Evaluation and Technology Review of Energy Storage for the PREPA System

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Abstract

A collaborative study made by a team composed of the University of Puerto Rico at Mayagüez, PREPA and Raytheon/Westinghouse is discussed. The study determined the energy requirements of an energy storage unit capable of providing rapid spinning reserve to prevent a blackout under generation deficiency conditions in PREPA's system. Alternative energy storage technologies were evaluated. The technical and economic parameters required to design a Superconducting Magnetic Energy Storage (SMES) system were determined. We found that the SMES option alone will not be an economical solution to the problem because the electric system requires a 60 MW injection for at least 5 minutes. The SMES unit becomes uneconomical if it is required to discharge for longer than one minute. A SMES plus diesels option, a combination that will keep the required power output over a five minutes period or more, will solve the problem with a present value cost of $133 million. A 60 MW BESS will also solve the problem with a present value cost of $104 million. The most economical of the solutions considered is the 60 MW BESS.

1.0 Introduction

The Puerto Rico Electric Power Authority (PREPA) identified its island condition and the relatively large size and slow response of its generating units as main factors leading to unacceptable system performance (blackouts) when generation deficiency occurs. This paper discusses a recent collaborative study made by a team composed of the University of Puerto Rico at Mayagüez, PREPA and Raytheon/Westinghouse to review the additional requirements for energy storage in the PREPA system. In specific, the study objective was to evaluate possible energy storage solutions to Puerto Rico's rapid response spinning reserve insufficiency under generation deficiency conditions.

Although PREPA's capital improvements planning budget includes future Battery Energy Storage Systems (BESS) projects, recent experience with its BESS plant and questions about alternative storage technologies prompted a new planning study. Our study determined:

1. the energy requirements (size) of an energy storage unit that will support Puerto Rico's electrical system with rapid spinning reserve to prevent a blackout under generation deficiency conditions;
2. the technical and economic parameters required to design a Superconducting Magnetic Energy Storage (SMES) system to meet the previously mentioned energy storage requirements; and
3. an operational and economic evaluation of SMES and BESS to achieve the most economical solution to Puerto Rico's electric power system rapid response spinning reserve insufficiency.

2.0 Dynamic Simulations Study

In any power system, the failure of a generator unit changes the ratio of demand to on-line generation capacity instantaneously. This change causes a corresponding decline in the speed of the remaining generators and consequently in the frequency of the electricity that these generators produce. Uncorrected, the decline in frequency can damage the remaining generators and within a few seconds, cause the collapse of the entire power system [1]. Unless sufficient generation with the ability to rapidly increase output (rapid response spinning reserve) is available, the decline in frequency will be largely determined by frequency sensitive characteristics of the loads and by the magnitude of the overload. In many situations, the frequency decline may reach levels that could lead to tripping of steam turbine generating units by underfrequency protective relays. To prevent extended operation at lower than normal frequency, load-shedding schemes are employed to reduce the connected load to a level that can be safely supplied by available generation [2].

Spinning reserve requirements and frequency control are critical operating problems on island electric utilities such as PREPA. The unavailability of interconnections with larger grids forces island utilities to provide ample spinning reserve. In spite of this, the sudden outage of a large generating unit often results in load interruptions. This occurs because generator turbine-governors are capable of following the change in demand during peak hours when the

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fastest load changes occur, but they are not capable of following the change that is produced by a severe disturbance, due to their time delay of 3 to 5 seconds [2]. Also, the lower inertia of island systems causes frequency to deviate rapidly as the load and topology of the system changes. These deviations have a negative effect on the quality of power. Therefore, means for fast acting frequency control are required [3].

PREPA began in 1989 a search for possible solutions to the rapid response spinning reserve insufficiency. The possible solutions included both traditional and non-traditional methods of providing spinning reserve such as load management, upgrading existing generation facilities, enhancing planned generation, offering interruptible service credits to customers, and installing energy storage. Preliminary analysis showed that combustion turbines and battery energy storage were the most cost-effective options. Subsequent studies compared the benefits of combustion turbines and battery energy storage, a battery energy storage system (BESS) was selected as the most economical solution [1]. In 1997, Raytheon Engineers & Constructors proposed a Superconducting Magnetic Energy Storage (SMES) system as an alternative solution to the problem [4]. Raytheon suggested that an 80 MW SMES system with one minute, or less, of energy storage capacity will solve the problem more economically than BESS. On the other hand, PREPA has estimated energy storage requirements to be on the order of two minutes or more [5]. A detailed simulation study was needed to determine the amount and duration of rapid response spinning reserve required to avoid load shedding in Puerto Rico's power system under generation deficiency conditions. This was achieved by performing midterm and long-term stability computer simulation [6].

We used the following procedure to determine the amount of rapid response spinning reserve necessary to avoid load shedding under generation deficiency conditions:

1. *Frequency without load shedding* – determine the frequency at which the system settles without load shedding following a large generator disconnection.
2. *Frequency with load shedding* – determine the frequency at which the system settles with load shedding following a large generator disconnection. This is our base case.
3. *Determination of Energy Storage System (ESS) power output* –determine the ESS power output required to avoid underfrequency load shedding.
4. *ESS ramp down selection* – in this step we choose the proper ramp down of the ESS to avoid an unwanted frequency dip when the ESS is turned off. If the ESS output is abruptly terminated the system will suffer another disturbance.
5. *Calculate ESS capacity* – compute the capacity of the ESS in MJ and in MWh.

Dynamic simulations were performed using the Power System Simulator and Engineering program (PSS/E) from Power Technologies, Inc. (PTI). Generators are modeled using the Round Rotor Generator Model (GENROU, the exciters of generator 1 and 2 are modeled using IEEE Type AC1 Excitation System (EXAC1) and IEEE Type 3 Excitation System (IEEET3). Gas turbine governors are modeled using Gas Turbine Model (GAST2A) and Gas Turbine-Governor (GAST). Steam turbine governors were modeled using IEEE Standard Governor (IEESGO) for simulations of 30 seconds or less and using IEEE Type 1 Speed-Governing Model modified to include boiler controls (TGOV5) and Automatic Generation Control (AGC) effect, for simulations above 30 seconds [7].

The conditions of operation for this study were defined by PREPA. A system model for year 2005 was established, the units were economically dispatched and the trip of the largest generator, while generating 400 MW, was established as the contingency for the purpose of ESS design.

Our dynamic simulations show that the energy storage unit needs to store 60 MW, bringing the total amount of stored energy in Puerto Rico's system to 80 MW (including the 20 MW BESS actually in use). If generation deficiency occurs caused by trip-out of 400 MW the energy storage units will provide rapid response spinning reserve. The energy storage units must provide 80 MW for at least 5 minutes (The new 60 MW ESS should supply 3.5 MWh for approximately 3 minutes with a ramp down slope of 35 MW/min for another 2 minutes.) to prevent underfrequency load shedding and restore the system frequency as shown in Figure 1. The horizontal line at 59.5 Hz depicts the minimum frequency for the long-term safe operating range of steam turbine generators.

3.0 SMES Design [8]

SMES technology is based on storing energy in the magnetic field of a superconducting coil. Because direct current flows with negligible losses in superconductors, SMES systems can be used for small and large-scale energy storage [9]. Because no conversion of energy to other forms is involved (e.g., mechanical or chemical), round-trip efficiency can be very high. Moreover, SMES can respond very rapidly to dump or absorb power from the grid/load as the only limitations are the control loop and the switching time of the solid-state components connecting the coil to the grid, and, in addition, SMES can be repeatedly deep discharged.

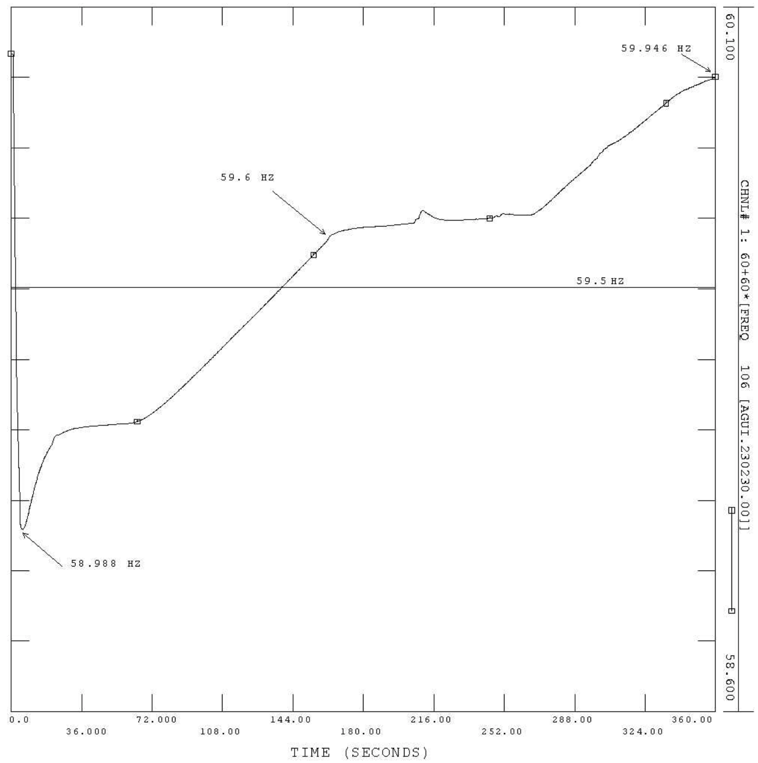

Figure 1. System frequency with 20 MW BESS and 60 MW ESS, ESS ramp down of 35 MW/min.

As the discharge duration of SMES increases to more than a few seconds, its costs increase drastically. To overcome this effect, the Raytheon and Westinghouse designers proposed combining a short duration SMES with back-up diesel generators. The SMES provides 60 MW of instantaneous power (added to the existing 20 MW of battery power already on the electric grid) for 30 seconds, and diesel generators, capable of quickly starting and taking over the load provide power for a longer term.

The conceptual design proposed for this application is a 12-segment toroid coil with a stored energy of 2250 MJ sized for a delivered energy of 1800 MJ. Conductor current is 10.7-kA at a maximum magnetic field of about 5.0 T, and operating temperature of 4.5 K. A toroid configuration was selected based on the need to minimize magnetic field external to the SMES device. Figure 2 shows a cross-section view of the overall toroid SMES. Included in Figure 2 is the "D" shaped geometry of the segment of toroid coil, the central fabricated (from insulated material) bucking cylinder, supports to ground, vacuum vessel, and the side mounted lead box.

A Cable Inside a Conduit Conductor (CICC) with a nominal transport current of 10 kA is proposed for the SMES coils. Cooling will be by forced flow supercritical helium at 4.5 K. The primary function of the vacuum vessel (or cryostat) is to house the superconducting toroidal coil assembly and provide an environment in which the coil may be maintained at its operating temperature (~4.5 K) by the helium refrigeration system. The latter can only be accomplished if the coil is very well insulated from ambient conditions, so as to minimize heat transfer from ambient (~300 K) to the coil at 4.5 K. As shown in Figure 2, the SMES cryostat is a cylindrical vessel about 14.24 m in diameter and about 5.74 m high, with a flat bottom and a torispherical or elliptical flanged and dished head for the top cover; the bottom is flat in order to provide a support surface for the toroidal coil assembly.

Liquid nitrogen (LN_2) is required for operation of both the helium liquefaction/refrigeration system and the SMES coil. It may also be needed for shield cooling on the liquid helium transfer lines. The helium refrigeration system uses liquid nitrogen in the first stage heat exchanger to pre-cool the compressed helium gas stream. Typically about one liter of LN_2 is required for each liter of helium liquefied.

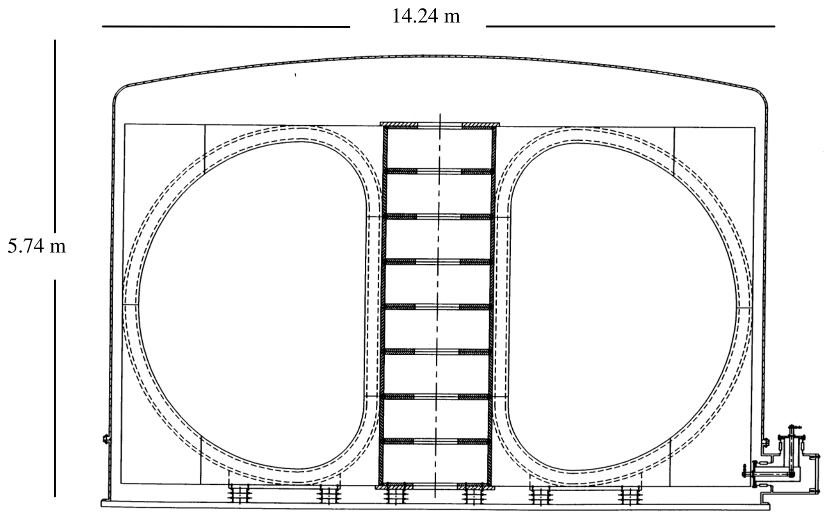

Figure 2 — Cross-Section View of Toroid 60 MW SMES

Once the conceptual design for the toroid was complete, a detailed external magnetic field mapping around the toroid was done using a computer program. The goal of the external field calculation was to determine the location of the 100 Gauss (0.01 Tesla) and 10 Gauss (0.001 Tesla) field contours. Most electronic equipment must be located beyond the 100 Gauss line, and the 10 Gauss line is customarily taken as the boundary for personnel safety. The maximum radii for the 100 Gauss and 10 Gauss field magnitudes are 5.88 m and 6.93 m respectively, which for the 100 Gauss field line is only 1.31 m (4.3 ft.) from the outside of the vacuum vessel, and for the 10 Gauss field line is only 2.36 m (7.74 ft.) from the outside of the coil.

The energy stored in a SMES system is delivered and received in the form of direct electric current. The energy stored in a SMES is characterized for the purpose of designing the "dc end" of the Power Conditioning System (PCS) as a mostly current source device. The PCS acts as the power interface between the energy store and the utility system by effecting a bi-directional energy transfer between the two. The PCS can also generate or absorb reactive power from the utility system concurrently with the real power exchanged. The ratio of real and reactive power exchanged at any instant will be adjusted by an external system controller in response to system conditions. The PCS will be designed with the capability to deliver any combination of real and reactive power instantaneously within its rating envelope and capacity of the energy stored.

Table 1 summarizes the costs of the 60 MW SMES plus Back-up Diesels plant.

Table 1 — Overnight Capital Costs: Puerto Rico 60 MW SMES plus Back-up Diesels

SYSTEM COSTS	millions of 1999 dollars
SMES Unit (Toroid Coil 2250 MJ of stored energy)	$61.6
Construction (Building and site, substation, PREPA overhead)	$15.8
Total for SMES	**$77.4**
Back-up Diesel Facility (includes construction)	$47.6
TOTAL	**$125.0**

4.0 Economic Comparison between SMES and BESS

An economic analysis comparing the operational and cost factors of BESS with the proposed SMES, specifically applied to the PREPA system was performed. We evaluated SMES and BESS plant designs that comply with the functional specification previously discussed.

PREPA derived the baseline design of the BESS alternative from the existing PREPA 20MW BESS facility at the Sabana Llana Substation. To estimate the costs of the new BESS alternative design, modifications were made to the original specifications to account for differences in the requirements of the new facility as well as lessons learned based on operating experience. One of the main differences is in the requirements of the duty cycle. The Sabana Llana BESS was specified to perform rapid (spinning) reserve duty as well as frequency control. Thirty percent of the rated energy capacity of 14 MWh was reserved for the frequency control function. On the other hand, the baseline BESS provides rapid reserve duty only, the same as the SMES design.

Another major difference is in the stored energy requirement for the rapid reserve duty. The Sabana Llana BESS rapid reserve discharge profile was specified as 20 MW for 15 minutes followed by a ramp down to zero MW over the next 15 minutes. The simulations described in section 1.0 showed we can reduce the discharge profile substantially. For this evaluation, we decided to reduce only the ramp down portion of the discharge from 15 minutes to 5 minutes. The resulting stored energy is sufficient to provide the requirement as determined in the first part of the study, and maintain the operating reserve during the maximum 15 minutes required to start-up emergency gas turbine units.

The following are the most important assumptions of the baseline plant design review, which have an impact the capital and operating costs of the BESS.

1. Three individual 20 MW BESS plants will be built to obtain the 60 MW power requirement as determined in Phase IA.
2. The stored energy requirement for the baseline design is 7.7 MWh. This is only about half of the 14 MWh rating of the existing facility. The reduction is based on supplying the spinning reserve requirement only. This capacity is sufficient to allow the start-up of gas turbine units to maintain the reserve power of the BESS.
3. The new battery cell specification is more stringent and will require improved design and fabrication. This will probably result in a premium cost when compared to the cells purchased for the first BESS facility.
4. The expected life of the cells was reduced from ten years to eight years. The original specifications asked for a warranted life of ten years. A more realistic expectation is 8 years.
5. The logistics for battery cell maintenance are improved. The main requirement is to provide a cargo elevator in the battery building.
6. The cooling system specification for the power converter room will include an air conditioning system. The original design HVAC equipment used vacuum blower fans and filters. This system proved inadequate, as it was unable to control high humidity and coastal salt contamination, which caused many operational problems induced by corrosion of electronic components.
7. The power transformer rating is 20 MVA. The original specification was 40 MVA to provide additional capacity for a future 20 MW facility at the same site.
8. The fire protection system of the existing plant includes expensive ($250,000) improvements to the local water system in order to provide adequate water pressure. This extraordinary cost is not included in the baseline plant estimate.
9. The maintenance will include the replacement of 4% of the cells every year during their 8 year expected life. This assumption is considered severe but justified based on experience to date.

The capital cost for the SMES plant is for a single 60 MW unit rated for 30 seconds. We assume that the technology for large SMES plants is mature and ignore the need for investment in a proof-of-concept pilot plant. The design includes a nitrogen refrigeration plant for the SMES cooling system. In addition to the cost elements developed in the SMES design, other costs have been added, such as for the building, the utility interconnection, shipping, taxes and PREPA overhead. Also included are escalation costs and the cost of interest during construction.

The diesel back-up facility comprises eight diesel generators; each rated at 8 MW standby and capable of starting, synchronizing and loading in less than 30 seconds. The cost of the generator modules includes the generator; its weather protected enclosures, a switchgear enclosure for the 13.8 kV breakers and a central starting system module. The diesel generator facility includes a 300,000-gallon fuel tank, with sufficient reserve for seven days of peak hours operation.

We made the economic comparison using PREPA's standard methodology based on the present value of revenue requirements (PVRR). In this methodology, we convert the capital costs of each alternative to equivalent annual costs and add the annual operation and maintenance expenditures. We then calculate the PVRR by finding the present value of the total annual expenditures during the expected operational life of the alternative facility. As is true of all engineering economy analysis, it is a basic requirement to compare alternatives with similar capacities and functions and with similar operating lifetimes.

The calculations showed the BESS alternative is the economic choice, with a PVRR of $104 million compared to $133 million for the SMES-Diesel alternative as shown in Table 2. In spite of the higher operation and maintenance cost of the BESS, the high capital cost of the SMES and back-up diesels cannot overcome this handicap.

Table 2. PVRR of a SMES (60 MW optimized plant) and BESS Alternatives (in millions of 1999 dollars)

	SMES	BESS
Capital	118	82
Operation and Maintenance	15	22
Total	133	104

5.0 Conclusions

The combined results of our study showed that the 60 MW SMES option alone will not be a solution to rapid spinning reserve insufficiency to prevent a blackout under generation deficiency conditions. This is so because the electric system requires a 60 MW injection for at least 5 minutes. The SMES unit becomes uneconomical if it is required to discharge for longer than one (1) minute. A BESS unit will solve the problem since it can sustain the required discharge for more than 5 minutes.

A SMES plus diesels option, a combination that will keep the required power output over a five minutes period or more, will also solve the problem. The SMES plus diesels solution present value was calculated as $133 million. The 60 MW BESS present value was calculated as $104 million ($29 million less than the SMES plus diesels solution.) The most economical of the solutions considered is the 60 MW BESS.

6.0 References

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