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ASSESSMENT OF UTILITY SIDE COST SAVINGS FROM BATTERY ENERGY STORAGE

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***Abstract*- A method of determining the dynamic operating cost benefits of energy storage systems for utility applications is presented. The production costing program DYNASTORE is used to analyze economic benefits for "utility B," an isolated island utility, using heuristic unit commitment algorithms. The unit commitment is done using chronologic load data and a detailed model of the utility characteristics. Several unit commitment scenarios are run for utility B, and the results are presented. Comparisons between various Battery Energy Storage System (BESS) applications, as well as cases with and without battery storage, are shown. Results show that for utility B, a BESS of 300 MW size used for either load leveling or spinning reserve provides the greatest economic benefit.**

I. INTRODUCTION

The primary motivation of this work is to achieve more economical operation of the electric utility system while enhancing reliability with additional energy sources. To reduce costs during peak demand periods, utilities employ Demand Side Management (DSM) strategies. Direct Load Control (DLC) is one common DSM program which enables the utility to offer customers a rate discount in exchange for utility control of certain loads such as air conditioners, clothes dryers, and water heaters, in order to curtail power demand during peak periods when electricity is very expensive.

Energy storage is an attractive energy source to augment DSM implementation. By using energy storage systems, a lower cost source of electricity can be effectively provided to meet the peak demand. An energy storage device can be charged during off-peak periods with lower cost sources such as nuclear or coal fired units. This stored energy is then used during peak periods so that high cost units such as combustion turbines do not have to serve the load.

For purposes of system security, utilities are required to maintain a certain amount of ready reserve which can be used when a generating unit failure occurs. In general, the ready reserve requirement is a fixed percentage of the peak load, and also must be greater than the capacity of the largest generating unit. Because energy storage devices can be ramped from full charge to full discharge almost instantaneously they can provide a source of instantaneous ready reserve power. Utilities also must have a certain amount of capacity online set aside for Load Frequency Contol (LFC). The LFC requirement allows the utility to adjust the power generation to match fluctuations in the load. Energy storage devices (ESD) can be used to satisfy the spinning reserve or frequency regulation requirements, therefore requiring fewer generating units to be synchronized to the grid. Energy storage systems may be used for this purpose include Pumped Storage, Compressed Air Energy Storage (CAES), Superconducting Magnetic Energy Storage (SMES), and Battery Energy Storage Systems (BESS). This paper will focus on Battery Energy Storage, however many of the concepts explored can be easily extended to include other energy storage facilities.

Many reports have been written regarding various aspects of battery energy storage including battery technologies [1-6], economic benefits of BESS [7-11], BESS dispatch strategies [12-15], BESS power converter system design and control [16-17], and power system security and reliability.

In recent years, the Department of Energy (DOE), the Electric Power Research Institute (EPRI), and the International Lead Zinc Research Organization, Inc. (ILZRO) have spent a great deal of time and effort on BESS development. Their intent is to enable energy customers to easily make economic decisions regarding the installation of battery storage equipment. BECHTEL GROUP, Inc. has completed BESS cost studies for EPRI [8] including maintenance, operation, battery, converter, and engineering costs. Other projects [9,10] have developed spreadsheet programs to evaluate the economic value of using a BESS system. These models calculate savings from peak shaving and energy displacement using load duration data, without

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considering the effects of spinning reserve (SR) and LFC requirements. A more accurate method is needed. One approach is the unit commitment scenario, which offers results that match the time variation of load and includes the effects of SR and LFC for chronological load data.

II. DEVELOPMENT METHOD

Production Costing Methodology

In order to determine the dynamic operating benefits of energy storage for utility applications, the production costing program DYNASTORE [18] is used. Dynastore has several advantages over previous production costing methods, such as PROMOD III. DYNASTORE uses chronological data instead of load duration curve data, which allows start up costs, minimum up time, and minimum down time constraints to be included in the unit commitment process and subsequent cost calculations. DYNASTORE dynamically models the unit commitment and economic dispatch process over a specified time period and includes the effects of energy storage devices such as BESS, CAES, and SMES. Energy storage system dispatch strategies include load leveling, spinning reserve, and load frequency control. The effects of generating unit maintenance and forced outages are also included.

Unit Commitment Algorithms

DYNASTORE uses heuristic methods to solve the unit commitment problem rather than algorithmic solution techniques, such as dynamic programming. These include:

a. Input Order Logic
b. Minimum Down Time Logic
c. Economic Shutdown Logic
d. Economic Cycling Logic

After the unit commitment problem has been solved DYNASTORE solves for the economic dispatch using the equal-incremental-cost criterion. When the storage system is used for load leveling, DYNASTORE creates an incremental cost threshold. If the incremental cost is below the threshold and the battery is not fully charged, the storage system will be charged. If the incremental cost is above the threshold and the battery is not fully discharged, the storage system will be discharged.

DYNASTORE Simulation Methods

DYNASTORE provides for several methods of production cost simulation. Those methods are deterministic, standard Monte Carlo, and antithetic Monte Carlo. The difference in each of these methods concerns the issue of generating unit availability. The deterministic method assumes that there are no forced outages. In this method, all generating units are considered to be available at all times, except any units which may be on maintenance outage.

The standard Monte Carlo method uses a pseudo random number generator to simulate random forced outages based on the generating unit reliability data specified in the input data, namely the Equivalent Forced Outage Rate (EFOR) and the Mean Time To Repair (MTTR).

The antithetic Monte Carlo sampling method improves the convergence of the standard Monte Carlo sampling method. The antithetic Monte Carlo algorithm alternates standard Monte Carlo iterations with antithetic iterations. The antithetic iteration is based on the principle that the variance of two negatively correlated random numbers is less than the sum of the variance of two independent random numbers. During the antithetic iteration, the antithetic of each random number generated in the previous standard Monte Carlo iteration is used to determine the present state of each generating unit. If the random number for the standard Monte Carlo sample is r_i, then the antithetic of that number, $a_i = 1 - r_i$, is used for the antithetic sample. This allows for quicker convergence of operating cost calculations.

III. DESCRIPTION OF TEST SYSTEM

Utility Characteristics

The sample utility studied in this project will be referred to as Utility B. It consists of a single control area, and is isolated from interconnection with other utilities. The system peak loads for the years 1996 and 1997 are 2750 MW and 2850 MW respectively. The maximum generation capacity for the 1996 and 1997 simulation periods is 5135 MW, including 311 MW of coal fired generation, 3099 MW of oil fired generation, 592 MW of combined cycle generation, and 1133 MW of gas turbine generation.

Study Parameters

The operating reserve and spinning reserve requirements are given by the following equations:

$$OR = L \times P\% + C \times Q\% + R$$
$$SR = OR \times S\%$$

Where *OR* represents the System Operating Reserve Requirement (MW), *SR* represents the System

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Spinning Reserve Requirement (MW), *L* represents the peak (or hourly) system load (MW), *C* represents the capacity of the largest thermal unit (MW), *P%* represents a percentage of the peak (or hourly) system load, *Q%* represents a percentage of the capacity of the largest thermal unit, *R* represents a constant MW value, and *S%* represents the percentage of the operating reserve which must be spinning.

These parameters allow the user to model operating reserve in a variety of ways depending on the requirements necessary to maintain reliability on a specific system. Any combination of one or more of the above parameters may be used to determine the operating reserve requirement. In order to allow for diversity of reserve, DYNASTORE allows the user to specify a Maximum % of Spinning Reserve on One Unit. Table I lists values used for key parameters in each of the study cases described herein.

IV. PRODUCTION COST RESULTS

Sensitivity Analysis

Effects of BESS on spinning reserve, load leveling, and frequency control requirements are considered. These test cases have been based on typical generator and load data obtained from Utility B. The list of generators includes all units which are to be in service on the specified utility by the beginning of the 1996 calendar year. BESS parameters have been adjusted to reflect the actual desired application of the batteries. The range of the BESS capacity has been extended from 40 MW to 500 MW in order to determine the best BESS size. Figures 1 and 2 show that the BESS savings are almost linear from 40 MW to 300 MW for spinning reserve and load leveling respectively but begin to level off above 300 MW. A spinning reserve requirement of 15% of the peak load computes to 412.5 MW for the 1996 simulation year and 427.5 MW for 1997. Therefore, a minimal increase in operating cost benefits is obtained by increasing the BESS size above 300 MW. While the overall savings levels out, the average savings per MW decreases above 300 MW. This is shown in Figure 1.

Table I - Parameters used in DYNASTORE study	
P%	20
Q%	0
R	0
Spin % of Operating Reserve (S%)	75
Maximum % of Spinning Reserve on One Unit	100
Peak or Instant	Peak
Study Period	1996-1997
Unit Commitment Option	Economic shutdown logic

A summary of BESS parameters appears in Table II.

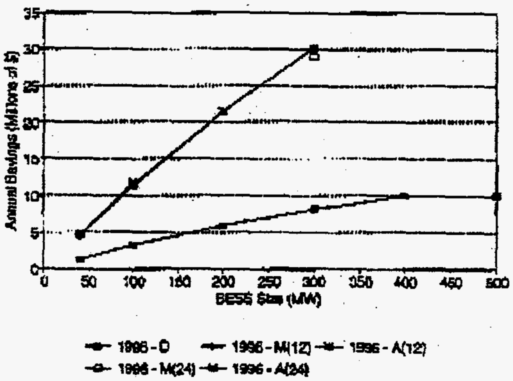

Figure 1: BESS used for Spinning Reserve - 1996

BESS Used For Spinning Reserve

Table II - BESS Parameters	
Discharge Capacity	variable -- 40 MW - 500 MW
Charge Capacity	variable -- 40 MW - 500 MW
Variable O&M Cost	0 $/MWh
Efficiency (ac-dc-ac)	70%
Energy Storage Capacity	variable -- 40 MW - 500 MW

Several scenarios have been simulated which show how BESS savings vary with BESS size. In each scenario considered here, the BESS is used for spinning reserve only, and the BESS charge and discharge capacity are varied. Scenarios are run with the deterministic, standard Monte Carlo, and antithetic methods. A summary of operating cost savings for the various spinning reserve scenarios appears in Table III. A graph of BESS savings vs. BESS size for the 1996 simulation year appears in Figure 1. It shows that increasing the number of Monte Carlo iterations from 12 to 24 does not produce any noticeable change in savings. Hence, the remainder of the analysis was done using 12 iterations.

BESS Used For Load Leveling

Table III - Summary of annual savings when BESS is used for spinning reserve only (Millions of $)

Simulation Method	Deterministic		Monte Carlo (12 iterations)		Antithetic (12 iterations)	
Simulation Year	1996	1997	1996	1997	1996	1997
BESS Size (MWh)						
40	1.232	2.845	4.534	6.205	4.743	6.232
100	3.168	5.411	11.247	14.803	11.533	15.248
200	5.890	8.584	21.313	29.023	21.530	29.498
300	8.083	11.483	30.366	41.106	30.181	41.260
400	9.865	13.720	Base Case Cost w/o BESS		611.32	690.05
500	9.985	14.228				

Several scenarios have been simulated which show how savings vary with BESS size. In each scenario considered here the BESS is used for load leveling, and the BESS charge and discharge capacity are varied. It should be noted that if the entire BESS is not needed for load leveling at a specific instant of time, the remainder will be credited toward the spinning reserve requirement. Scenarios are run with the deterministic, standard Monte Carlo, and antithetic methods. A summary of savings for the various load leveling scenarios appears in Table IV. A graph of BESS savings vs. BESS size for the 1996 simulation year appears in Figure 2.

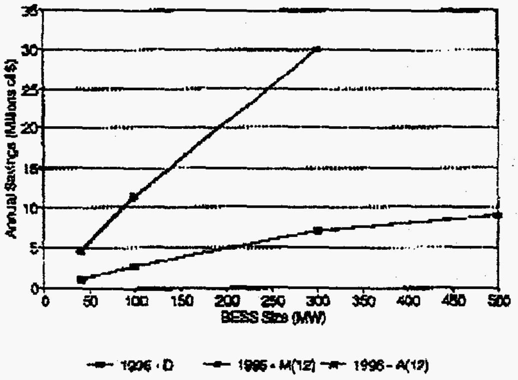

Figure 2: BESS used for Load Leveling - 1996 Simulation Results

BESS Used For Load Frequency Control

Several scenarios have been simulated which show how BESS savings vary with BESS size. In each scenario considered here the BESS is used for LFC, and the BESS charge and discharge capacity are varied. Savings are based on the difference in production cost when LFC is done with base and cycling unit generators and the production cost when LFC is done with the BESS. Scenarios are run with the deterministic, standard Monte Carlo, and antithetic methods. A summary of savings for the various LFC scenarios appears in Table V. A graph of BESS savings vs. BESS size for the 1996 simulation year appears in Figure 3.

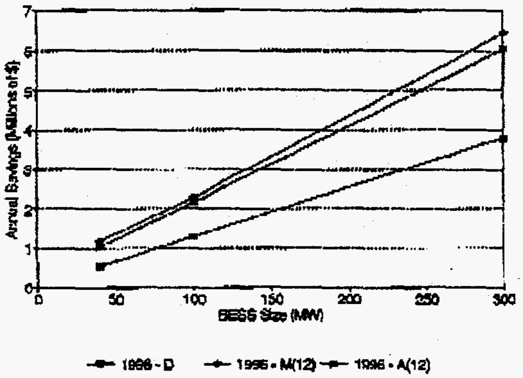

Figure 3: BESS used for Load Frequency Control - 1996 Simulation Results

Comparison of BESS Scenarios

In order to determine the relative benefits of different energy storage scenarios it is useful to compare the savings when energy storage is used for spinning reserve, load leveling, and frequency regulation respectively. Graphs of BESS savings vs. BESS size for each energy storage scenario for the 1996 and 1997 simulation years using the standard Monte Carlo method with 12 iterations are shown in Figure 4 and Figure 5 respectively.

Table IV - Summary of annual savings when BESS is used for load leveling (Millions of $)

Simulation Method	Deterministic		Monte Carlo (12 iterations)		Antithetic (12 iterations)	
Simulation Year	1996	1997	1996	1997	1996	1997
BESS Size (MWh)						
40	1.093	2.596	4.395	6.099	4.667	6.187
100	2.669	4.975	11.051	14.546	11.370	15.092
300	7.143	10.424	29.940	40.618	30.061	41.114
500	8.994	13.419				

Table V - Summary of annual savings when BESS is used for load frequency control (Millions of $)

Simulation Method	Deterministic		Monte Carlo (12 iterations)		Antithetic (12 iterations)	
Simulation Year	1996	1997	1996	1997	1996	1997
BESS Size (MWh)						
40	0.535	0.596	1.160	1.362	1.021	1.136
100	1.301	1.450	2.281	2.521	2.158	2.350
300	3.805	4.307	6.443	7.264	6.051	6.985

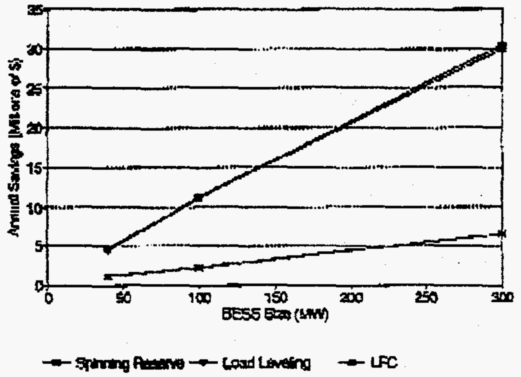

Figure 4: Comparison of BESS Strategies - 1996 Monte Carlo Simulation Results

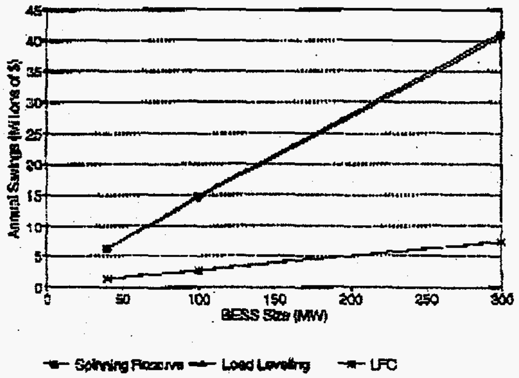

Figure 5: Comparison of BESS Strategies - 1997 Monte Carlo Simulation Results

Notice that the savings when the BESS is used for load leveling are almost the same as the savings when the BESS is used for spinning reserve. This is a coincidence based on the data for this specific system. In general, the benefits of using a BESS for load leveling and spinning reserve will not be the same. Some insight into the comparison of BESS benefits for these scenarios can be obtained by considering how the BESS benefits are formulated.

When the BESS is used for load leveling, the BESS will be charged during off-peak periods when the incremental cost is low and the BESS will be discharged during on-peak times when the incremental cost is high. The relative production cost of various generating units with respect to one another will affect the relative incremental cost and hence, the overall savings. Some energy is lost in the conversion of ac power to dc power stored in the BESS and the conversion back to ac power. In order to ensure that the BESS provides savings, the ratio of incremental cost during charging to incremental cost during discharging must be less than the efficiency of the entire ac-dc-ac cycle.

BESS Used For Multiple Scenarios

In addition to the system characteristics which have been used for previous cases, consider the BESS used on combinations of load leveling, spinning reserve, and load frequency control. Each of the following three cases has a combined total of 100 MW of either generators on LFC or BESS on LFC or a combination thereof. In each of these cases the total BESS capacity is 100 MW. The three cases to be considered are (1) when the BESS is used for 50 MW of load leveling and 50 MW of spinning reserve, (2) when the BESS is used for 50 MW of load leveling and 50 MW of LFC, and (3) when the BESS is used for 50 MW of spinning reserve and 50 MW of LFC. A summary of the savings when the BESS is used for each of these cases appears in Table VI. These savings are compared with the savings shown in Tables III, IV, and V respectively. The results show that the optimum commitment scenario includes the BESS implementation for both SR and LL.

Table VI - Summary of annual savings when BESS is used for some combination of load leveling, spinning reserve, and LFC strategies (Millions of $)

Strategy	1996	1997
BESS used for 50 MW of LL and 50 MW of SR	12.215	15.918
BESS used for 50 MW of LL and 50 MW of LFC	6.569	8.778
BESS used for 50 MW of SR and 50 MW of LFC	6.700	8.939

V. CONCLUSIONS

The results presented illustrate that economic benefits can be obtained by utilizing energy storage for spinning reserve, load leveling, and frequency control. It is shown that the greatest economic benefit of storage will be obtained when the BESS is used for load leveling and/or spinning reserve. The operating benefits of using the BESS for load frequency control on this utility are much less than spinning reserve or load leveling. For this particular simulation period for this particular utility, the economic benefits of using a BESS for load leveling and spinning reserve are nearly identical. As fuel prices fluctuate, this relationship may change in favor of one scenario or the other. However it was shown that a 300 MW BESS used in any combination of load leveling and spinning reserve will have the most savings per MW BESS capacity. Recall that the economic benefits of the BESS begin to saturate above 300 MW for both load leveling and spinning reserve applications. This suggests that if a BESS larger than 300 MW is chosen it should be ensured that neither the portion used for spinning reserve, nor the portion used for load leveling, exceeds 300 MW in order to achieve maximum benefit.

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Biographies

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Rudolph G. Jungst received his B.A. degree from Luther College in 1968 and completed studies for the Ph.D. degree in inorganic chemistry at the University of Illinois in 1976. Dr. Jungst is a Senior Member of the Technical Staff at Sandia National Laboratories, specializing in energy components. His recent work has been in the development of improved batteries and battery components for utility energy storage systems, battery recycling, and thermal analysis of battery facilities. He is a member of the American Chemical Society.