THE DESIGN OF LARGE LOW ASPECT RATIO ENERGY STORAGE SOLENOIDS FOR ELECTRIC UTILITY USE

R.W. Boom*, R.F. Bischke,** G.L. McIntosh* and Y.M. Eyssa*

Abstract - The preliminary conceptual design of a low aspect ratio solenoid (large diameter and small height) for diurnal energy storage use is presented. The main advantage of this design is that the total radial force is only 5 ~ 10% that of previous designs resulting in small conduction heat leak through the insulating struts. The external pressure is less than 2 atmospheres which allows surface trench construction in surface rock; the pressures for previous underground bedrock designs were 20 to 100 atmospheres.

A new use for diurnal storage is presented in which larger SMES storage units replace intermediate load generation. In the example given an allowance of $60-100 per kWh could be credited to SMES. This new higher value comes from replacing cycling coal or large oil burning intermediate generation. SMES can be used for intermediate load because its storage efficiency is 95%; all other storage systems, only 50 to 80% efficient, could not meet the intermediate use requirement.

INTRODUCTION

Superconductive magnetic energy storage studies at Wisconsin were last reported to the MT conference in Rome in 1975 [1]. The system design which has evolved since then consists of a large solenoid constructed in bedrock which stores about 5000 MWh. The bedrock structure is needed to economically carry the magnetic loads. The conceptual design details of one such diurnal energy storage magnet is presented in this paper, the "low aspect ratio system".

The Wisconsin energy storage magnet winding consists of a rippled single layer solenoid wound from an aluminum-NbTi composite conductor. The ripple allows the magnetic loads to be transmitted to the rock at discrete locations through thermally insulating struts. These struts have intermediate cooling stations to reduce overall refrigeration loads. The high current conductor is supported by the struts and is housed in a dewar containing superfluid liquid helium at 1.8 K.

A low aspect ratio solenoid (low height to diameter ratio) has an important advantage in that the axial height of the coil is small enough so that internal cold axial structure may be economical. Only radial forces need to be carried to bedrock [2].

*University of Wisconsin, Madison WI 53706 USA
**Wisconsin Electric Power Company, Milwaukee, WI 53201 USA.

ELECTRIC SYSTEM USAGE

In comparison to other storage units only superconductive magnetic energy storage is 95% efficient. The storage efficiency is determined by losses in the three phase converter system which connects the DC storage coil to the three phase AC external power system, via a Graetz bridge, transformers, leads, and current balancing reactors. Other advanced storage concepts include Compressed Air Energy Storage (CAES), Advanced Batteries and Underground Pumped Hydrostorage (UPH). CAES burning fuel is the lowest in efficiency at 50-70% while Advanced Batteries may become the best of the rest at 70-80% efficiency. Pumped Hydrostorage, ordinary or UPH, 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 [3].

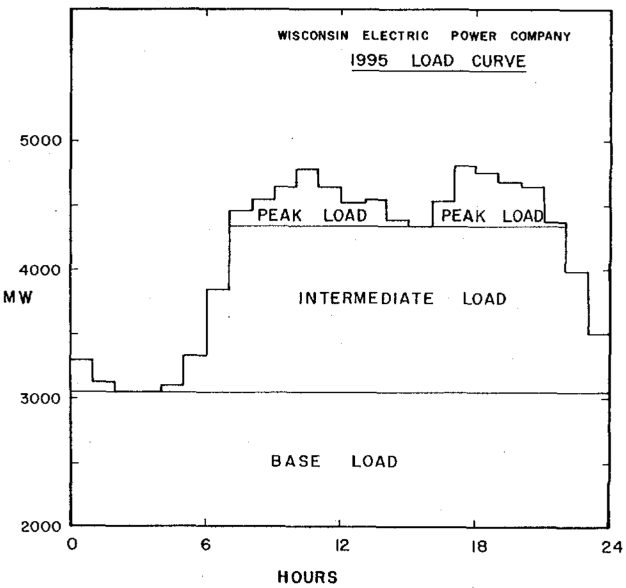

Fig. 1. Typical generation curve without SMES.

In a recent planning study at the Wisconsin Electric Power Company (WEPCO) we have projected the use for SMES in the year 1995. Figure 1 is a curve of a typical load for a 24 hour period. This load pattern is relatively unchanged as to difference between valley and peak from season to season throughout the year 1995 and is similar to 1981. The main difference predicted over the years is for the base load to increase at a 3% per year rate. Note that base load

0018-9464/81/0900-2178$00.75 © 1981 IEEE

generation, nuclear or coal in Wisconsin, would total 3000 MW maximum for continuous operation. In Fig. 2 is shown the same load with SMES and now the base load generation could be 4000 MW. Since baseload generators are the most efficient the increase by 1000 MW in base generator rating is a significant improvement.

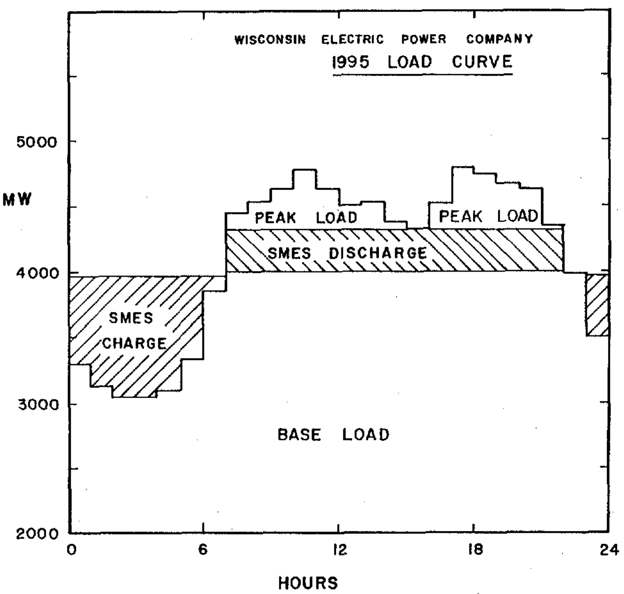

Fig. 2. Typical generation curve with SMES.

The simplest value calculation for using SMES here is to compare a 350 MW cycling coal generator to the SMES unit, since either could provide the energy in the cross-hatched region labeled "SMES discharge". In 1981 dollars a cycling coal unit could cost about \$1000 per kW. If SMES is given a 50% spin reserve credit (as is the coal unit) then SMES would be valued at \$100 per kWh of energy delivered. For a 95% storage efficiency the allowed construction cost of SMES is \$95 per kWh of constructed size. Both coal and SMES units would be financed and amortized in the same way so the above comparison is complete except for fuel differences which would increase the SMES value by 10-20% to \$120 per kWh delivered, with allowed construction costs at 95% of \$120 or \$114 per kWh.

For intermediate load usage SMES would discharge for 15h at the 350 MW rate and charge for 9h at a variable rate up to 930 MW, see Fig. 2. The three phase Graetz bridge would thus be rated at 930 MW which means that 581 MW in spinning reserve discharge capacity is always available during the 15h discharge period. To accommodate a loss of load during the 15h discharge period SMES could convert from 350 MW discharge to up to 930 MW charge or a total charge of 1278 MW if that much power reversal is needed. During the 9h charging period the charging power can be changed from its instantaneous value in Fig. 2 to 930 MW, which accommodates that loss of load in the power system. Should generation be suddenly lost up to 930 MW in discharge capability is always available, but for varying lengths of time dependent on the state of charge for SMES.

Note from Fig. 2 that a pumped storage unit would need 930 MW of turbine-generator units for full daily charge to get only 242 MW of discharge power for 15h. Thus, the turbine units would be over-rated by a factor of 3.84 compared to ordinary pumped hydrostorage usage. The conclusion is that pumped hydrostorage cannot provide the large amounts of stored energy needed to replace intermediate generators. CAES and Advanced Batteries have similar difficulties due to low storage efficiencies and due to the need for larger charging capacity and thus also are less suitable for lare scale intermediate storage.

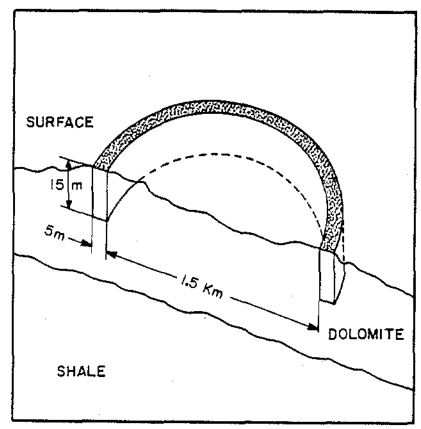

Fig. 3. Three dimensional view of Low Aspect Ratio 5000 MWh solenoid in a surface trench.

LOW ASPECT RATIO CONFIGURATION

The configuration currently under consideration is a single solenoid of aspect ratio β=0.01, where β=height ÷ diameter. The sketch in Fig. 3 is for a 5000 MWh unit mounted in a trench at surface. Specifications are listed in Table 1. The radial pressure on the rock is only about 4×10^5 N/m^2 as compared to 2×10^6 N/m^2 for previous β=0.3 designs [4]. Other design details of the pressure, field, and force calculations for rippled low aspect ratio solenoids are presented in a companion paper at this conference [5].

TABLE 1

Specifications Of Low Aspect Ratio Unit

E = 5000 MWh	I	= 768,000 amps (max.)
B = 3.5 tesla	V	= 2600 volts (max.)
R = 757 m	F_r	= 2.8×10^{10} N
H = 15 m	P	= 3.9×10^5 N/m^2 (average on rock)
N = 108 turns	P_L	= 6MW (auxilliary power)
L = 61 henries	$\Delta E/E$	= 3% weekly for P_L

The radial force and axial structure dependence on β used in the above discussion were plotted in Ref. [6] in terms of Q factors in Eq. (1) and (2),

$$M_{axial} = Q_c \frac{\rho}{\sigma} E \quad (1)$$

$$F_{radial} = Q_{fr} E^{2/3} B_M^{2/3} \quad (2)$$

where M_{axial} is the internal cold axial structure, ρ is the axial structure density, σ is the average stress, E is the stored magnetic energy and B_M is the maximum field on the median plane. The value of Q_c is only 0.18 for a β=0.01 low aspect ratio solenoid in comparison to 0.46 for previous β=0.3 designs. Thus internal cold aluminum alloy axial structure might be economic for the low aspect ratio design. All β=0.3 designs require axial forces to be carried by the rock structure either in shear or intercepted by several rock surfaces in multi-tunnel designs.

TABLE 2

Refrigeration Power Requirements for 5000 MWh, 3.5 Tesla Low Aspect Ratio Unit

Power Losses	One Shield	Two Shields
Radial Struts	4.61	2.18
Dewar	1.73	1.50
Leads	1.0	1.0
AC Losses	0.80	0.80
Total Power	8.14 MW	5.48 MW

The value of Q_{fr} is 18 for β=0.01 and 125 for β=0.3 (in SI units). For the low aspect ratio coil the heat leak through radial struts is 14% of the heat leak for β=0.3 solenoids and the axial heat leak is zero. The strut refrigeration per day is 1% E. The total refrigeration for radial struts, leads, AC losses and insulation is 3% per week of the energy delivered per week, see Table 2.

AXIAL AND RADIAL SUPPORT CONCEPTS FOR LOW ASPECT RATIO MAGNETS

For low aspect ratio energy storage magnets radial forces are much smaller than in previous designs, but axial forces are still high, although cold structure is tolerable due to short axial lengths. For example, a 3.5 tesla, 5,000 MWh magnet having a winding radius of 757 m has an average radial force per turn of 0.055 MN/m and a mid-plane cumulative axial force of 63.3 MN/m. A ripple design is needed since otherwise the radial thermal contraction of aluminum windings would be 2.4 m. The composite conductor must be limited to less than 0.2% strain, due to high purity aluminum requirements.

Analysis of the impact of these forces and constraints leads to an approach which separates the radial and axial supports [7]. Conceptual designs for the two supports allow for fabrication in a factory with only hand tools required for on site assembly. This approach simplifies installation of the dewar wall plates because the lateral rigidity of the axial supports is sufficient to permit mechanical attachment of the plates. Field welding will be primarily for vacuum sealing, not mechanical integrity.

The axial support concept is shown in Fig. 4. High strength 7075-T6 aluminum forgings are constructed to match the thermal coefficient and modulus of elasticity of the conductor. A pinned and keyed design is used which permits all fabrication in the factory and assembly by stacking one element on top of another. Fiberglass-epoxy straps on top and bottom support and electrically insulate the conductor tying the two forgings together to make a laterally rigid assembly. Longitudinal attachments provide stability to the entire axial assembly and close the electrical circuit to allow energy dumping by mutual inductance. Provision is made for mechanical attachment of the dewar walls so that no additional structure is needed. This method keeps the vertically flat surfaces from distorting due to internal pressure. The above design is based on closely spaced conductor support straps which hold the conductor essentially flat in the horizontal plane with very low stress in the axial direction. This method leaves most of the allowable conductor strain for radial loads. In turn, the design can be simplified with a longer ripple and radial support points farther apart.

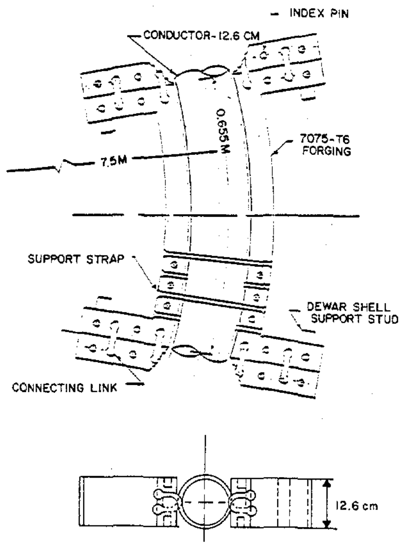

Fig. 4. Axial support concept for low aspect ratio design.

Separation of the axial and radial supports permits the radial struts to be designed for relatively small loads. This has an important bearing on the total magnet heat load since the struts react forces at 1.8 K to the tunnel wall at 300 K. Proposed design of a radial strut with one heat intercept is shown in Fig. 5. The strut assembly is a modular design with one unit required for each turn of the magnet at each radial support point. The assembly will be completely shop fabricated and attached to the dewar wall and vacuum jacket by stud welded pins or bolts. Aside from the aluminum support shoe and support termination sockets, forces are reacted by 9.5 cm dia. epoxy-fiberglass tubes which combine high strength, low thermal conductivity and low cost.

The relative weights of some components of the low aspect ratio design are compared in Table 3 to an older five tunnel design, such as the design in MT-5 [1]. The cold structure for a (single dewar) low aspect ratio coil is not much larger than the cold axial structure for a 5 tunnel unit, in which axial forces are intercepted by the four rock intercepting layers and not allowed to accumulate. The radial structure is much less which accounts for the very low heat leak.

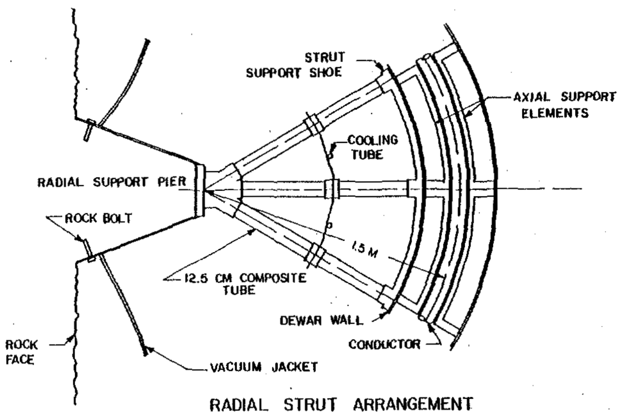

Fig. 5. Strut assembly with on shield at 77 K.

Table 3

SMES Component Weights

	Dewar	Conductor	Radial Strut	Cold Axial
5 tunnel unit	1.0	1.0	1.0	1.0
1 tunnel-low aspect ratio	.82	1.2	0.08	1.12

SAFETY

The design of all SMES coils is predicated on the safe discharge of a magnet or magnet subsection during unexpected catastrophies. No ordinary superconducting normal transition can become a problem because of the extreme over-stability of the conductor. It is felt that the worst credible accident, which might occur only once or twice in a coil lifetime, is a very rapid drop of the helium level to expose one or more turns. Preventative measures include rapid discharge, extra helium addition, forcing the whole coil normal for uniform energy deposition, current sharing with metallic structure, and discharging a bad subsection. A key point will be the early detection of a problem.

One could expect that the major problems could include a faulty cryogen supply, a deteriorating vacuum or a deteriorating resistive region in the conductor. These items are subject to detection and repair before any rapid discharges are required.

STRAY FIELD

The stray field for a low aspect ratio solenoid is 3 to 5 times larger than the stray field for large aspect ratio solenoids due to larger magnetic moments. The external field far from any solenoid varies as $1/r^3$. Figure 6 is a plot of magnetic field contours for the 5000 MWh, 3.5 tesla low aspect ratio unit.

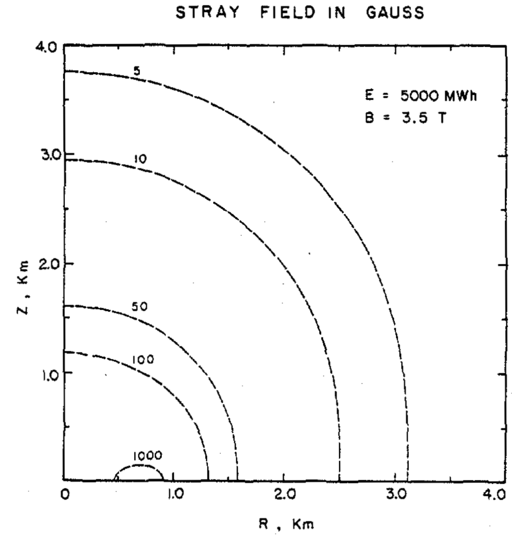

Fig. 6. External field contours in gauss; coil center is at origin and windings are at 757 m.

REFERENCES

1. "Magnet Design for Superconductive Energy Storage for Power Systems", R.W. Boom et al., MT-5, Rome, 1975, pp. 477-485.
2. "Superconductive Energy Storage for Diurnal Use by Electric Utilities, R.W. Boom, IEEE Trans. on Mag., MAG-17, Vol. 1, Jan. 1981, pp. 340-344.
3. "An Evaluation of Superconducting Magnetic Energy Storage," J. Nicol and B.M. Winer, ibid, pp. 336-340.
4. "Status of SMES Project at the University of Wisconsin", S.W. Van Sciver, Int. Symp. on SMES, Osaka, Japan, Oct., 1979, pp. 49-56.
5. "Force and Magnetic Field Calculations for Rippled Energy Storage Solenoids", Y.M. Eyssa and M.A. Hilal, (this conference, MT-7, Karlsruhe, April, 1981).
6. Wisconsin Superconductive Energy Storage Project, Vol. I, University of Wisconsin, Madison, WI 53706, (1976).
7. "Conductor and Structural Component Studies for Diurnal Energy Storage", S.W. Van Sciver et.al, DOE Contractors' Review, Mechanical and Magnetic Energy Storage, Nov., 1980, Conf. DOE Document-801128.

ACKNOWLEDGEMENTS

Work supported by Wisconsin Electric Utilities Research Foundation and the Department of Energy, Grant No. DE-AC02-76ET26602.