more turns which are inclined at about 40° from perpendicular. The above distribution of turns reduces end fields in each tunnel and generally makes the overall flux lines parallel to the winding layer in each tunnel. The parameters are listed in Table 2.

In comparison to earlier designs approximately the same amount of radial strut material is required to carry the magnetic force to the rock face. The axial strut material is only 4% of the previous designs. The saving of axial strut materials is due to the multi-tunnels and the circular configuration. The axial cold structure is only 1/8 as much as the cold structure for previous three tunnel designs.

The tunnels shown in Fig. 1 would be constructed by a Tunnel Boring Machine (TBM) in the Sinnipee dolomite of eastern Wisconsin. Such construction is much less damaging to the rock fabric at the tunnel perimeter with consequently fewer anomalies in the effective rock properties such as rock modulus.

The walls will be reinforced with resin encapsulated rock bolts. Water inflow can be controlled by grouting and pumping. No need is foreseen for structural lining of tunnels. Daily cycling of Sinnipee dolomite (one of the weaker rocks) to 5 tesla pressures for 250 years can be tolerated with a safety factor of 5. Details on the rock mechanics of magnetic storage are summarized in papers [6,8].

The second design currently under consideration is a single solenoid of aspect ratio β=0.01. The sketch in Fig. 2 is for an 1000 MWh unit mounted in a tunnel very near the surface. Specifications are listed in Table 3. It need not be very deep because the radial pressures on the rock are only about 30 psi as compared to 300 psi for the 15 tunnel unit. Thus simple surface trenching may be used to form the tunnel. Conductor installation, dewar assembly and eventual repair should all be easier for an open top tunnel.

Table 3

Single Segment Low Aspect Ratio Design
=0.01

Energy Stored	1050 MWh
Radius	560 m
Height	11.2 m
Total Turns	112
Current per Turn	400,000 A
Maximum Midplane Field	2.5 T
Maximum End Field	5.2 T
Total Radial Force	8.0×10^{9} N
Warm Radial Structure*	0.8×10^{5}Kg
Cold Axial Structure*	6.75×10^{6}Kg

*Material is polyester Fiberglass Used at $1.9\text{x}10^{8}$N/m^2 (27,000 psi)

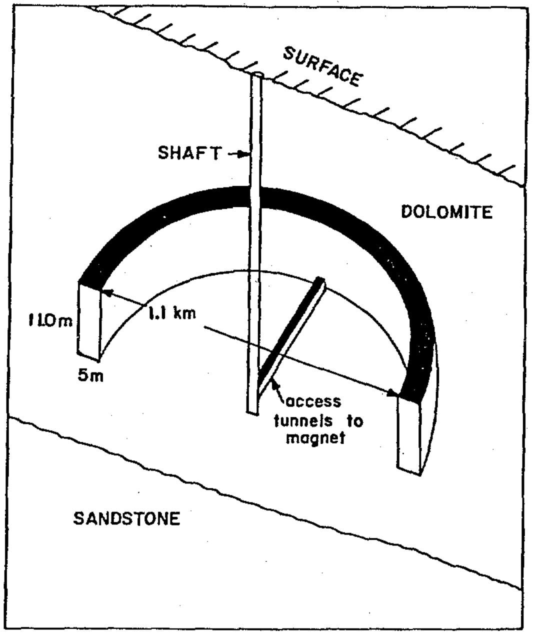

Fig. 2 Three-dimensional view of the Low Aspect Ratio 1,000 MWh cavern system for a dolomite site in Wisconsin. The cavern system was modeled at a mean depth of 30 m.

Another bonus for a low aspect ratio coil is the short axial length. Axial forces can be carried internally by cold structure without connection (and heat leak) to the rock surfaces. This option is possible for any solenoid but becomes too expensive for longer coils.

The heat leak through struts becomes very small for low aspect ratio coils since there is no axial connection outside the dewar and since the total radial force is small, $F_r(\beta=0.01)=1/10\ F_r(\beta=0.3)$. The heat leak for a $\beta=0.01$ coil is about 1% E per day. Thus the total efficiency is the electrical storage efficiency of 96% (charge and discharge) with a constant power requirement of less than 2% for all other losses.

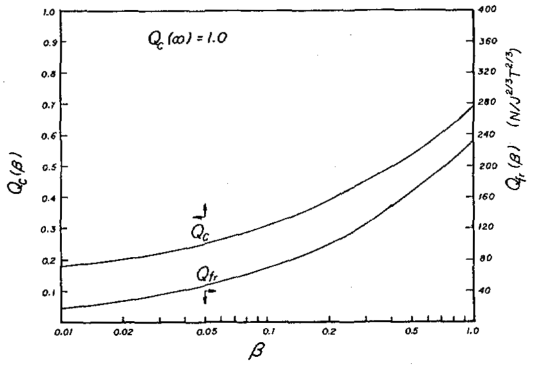

Fig. 3. Comparison structure quality factor Q_c and radial force quality factor Q_{fr} vs. aspect ratio β for single solenoids.

The radial force and axial structure dependence on β used in the above discussion are shown in Fig. 3 [5]. The quality factors Q_c and Q_{fr} plotted in Fig. 3 are defined in the following equations:

$$M_{axial} = Q_c \frac{\rho}{\sigma} E$$

$$F_{radial} = Q_{fr} E^{2/3} B_M^{2/3} ,$$

where M_{axial} is the internal cold axial structure, ρ is the structure density, σ is the average stress, E is the stored energy and B_M is the maximum field on the median plane.

A comparison of the two designs is presented in Table 4. The differences in forces and heat leaks favor the low aspect ratio system. The amount of fiberglass structure favors the 15 tunnel design. Conductor amounts favor the 15 tunnel unit slightly. Total efficiency is best for the low aspect ratio coil, although electrical storage efficiency is identical since storage efficiency depends only on the ac-dc bridge circuitry. The electrical storage efficiency refers to the fraction of energy stored which is available for discharge. Total efficiency includes power to run the cooling system which however does not deplete stored energy.

Table 5 is a comparison of cost factors. Since a proper design and cost estimate for the low aspect ratio system has not been made the factors given can be used only to identify cost trends. Preliminary cost estimates for the older 5 tunnel hourglass design and for the newer 15 tunnel design are in the range of 18-40 mills/kWh which is acceptable [6]. The low aspect ratio coil would appear to be comparable in cost according to the factors in Table 5. However, we expect large cost reductions because of less expensive surface rock excavation costs and surface open tunnel construction and repairs.

Table 4

DESIGN COMPARISONS

AREAS OF CHANGE	ONE TUNNEL LOW ASPECT RATIO		FIFTEEN TUNNEL SEGMENTED SOLENOID
RADIUS	560 m		120 m
HEIGHT	12 m		36 m
NO. OF TUNNELS	1		15
DEPTH OF TUNNELS	D > 10 m		D > 100 m
TOTAL RADIAL AND AXIAL FORCE CARRIED TO THE ROCK	1/20	:	1
HEAT LEAK THROUGH STRUTS	1/20	:	1
STRUCTURE (WARM AND COLD) IN LBS OF FIBERGLASS	17×10^6		10×10^6
NbTi (LBS)	330,000		280,000
ALUMINUM (LBS)	5.06×10^6		4.2×10^6
HELIUM (LITERS)	1×10^6		1×10^6
EFFICIENCY	94%		85%
SAFETY SCHEME	DUMP HELIUM		COUPLED, DISCHARGE ONE COIL
RADIAL PRESSURE	∿ 30 psi		∿ 300 psi
AREAS OF SIMILARITIES			
STORAGE EFFICIENCY	∿ 96%		∿ 96%
MEDIAN PLANE FIELD	2.5T		2.5T
STRUT LENGTH	1 m		1 m

TABLE 5. COMPARISON OF COST FACTORS FOR DIFFERENT DESIGNS

	DEWAR wt.	CONDUCTOR wt.	RADIAL STRUT wt.	AXIAL COLD STRUCTURE % of $\frac{\rho E}{\sigma}$
FIVE SEGMENTS HOURGLASS	1.0	1.0	1.0*	16%*
15 TUNNEL DESIGN	0.97	1.01	.78*	3.2%*
SINGLE SEGMENT DESIGN (β=.01)	.82	1.2	0.08	18%

*EXCLUDING EXTRA STRUCTURE REQUIRED FOR SAFETY

Conductor

The philosophy of extreme reliability dominates the design of the conductor. Propagation and recovery of normal regions cannot exist in the ordinary sense since propagation cannot occur in such a stable conductor. The cryogenic stability criteria is exceeded in every respect to achieve such reliability. There is no thought of obtaining short sample currents or of using inadequate stabilizing material. Instead we attempt to evaluate the benefit of using extra TiNb, extra cooling, extra high purity aluminum matrix material and extra margins of J, T and B.

The round conductor cross section shown in Fig. 4 is a 1 cm dia. developmental test conductor. The final conductor will carry 400,000 A and be 10 cm in dia. The aluminum alloy web is adequate to withstand tensile loads while each web sector is wide enough to prevent buckling due to compressive loads. The surface alloy skin is strong enough to withstand the magnetic pressures and confines the very soft high purity aluminum. The NbTi is a FNAL type braid in each sector. The conductor is round to facilitate manufacture and twisting.

When the current is shared between the aluminum and TiNb filaments a temperature gradient, ΔT, between the 1.8K helium and the hottest part of the conductor is set up. An extreme ΔT might be 1 K, except for millisecond transients which may be 10K to 20K [7]. However, ignoring thermal transients, we

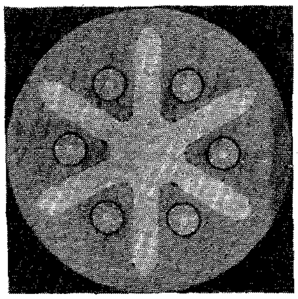

Fig. 4 Developmental aluminum composite conductor of alloy web, high purity wedges, NbTi and medium conductivity outer tube.

include TiNb sufficient to carry the total current at 2.8 K. A derating of TiNb by 1K is equivalent to a 60% extra amount of TiNb vs. the 1.8K quantity.

The amount of low resistance aluminum stabilizer is chosen according to the stability equation. However, we use $\rho \sim 10^{-8} \Omega$ cm even though our 2000 RRR aluminum measures less than $7 \times 10^{-9} \Omega$ cm at 5 tesla after 1000 strain cycles [8]. The resistivity of aluminum after 1000 cycles to 0.2% strain approaches a constant value independent of additional cycling. He II minimum film boiling flux at 1 atmosphere, MFBF, is measured to be 1.8 W/cm^2 [9]. Designing for $I^2R <$ MFBF insures recovery from any temperature extreme. Seven conductor sectors are sized to carry full current while 8 sectors are available. Thus joints in TiNb strands form no problem since individual perfect continuity is not required; low resistance mechanical overlaps should be sufficient.

The TiNb filament size is less than 10 μm based on the usual surface to volume ratios for surface cooling vs. heat generated. Another reason for small filaments is that during a transient from $S \rightarrow N \rightarrow S$ a small filament may only reach 10 K while a large filament, diameter 50μm, may reach 25 K. This complicated transient problem involves magnetic and thermal diffusion from a normal filament towards uniform current density in surrounding aluminum and back to full current in the filament. Details are given in paper [7].

Safety

Quenches, normal region propagation and superconductive recovery are nonexistent problems with helium present. However, if helium is lost there is the problem of safely discharging the storage solenoid without damage. The problem is more severe than for smaller magnets because of the larger stored energy per gram of conductor, see Table 6.

Table 6

Energy Per Gram For Several Superconductive Systems

System	12 FT Bubble Chamber	MHD Base Load	Torsatron Reactors	1000 MWh-SMES
Joules/gram (conductor)	2	7	66	429

We anticipate that a credible accident which might happen once in 10 to 20 years would be to lose vacuum or to lose capacity to refill helium with the solenoid fully charged. The catastrophic signal to take action would be that the helium level is dropping at an excessive rate. For the two designs different procedures would be followed.

The multi-tunnel case has been discussed by us previously [6]. In brief, ordinary copper switches could short out the good tunnels while the ac-dc bridge at full power rating could discharge the bad coil. Only 7% of the energy is associated with one tunnel and possibly one half is inductively coupled to nearby tunnels. The time for discharge would be 3% of 10 hours or 18 minutes. If part or all of the discharging coil became normal then some energy would be dissipated internally. However, no damage would result since the total energy, 429 joules/gram, would only raise the temperature to about 300 C. The key point is to start the discharge early.

The second design, the low aspect ratio coil, has only one dewar. The advantages of subdividing and mutually coupling out energy are not easily obtained, although switches per layer might be useful. A better approach would be to dump all of the helium quickly, possibly saving the liquid in an extra reservoir. A ± current pulse with eddy current heating should trigger the whole coil normal within one or two seconds, after which a safe discharge without excessive hot spots should follow by dissipating the 429 J/g uniformly. An alternative to dumping helium is to add extra helium and increase the discharge voltage for a fast discharge. The choice would depend on the rate the helium level drops.

Conclusion

Superconductive magnetic energy storage for diurnal use by electric utilities is technically attractive. Only magnetic storage at 96% efficiency can potentially cycle up to 25% of the daily electrical energy of a typical utility company. All charging energy could be provided at incremental costs below 75% capacity. Final designs, component development and model experiments are needed to confirm the attractive cost estimates.

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