16 Oct 1980

Superconducting Magnetic Energy Storage: A Cost and Sizing Study

Haur D. Shaw

J. Derald Morgan
Missouri University of Science and Technology

Max Darwin Anderson
Missouri University of Science and Technology, mda@mst.edu

SUPERCONDUCTING MAGNETIC ENERGY STORAGE: A COST AND SIZING STUDY

Haur D. Shaw, J. Derald Morgan, Max D. Anderson
University of Missouri-Rolla
Rolla, Missouri

Abstract

Two applications for superconducting magnetic energy storage (SMES) devices in power systems are studied. One is for peak shaving, and the other is for load leveling. Consideration is given to placing these devices near load centers to reduce the line losses. For (SMES) cases studied using smaller size devices at several load centers, the line losses are lowered. However, the efficiency of SMES is proportional to its size, and the capitol cost per MWH is much greater for a smaller size SMES unit when compared to a larger SMES unit. Once the location or locations for SMES have been selected, power and capacity specifications can be determined by examining the load profiles and using economic dispatch methods. By comparing the results in costs and credits, the best sizing and system location of SMES units can be established.

1. INTRODUCTION

Superconducting magnetic energy storage is an energy storage method with many advantages over pumped hydro storage methods, now being used by the electric utility industry. Several institutions such as the University of Wisconsin and Los Alamos Scientific Laboratory, sponsored by the Department of Energy and EPRI, have devoted efforts to the development of the hardware for superconducting magnetic energy storage units. Although the results from their reports are very encouraging, to date there have been few system studies directed toward evaluating superconducting magnetic energy storage devices for system applications to a utility system. The material presented here is an evaluation of two applications of superconducting magnetic energy storage systems to a utility system.

2. METHODS AND EXAMPLES TO DETERMINE THE SIZING AND LOCATION OF SMES

2.1 LOAD LEVELING OF A PARTICULAR SUBSTATION

The load of a major substation varies by season, week and day. For a one-week period, there is normally a heavy load on weekdays and a light load on weekends. For load leveling or peak shaving, it is necessary to have sufficient energy available for the SMES to provide storage for the coming day's usage. This suggests that load leveling or peak shaving be performed over a one-week period. The concept of load leveling is to obtain the maximum benefits of peak shaving. The peak load week profile at a major substation of a midwest utility company, shown in Figure 1, is used as an illustrative example.

The method to determine the power and energy capacity specifications for applying SMES to load level, a substation at any week is explained in the following steps:

1. Find the average load. The average load at this substation is equal to 155.5 MW.
2. Find the constant load K after adopting SMES as a load leveling device, and assume the SMES has an overall efficiency of 80%. From Figure 1, the total area above the K MW (the energy to be shaved) is equal to the total area below K MW times the SMES efficiency 80%.
By iterative methods, K = 159.34 MW, and the

subareas in Figure 1 are found and listed below:

Area 1 = 707.66 MWH
Area 2 = 657.80 MWH
Area 3 = 506.46 MWH
Area 4 = 362.25 MWH
Area 5 = 25.12 MWH
Area 6 = 136.94 MWH
Area 7 = 137.87 MWH/Total Area =

Area i = 373.46
Area ii = 237.95
Area iii = 331.33
Area iv = 303.81
Area v = 522.34
Area vi = 734.25
Area vii = 663.04 /Total Area =

3. Find the power specification for the SMES.

Power Specification = Substation Peak Load - K = 231 - 159.34
= 71.66 MW

4. Find the energy capacity specification for the SMES. SMES has to store more energy during the weekend in order to supply a large part of the stored energy to the system during the week days. The maximum energy available for storage during the weekend is the energy specification for the SMES.

Energy Capacity Specification = Area vi - Area 6/0.8 + Area vii - Area 7/0.8 + Area i = 1427.23 MWH.

This is the gross storage specification. The 80% efficiency of the SMES device is taken into account because more energy is needed to shave areas 6 and 7.

Since every weekly load profile is different, there are many power and capacity specifications that can be calculated for SMES at the same major substation. It is suggested that for studies one adopts the minimum size of SMES for load leveling. That is load leveling of the minimum load week or minimum load change week of a year. Then, during other weeks, the SMES can act as a peak shaving device.

The line losses will definitely decrease, because the SMES is acting as a generator at peak-load. However, at light load the SMES acts as load, which increases the losses. A detail line losses evaluation can be found by comparing the line losses before and after SMES usage. From a total system point-of-view the line losses will never increase when adopting SMES for load leveling at a substation.

2.2 PEAK SHAVING A POWER SYSTEM WITH A SINGLE SMES UNIT

Peak shaving a power system is different from peak shaving a particular substation. At peak time, peak shaving a substation adds no extra line losses. As a matter of fact, they even decrease, and this substation could be treated as a constant load at peak. However, providing peak shaving for the entire system with one SMES unit would cause the line losses to increase compared to the line

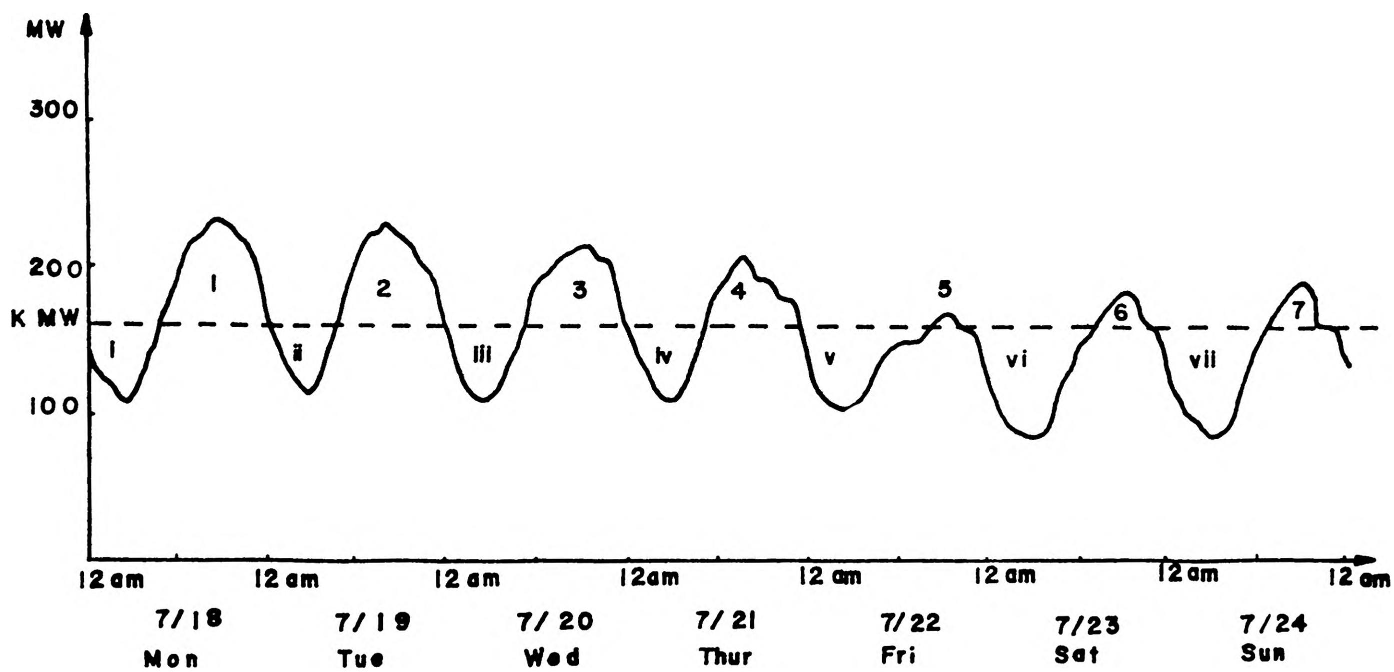

Figure 1. Load Curve for 1977 Summer Peak Week at a Major Substation

losses without an SMES unit, for the case in which several combustion turbine generators are replaced by a single SMES unit.

As an example, the predicted 1986 Summer peak load of a midwest utility company is studied for SMES application. There are 1051.3 MW of generation from combustion turbine generators planned as a part of a total 9804.4 MW generation predicted for the 1986 Summer peak day. From the load flow model, there are several load centers and major power plants, one of which would be the best site for the storage device. Using a load flow program, an analysis is made for replacing the combustion turbine generators with a single SMES device. The results of the power specification for the SMES and the line losses with respect to each different location for SMES are listed in Table I. The lowest line losses and peak power demand for SMES occurs in this study when the SMES is located at Bus 148. The values of these line losses and power demand for SMES are 141.64 MW and 1084.36 MW respectively. In the original study without SMES, the line losses are 108.45 MW at peak. There are extra line losses to charge SMES at light load when SMES is at substations, and there is hope that the SMES has Var control or voltage regulation capability. However, when SMES is located at a power plant, there are no extra line losses to charge SMES at light load, and the capability of the Var control of generators is more flexible and practical right now. SMES at substations might not be the best answer until the Var control strategy has been well developed.

A term "critical load" is defined as the load at which all the generation except the generation from the combustion turbine generators has to be operated. The corresponding generation is called "critical generation". If the generation is less than the critical generation, then the generation follows the economic generation dispatch schedule. If the generation need is greater than the critical generation, then the SMES is on as swing generator. The power specification of SMES can be found at every different load when the corresponding generation need is greater than the critical generation.

Because of variation in generation schedule and load characteristic at each bus, the following assumption is made. Assume the load at each bus is changed by the same percentage as system load change. Consider a SMES at Bus 148 as an example. By analysis, the critical load occurs at 88.68% of the peak load. At this load, there is no need for combustion turbine generators. Selecting other loads

Bus	Voltage	Type	Load (MW)	Line Flow out of bus	Number of Bus Connected to the Bus	Generation MW	Line Losses MW at Peak	Power Demand MW for SMES at Peak
47	345 kV	Substation	604	0	2	0	161.8	1105.4
54	138 kV	Substation	0	315.6	7	0	145.5	1089.1
72	34 kV	Substation	387	706.4	4	0	149.9	1093.4
129	138 kV	Substation	0	598.4	10	0	145.2	1088.8
131	345 kV	Substation	0	1060.8	6	0	143.4	1087.0
148	345 kV	Substation	0	997.7	7	0	141.6	1084.5
10	345 kV	Plant	0	2220.0	6	2220	155.9	1099.5
15	345 k	Plant	0	1150.	4	1150	154.9	1098.5

POWER SPECIFICATION FOR SMES AND LINE LOSSES IN SYSTEM WITH SMES FOR DIFFERENT LOAD CENTERS

Table I

at 92%, 95% and 98% of peak load, the load flow analysis yields the power need for SMES at each corresponding percentage load. The sum of the power demand of the SMES at different percentage load with respect to the time that the percentage load occurs gives the capacity specification in MWH for the SMES. An example is studied for SMES on Bus 148 used as a peak shaving device. The power specification for SMES at each different percentage of peak load and the corresponding time that this percentage of peak load occurs are listed in Table II. Assume the system load curve follows the same curve in Figure 1, except for magnitude. Using the information from load flow analysis shown in Table II, the area, which is the capacity specification of SMES, can be formed as shown in Figure 2.

The area in Figure 2 is equal of 6009 MWH. Assuming the efficiency of a large SMES unit is equal to 90%, then the capacity specification for sales should be equal to 6009/0.9 = 6677 MWH. The power specification, or maximum power need for SMES, is equal to 1084.5 MW, which is equal to 11.06% of the total system peak power demand. This amount is within the maximum rate of energy storage (Reference 4-6).

2.3 PEAK SHAVING A SYSTEM WITH SMES UNITS

A computer program was developed to perform the calculations for the study (10). It includes an economic dispatch program with a modified Gauss iterative load flow program. It uses the idea of equal "Incremental Cost" criteria with the correction in "Incremental Transmission Line Losses" described by Elgerd (7). This theory is extended in application to determine the power specifications of SMES units. As soon as the generation is greater than the critical generation, the SMES' will be on as generators. The critical generation is treated as negative load at each generation bus, and there exists a best combination of SMES units (generators) in the power economic dispatch to give minimum line losses. For every different peak load there is a corresponding best combination of SMES units in power as their power specification at that peak load. The sum of the power specification of each SMES unit at every different peak load with respect to the time that peak load occurs gives the capacity specification of each SMES unit.

System Percentage of Peak Load	Power Specification for SMES at that Percentage of Peak Load	Time that the Percentage Load Occurs At Peak Load Day
88.68%	0	12:25 & 10 p.m.
92	315.7 MW	1:25 & 9:09 p.m.
95	600.5 MW	2:35 & 7:37 p.m.
98	891.2 MW	4 & 7 p.m.
100	1084.5 MW	5 p.m.

POWER SPECIFICATION FOR SMES AT EACH DIFFERENT PERCENTAGE OF PEAK LOAD AND THE CORRESPONDING TIME THAT EACH PERCENTAGE OF PEAK LOAD OCCURS

Table II

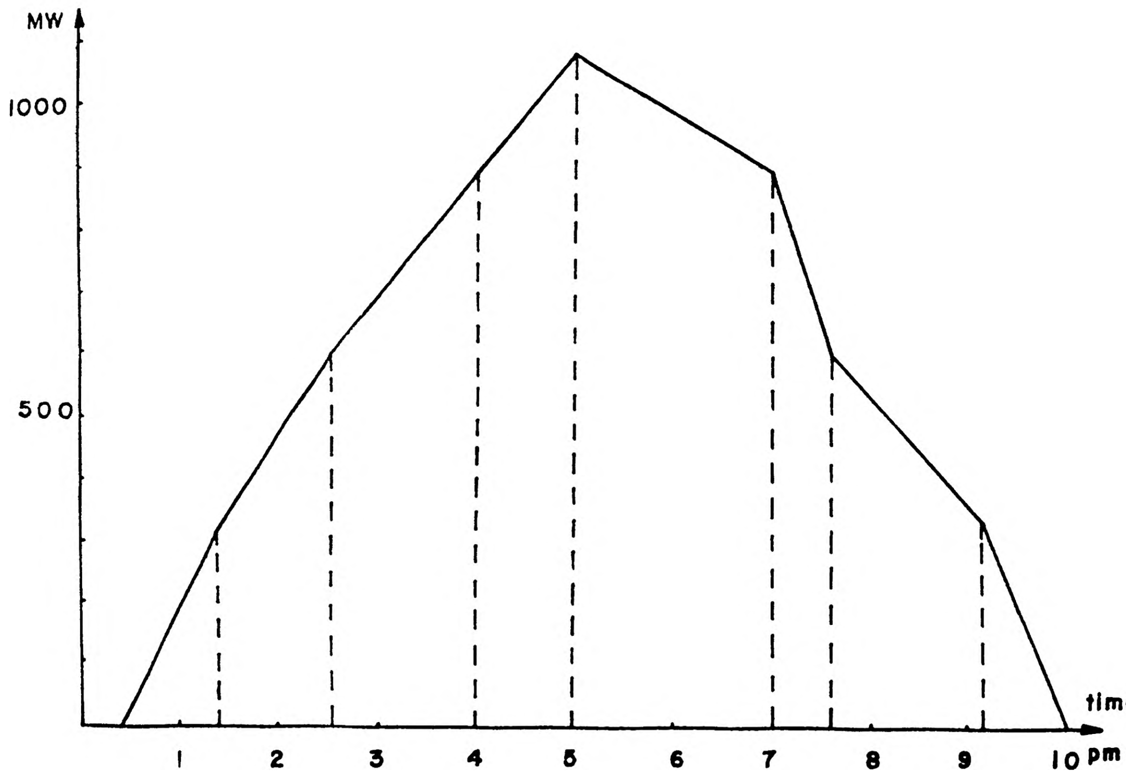

Figure 2. Capacity Specification for SMES at Peak

Three different examples for peak shaving are studied. The first is one SMES on one generation plant; the second is 3 SMES on 3 generation busses, and the third is 6 SMES on 6 load centers. Before going to the example, following assumptions have been made:

1. Assume the system has the same load curve pattern as the load curve at a major substation except the magnitude is different, as only the load curve at one major substation is available for this example.
2. Form the simplified midwest utility system by taking all 345 kV busses and lines. There are 22 busses and 29 lines in this simplified system. Let the line flow out of region be the equivalent load at each corresponding bus. Solve the load flow within the simplified region. The line flow within this region is very close to the original case and justifies this approach.
3. Assume the load at each bus will be changed by the same percentage. This means the load at each bus is changed in the same percentage and at the same time for system load changes. The precise data is not available and forces this assumption.
4. It is reasonable to assume there exists a constant such that the capacity specification is equal to the product of the maximum power specification and this constant. By examining the power specification and the capacity specification in part B, the constant is equal to 5.325. The constant will also be used to calculate the line losses energy if the line losses in power peak is known.
5. From the Los Alamos Laboratory reports (6), the capitol cost of a SMES unit is a function of $E^{2/3}$ (energy stored in total). They estimated at 10,000 MWH storage SMES unit cost to be 423 million dollars. So the following approximate equation will be used. $X \ \$/WH \times (10{,}000 \times 10^6)^{2/3} = 423 \times 10^6 \ \$$. After calculation, X is found to equal 91.13256 $/WH and the capital cost of any size of SMES unit can be found.
6. Using the economic dispatch program to find the best combination of SMES units in power at peak in the simplified 22 bus region, then fitting SMES generation into the original system to remove the combustion turbine generators, the load flow program is run to find

the line losses in the whole system and monitor overloaded lines. The method is applied to examples 2 and 3. From the new load flow data, the generation on the swing bus is equal to 1156.7 MW and 1150.6 MW compared to the original swing bus generation of 1150 MW, this yields the similarity between the original system and the simplified system.

7. Assume the cost to reconductor a line is equal to 1.5 x 10^5 \$/Mile.

8. Assume the SMES unit can have Var or Q control (4, 8, 9).

9. Assume the line losses when recharging the SMES units in example 3 are greater than the line losses without SMES units by 5 MW, based on the uncertainty of the system generation schedule.

2.4 EXAMPLES AND DATA

Three examples are illustrated and tabularized based on the above assumptions:

1. One SMES unit on Bus 15 in a midwest utility system (there is no need for use of the economic dispatch program):

a. Maximum power specification for SMES : 1082 MW

b. Line losses in power peak in the simplified region: 26.86 MW

c. Line losses in energy for the simplified 22 bus region: 153.7 MWH (assumption 4 applied, and this bus is a power plant, so there is no loss when recharging the SMES unit at light load)

d. Line losses in power at peak in the utility system: 154.9 MW (original without SMES line losses is equal to 108.45 MW)

e. Line losses in energy in the utility system: 886.38 MWH (original without SMES there are 620.6 MWH energy losses), (assumption 4 applied)

f. Equivalent capacity specification: 5756.8 MWH (assumption 4 applied)

g. Total capacity specification (taking 90% efficiency for SMES in account): 6396.4 MWH

h. Loss due to the efficiency of SMES (most of the energy loss is in the cryogenic process and part in the converter-inverter bridge): 639.6 MWH

i. Capital cost of SMES unit: 314 x 10^6 \$ (assumption 5 applied)

j. Overloaded lines when replacing combustion turbine generators by SMES unit at peak are listed as follows:

From bus	To bus	R(Ω)	Eq. miles	Cost (\$)
107	99	11.49	60.1	9.015x10^6
147	146	1.98	10.4	1.56x10^6
148	147	0.04	0.2	3x10^4
150	149	0.65	3.4	5.1x10^5
150	100	0.91	4.8	7.2x10^5

Total : 11.835 x 10^6 \$

2. Three SMES units on three generating busses, Bus 1, 2 and 3 in the Simplified System. (Economic dispatch program is used to find the allocation of SMES units.)

a. Maximum power specification for each SMES:

At Bus 1 : 361.82 MW
At Bus 2 : 360.97 MW
At Bus 3 : 359.35 MW

b. Line losses in power at peak in the simplified region: 20.2 MW

c. Line losses in energy in the simplified region: 107.6 MWH (assumption 4 applied)

d. Line losses in power at peak in the utility system when combustion turbine generators replaced by SMES units: 145.12 MW (assumption 6 applied)

e. Line losses in energy in the utility system: 773.01 MWH (assumption 4 applied)

f. Equivalent capacity specification for each SMES unit needed for peak shaving:

At Bus 1 : 1925.1 MWH
At Bus 2 : 1920.5 MWH
At Bus 3 : 1911.9 MWH (assumption 4 applied)

g. Total capacity specification for each SMES unit (taking 80% efficiency for smaller size SMES):

At Bus 1 : 2406.4 MWH
At Bus 2 : 2400.6 MWH
At Bus 3 : 2389.9 MWH

h. Loss due to the efficiency of SMES in toal in energy: 1439.3 MWH

i. Capital cost of each SMES unit:

At Bus 1 : 163.6 x 10^6\$
At Bus 2 : 163.38 x 10^6\$
At Bus 3 : 162.9 x 10^6\$
Total : 489.9 x 10^6\$

j. Overloaded lines when replacing combustion turbine generators by SMES units in the whole system (assumption 4 applied) are listed as follows:

From bus	To bus	R(Ω)	Eq. miles	Cost (\$)
97	94	0.95	4.9	7.35x10^5
107	99	11.49	60.1	9.015x10^6
147	146	1.98	10.4	1.56x10^6
148	147	0.04	0.2	3x10^4

From bus	To bus	R(Ω)	Eq. miles	Cost ($)
150	100	0.91	4.8	7.2×10^5
150	149	0.65	3.4	5.1×10^5
177	2	0.61	3.2	4.8×10^5
				Total : 13.05×10^6

3. Six SMES units on six load substation which have large load variation.

a. Maximum power specification for each SMES:

At Bus 4 : 179.6 MW
At Bus 12 : 180.2 MW
At Bus 13 : 179.8 MW
At Bus 17 : 179.2 MW
At Bus 20 : 178.9 MW
At Bus 21 : 178.4 MW

b. Line losses in power at peak in the simplified region: 13.86 MW

c. Extra line losses when charging SMES units at minimum load compared with the line losses at minimum load without SMES units: 4.0 MW (in 22 busses)

d. Line losses in energy in the simplified region (taking into account the extra line losses when charging the SMES units at minimum load): 95.1 MWH (assumption 4 applied)

e. Line losses in power at peak in the utility system: 133.9 MW

f. Extra line losses when charging the SMES units at minimum load: 5 MW (assumption 9 applied)

g. Line losses in energy in the utility system (taking into account the extra line losses when charging the SMES units at minimum load): 739.66 MW

h. Equivalent capacity specification for each SMES needed for peak shaving:

At Bus 4 : 956.4 MWH
At Bus 12 : 959.6 MWH
At Bus 13 : 957.4 MWH
At Bus 17 : 954.2 MWH
At Bus 20 : 952.6 MWH
At Bus 21 : 950 MWH

i. Total capacity specification for each SMES (taking into account the efficiency 75% for SMES):

At Bus 4 : 1275.2 MWH
At Bus 12 : 1279.5 MWH
At Bus 13 : 1276.5 MWH
At Bus 17 : 1272.3 MWH
At Bus 20 : 1270.1 MWH
At Bus 21 : 1266.7 MWH

j. Losses due to the efficiency of SMES in total: 1910 MWH

k. Capital cost of each SMES unit:

At Bus 4 : 107.1×10^6\$
At Bus 12 : 107.4×10^6\$
At Bus 13 : 107.2×10^6\$
At Bus 17 : $107.\ \times10^6$\$
At Bus 20 : 106.9×10^6\$
At Bus 21 : 106.7×10^6\$

1. Overloaded lines are listed as follows (assumption 6 applied):

From bus	To bus	R(Ω)	Eq. miles	Cost ($)
97	94	0.95	4.9	7.35×10^5
107	99	11.49	60.1	9.015×10^6
147	146	1.98	10.4	1.56×10^6
148	147	0.04	0.2	3×10^4
150	100	0.91	4.8	7.2×10^5
150	149	0.65	3.4	5.1×10^5
				Total : 12.57×10^6

These three examples give an evaluation of the applications of SMES units to a utility system. There are many other combinations of SMES units, however, the methods developed are generally applicable.

3. COMPARISON AND CONCLUSION

Three examples were presented:

1. One (1) SMES unit placed at a generating station.
2. Three (3) SMES units placed at three different generating stations.
3. Six (6) SMES units placed at six different load substations.

The results are compared to determine which application is better under the adopted assumptions. First, define the term "fixed cost" as SMES hardware cost plus the cost of reconductoring the overloaded lines. Assume there is a 20 years payout on the SMES hardware and the replacement of transmission lines. Also assume that the cost after 20 years will double current value, then the annual finance charge can be found. The energy for charging the SMES units is from the generation which supplies base load. It costs 13.16 $/MWH (this cost information is from a midwest utility company).

Assume the annual usage of SMES follows a rule of 50% for replacing the peak generation, which has a cost of 56.82 $/MWH, and 50% for replacing the intermediate generation, which costs 29.22 $/MWH. Then, the annual fuel savings can be found. As the line losses are different in each case, it will be in SMES capacity specification. For example, one SMES case has a maximum line loss, so it has a maximum SMES capacity or MWH which includes the extra line losses.

Detailed comparisons follow. One part is a "fixed cost" analysis and the other is a "fuel saved credit" analysis.

3.1 FIXED COST ANALYSIS

Cost	Example 1	Example 2	Example 3
Hardware SMES (1978)	314×10^6	489.9×10^6	642.3×10^6
Reconductoring line cost	11.8×10^6	13.05×10^6	12.57×10^6
Total (1978)	325.8×10^6	502.95×10^6	654.87×10^6
Total (1998) (double 1978, including interest)	651.6×10^6	1005.9×10^6	1309.74×10^6
Average annual cost	32.58×10^6	50.3×10^6	65.52×10^6

3.2 FUEL SAVED CREDIT

a. Example 1

6396.4 MWH x 90% x 0.5 (peak) x 365 days x 56.82 \$/MWH + 6396.4 MWH x 90% x 0.5 (intermediate load) x 365 days x 29.22 \$/MWH - 6396.4 MWH x 365 days x 13.16 \$/MWH = 59.67×10^6 \$

b. Example 2

(2406.4 MWH + 2400.6 MWH + 2389.9 MWH) x 80% x 0.5 x 365 days x 56.82 \$/MWH + (2406.4 MWH + 2400.6 MWH + 2389.9 MWH) x 80% x 0.5 x 365 days x 29.22 \$/MWH - (2406.6 MWH + 2400.6 MWH + 2389.9 MWH) x 365 days x 13.16 \$/MWH = 55.84×10^6 \$

c. Example 3

(1275.2 MWH + 1279.5 MWH + 1276.5 MWH + 1272.3 MWH + 1270.1 MWH + 1266.7 MWH) x 75% x 0.5 x 365 days x 56.82 \$/MWH + (1275.2 MWH + 1279.5 MWH + 1276.5 MWH + 1272.3 MWH + 1270.1 MWH + 1266.7 MWH) x 75% x 0.5 x 365 days x 29.33 \$/MWH - (1275.2 MWH + 1279.5 MWH + 1276.5 MWH + 1272.3 MWH + 1270.1 MWH + 1266.7 MWH) x 365 days x 13.16 \$/MWH = 53.28×10^6 \$

In the three examples, the more SMES units used, the lower the line losses. However, the smaller SMES units have a lower efficiency. The line losses in energy compared to the loss from the efficiency is not significant. Also, energy available for peak shaving includes the extra line losses, so that line losses effect can be omitted from the analysis. Comparing the three examples, the usage of one SMES unit gives the best results. The comparison listing is as follows:

Cost or Credit	Example 1	Example 2	Example 3
Cost (fixed)	32.58×10^6 \$	50.3×10^6 \$	65.52×10^6 \$
Credit (fuel save)	59.67×10^6 \$	55.84×10^6 \$	53.28×10^6 \$
Net savings (annual)	27.09×10^6 \$	5.54×10^6 \$	-12.24×10^6 \$

Consideration of the credit for using SMES should include as a cost saving the deletion of some combustion turbine generators, their maintenance, and the increased fuel costs. If the annual usage of SMES for replacing the peak generation is higher, there is no doubt that more fuel savings can be achieved. Assuming a 60% annual usage of SMES to replace the peak load generation, and the remaining 40% for replacing the intermediate load generation, the costs and credits are given as follows:

Cost and Credit	Example 1	Example 2	Example 3
Cost (fixed)	32.58×10^6 \$	50.3×10^6 \$	65.52×10^6 \$
Credit (fuel savings)	65.47×10^6 \$	61.64×10^6 \$	59.05×10^6 \$
Net Savings (annual)	32.89×10^6 \$	11.34×10^6 \$	-6.47×10^6 \$

Also, assuming 70% annual usage of SMES for replacing peak load generation, and 30% for replacing intermediate load generation, the costs and credits are listed as follows:

Cost and Credit	Example 1	Example 2	Example 3
Cost (fixed)	32.58×10^6 \$	50.3×10^6 \$	65.52×10^6 \$
Credit (fuel savings)	71.27×10^6 \$	67.44×10^6 \$	64.92×10^6 \$
Net Savings	38.69×10^6 \$	17.14×10^6 \$	-0.7×10^6 \$

The greater the percentage usage of SMES for replacing the peak load generation, the greater the savings. However, the total energy available for charging SMES should be carefully examined before adopting any plan.

The sizing and location of SMES can be solved more accurately by a utility company, for the economic dispatch program, load profiels, system prediction, and fuel cost data are available. It is suggested that peak shaving be performed at the week that maximum power demand occurs, so that there is no need of high cost generators at peak and makes the analysis simpler.

After the sizing and location of SMES are carefully selected, then studies in steady state stability and transient stability when adopting new storage devices should be carefully examined.

Bibliography

1. Keller, W. E., "Applications of Superconductivity in Electric Power System", 1976 Frontiers of Power Technology Conference, 1976, pp. 1 - 12.

2. Boom, R. W., et al., "Wisconsin Superconductive Energy Storage Project", Feasibility Study Report, Volume I, 1974, pp. II-1 - II-16, III-1, and IV-1 - IV-15.

3. Kimbark, E. W. Direct Current Transmission, John Wiley & Sons, Inc., 1971, pp. 31 - 128.

4. Boom, R. W., et al., "Wisconsin Superconductive Energy Storage Project", Feasibility Study Report, Volume II, 1976, pp. II-1 - II-39 and VIII-11 - VIII-53.

5. Turner, R. D., Complier, "Cornell University Seminar Summary to Electric Utility and Power Industry Representatives on Superconducting Magnetic Energy Storage", 1977, pp. 6, 11 - 16, Appendix B and C.

6. Los Alamos Scientific Laboratory, "Superconductive Magnetic Energy Storage (SMES) for the Electric Power Industry", LASL-77-7, 1977, pp. 1 - 33.

7. Elgerd, O. I., Electric Energy Systems Theory: An Introduction, McGraw-Hill Book Company, New York, 1971, pp. 275 - 312.

8. Morgan, R. J. Titus, C. H., and Tice, J. B., "Solid State Converters for Power Voltage Control", American Power Conference, 1975.

9. Becker, H., Brandes, D. and Gappa, K., "Three Phase Shunt Reactor with Continuously Controlled Reactive Current", C.I.G.R.E., 1972, Report 31-13.

10. Shaw, Haur D., Evaluation of Superconducting Magnetic Energy Storage Systems for Application to Electric Utility Systems, MSEE Thesis, University of Missouri-Rolla, 1978.

***

Bibliography

Haur Daniel Shaw was born on January 16, 1953 in Taipei, Taiwan, Republic of China. He received his primary and secondary education in Taipei, Taiwan. He enrolled in Taiwan Provincial Taipei Institute of Technology in August, 1971, and received his equivalent Bachelor of Science degree in Electrical Engineering in July, 1974.

He served in the Chinese Navy from October, 1974, to August, 1976, as an Ensign Officer. He has been enrolled in the Graduate School of the University of Missouri-Rolla since January, 1977. He serves as a Graduate Research Assistant.

J. Derald Morgan received his BSEE in 1962 from Louisiana Tech University, his MSEE in 1965 from the University of Missouri-Rolla and Ph.D. from Arizona State University in 1968. Since 1976 he has been Emerson Electric Professor of Electrical Engineering, and from 1978 has been Chairman of the Electrical Engineering Department at the University of Missouri-Rolla.

Max D. Anderson is Associate Professor of Electrical Engineering at the University of Missouri-Rolla. His areas of research are power system monitoring, control, and operations.

He is a member of IEEE and Chairman of the Working Group on Operator Training. For EPRI, he served as Editor of the Proceeding of the Workshop on Operator Training Simulators held in New York City, September, 1978.