Evaluation of Superconducting Magnetic Energy Storage For San Diego Gas & Electric

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REPORT SUMMARY

By providing rapid-response, real-power (P) or reactive-power (Q) modulation, superconducting magnetic energy storage (SMES) devices can increase power transfer capabilities. This report documents two phases of a technical study to determine potential benefits of locating a SMES unit at San Diego Gas and Electric's Blythe site.

Background

Part of a larger west coast study that is evaluating SMES transmission stability enhancements, this project was performed by Battelle Northwest (BNW), funded by EPRI, and administered by San Diego Gas and Electric (SDG&E). SMES is a member of flexible ac transmission system (FACTS) devices that enhance power transmission. The SMES device used in this study (designed by Bechtel/Lockheed Martin) has a nominal energy storage capacity of 1 MWh. Typically, an actual unit would include a power conditioning system (PCS) rated at 500 MW for 20 seconds. The study evaluated whether such a unit connected to the Palo Verde-Devers line near SDG&E's Blythe site could boost Southern California's import capability.

Objectives

- To investigate the optimum SMES size and modulation design for Blythe (Phase I).
- To determine the potential improvement in East-of-River (EOR) and Southern California Import Transmission (SCIT) transfer capability (Phase I).
- To examine effects of increasing the EOR transfer capability (Phase II).
- To evaluate the multiple benefits of SMES at Blythe (Phase II).
- To explore combination of real- and reactive-power modulation (Phase II).

Approach

Investigators modeled SMES using EPRI's Extended Transient/Midterm Stability Package (ETMSP). They used a 5000-bus representation of the western North American power system, simulating heavy summer system load and configuration for 1999. To ensure proper functioning, the investigative team performed extensive testing of their modified ETMSP design. Using this model, the study focused on examining system stability performance improvement. (To realize increases, thermal constraints also would have to be increased; however, consideration of these constraints was beyond the study's scope).

Results

The study's model demonstrated that a 500-MVA SMES unit at Blythe could increase the non-simultaneous East-of-River (EOR) limit by 300 MW when supplying real-power (P) modulation. The increase was greater than 500 MW with reactive-power (Q) modulation. The greatest increase, however, resulted with modulation of P and Q applied simultaneously. Such modulation had more control leverage than either P or Q applied separately (for example, simultaneous P and Q modulation allowed a 300-MVA SMES unit to match the performance of a 400-MVA unit using Q modulation alone).

EPRI Perspective

In this study, SMES shows great potential in increasing transmission capacity to Southern California. When transmission enhancement is valued at $10,000/MW-year, the estimated total present value of SMES benefits at Blythe range between $82 million and $135 million. Beyond increasing transmission capacity, SMES can provide secondary benefits, including tie-line control, spinning reserve, load-leveling, and voltage control. Similar benefits are expected in other parts of the country as existing transmission resources become more burdened in the de-regulated business environment.

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Interest Categories

FACTS & substations, communication, protection & control
Power system operations & control
Bulk power markets & transmission
Energy storage

Keywords
Energy storage
FACTS
Transmission stability
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ABSTRACT

To determine potential benefits of locating a superconducting magnetic energy storage (SMES) device at San Diego Gas and Electric's (SDG&E) Blythe site, researchers used EPRI's Extended Transient / Midterm Stability Package (ETMSP) to model their proposed unit. They simulated heavy summer system load and configuration with a 5000-bus representation of the western North American power system. Using this model, the two-phase study evaluated whether their SMES unit (designed by Bechtel/Lockheed Martin) connected to the Palo Verde-Devers line near SDG&E's Blythe site could boost Southern California's import capability. Test results indicated that the greatest increase in transfer capability occurred with rapid-response, real-power (P) and reactive-power (Q) modulation applied simultaneously (results were greater than either P or Q applied separately). P and Q simultaneous modulation allowed a 300-MVA SMES device to match the performance of a 400-MVA device using Q modulation alone. Valuing transmission enhancement at $10,000/MW-year, the estimated total present value of SMES benefits at Blythe range from $82 million to $135 million.

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EXECUTIVE SUMMARY

This report documents Phase I and Phase II technical studies performed by Battelle Northwest for San Diego Gas and Electric (SDG&E) to evaluate the benefits of locating a superconducting magnetic energy storage (SMES) device at SDG&E's Blythe site. SMES is a new technology with the unique ability to provide rapid-response, real-power (P) or reactive-power (Q) modulation and is a member of the flexible ac transmission system (FACTS) device family capable of increasing asset utilization and reliability of the transmission system. In addition to increasing power transfer capability, SMES employed in this manner can also provide secondary benefits at a single location including voltage control, subsynchronous resonance (SSR) damping, tie-line control, spinning reserve, load-leveling and prevention of underfrequency load-shedding.

Bechtel/Lockheed Martin have designed a device known as SMES-1. This unit has a nominal energy storage capacity of 1 MWh and would typically be equipped with a power conditioning system (PCS) rated at 500 MW for about 20 seconds. The principal objective of this study was to determine the potential of such a unit to increase the Southern California import capability if it were located at the Blythe site and connected to the existing Palo Verde-Devers 500 kV transmission line.

The study effort was conducted in two phases. Phase I consisted of nine analytical tasks that investigated the optimal SMES location, size and modulation, and the potential improvement SMES would enable in East-of-the-River (EOR) and Southern California Import Transmission Nomogram transfer capability. Phase II efforts examined the effect of increasing the EOR transfer capability proposed by Southern California Edison, increasing the SMES output to 900 MVA, and evaluated the secondary benefits provided by SMES at Blythe.

The magnitude of the transmission benefit was analyzed using the Extended Transient/Midterm Stability Package, developed by the Electric Power Research Institute. This tool was used in conjunction with a 5000-bus model representation of 1999 heavy summer system load and configuration conditions developed by member utilities of the Western States Coordinating Council. For heavy power transfers from Arizona to California, the most critical disturbance that limits system stability is a three-phase fault at the Palo Verde 500-kV bus followed by the loss of the Palo Verde-North Gila 500-kV line.

Significant Results

The ability of SMES to increase power transfer between Arizona and California, based on this limiting contingency, is indicated in Table 1-1. A 500-MVA SMES device located at Blythe is shown to increase the non-simultaneous EOR limit by 300 MW when supplying P modulation and greater than 500 MW with Q modulation. The corresponding EOR increases enabled by a 900-MVA SMES unit are 407 MW and more than 500 MW, respectively. **Thermal transfer constraints would also need to be addressed and would require further transmission upgrades to utilize the SMES-enhanced transmission capacity.** Consideration of these thermal limitations was beyond the scope of the study, and has been addressed in other studies by the utilities in the Southwest.

A SMES unit configured as a four-quadrant control device is capable of providing P or Q modulation, or a combination of both. The modulation of P and Q applied simultaneously was found to have more benefit (ratio of the power transfer enhancement to controlled modulation power) than either P or Q applied separately. The P/Q ratio providing a control power angle of 60° allowed a 300-MVA SMES device to achieve a 400-MVA increase in EOR loading. This represents control leverage more than 30% greater than the approximately 1 MW/MVAR leverage achieved with reactive-power modulation alone.

Table 1-1
Increasing the Non-Simultaneous Arizona-California Limit

SMES Converter Rating Located at Blythe	EOR Increase (MW)	
	Real-Power Modulation	Reactive-Power Modulation
500 MVA	300	> 511[1]
900 MVA	407	> 511[1]

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[1] When either the EOR corridor is loaded beyond 8400 MW (an increase in EOR of about 500 MW beyond the benchmark case stability limit) or Midway-Vincent greater than 2631 MW (an increase in SCIT of 882 MW) the benchmark case fails to converge in the power flow solution and is the reason upper-bounds for the reactive-modulation cases are not identified. This effect appears to be the result of poor voltage support in the region, which may be an artifact of the model used in this study or program solution.

Table 1-2 summarizes unit values, present values and ranges of all SMES benefits evaluated in this study. Transmission enhancement is shown to be the dominant benefit when valued at $10,000/MW-year. This value, recommended by SDG&E, represents the annual worth of adding transmission capacity to the EOR system for increased economy purchases. The estimated total present value of SMES benefits at Blythe is shown to range between $82 million and $135 million.

The study included a cursory review of the spinning reserve and load-leveling benefits provided by larger SMES units. Spinning reserve, load-leveling and capital cost saving benefits were assessed for a 150-MW SMES unit with 1-hour storage capacity. This unit was assumed to be capable of deferring the need for a combustion turbine of the same power, as shown in SDG&E's resource acquisition plan in the year 2006. The net present value of this scenario was shown to be $10 million based on present values of benefits and capital costs of $208 million and $198 million, respectively.

Conclusions

The most important conclusion of this study is that, under expected 1999 heavy summer system load and configuration conditions, P and Q modulation applied simultaneously at Blythe was found to have better control leverage than either P or Q modulation applied separately.

The lower and most conservative bound of the SMES-1 benefit range is close to the $82-million capital cost of an appropriately sized, first-of-a-kind SMES unit and is also twice the $41-million cost estimated for an nth-of-a-kind device. These comparisons do not include the cost of required thermal line upgrades, or costs associated with connecting SMES to the system.

Table 1-2
Summary of 500-MVA (1MWh) SMES Benefits at Blythe

Benefit	Unit Value ($M)[1]	Present Value ($M)[2]
Transmission enhancement/yr	5 - 6.7	69 - 92
Voltage control (capital)	0.3 - 12.5	0.3 - 12.5
SSR damping (capital)	2 - 7	2 - 7
Tie-line control/yr	0.5	6.9
Spinning reserve/yr	0.07	0.94
Load-leveling/yr	0.001	0.014
Underfrequency load-shedding/occurrence	2 - 5.7	2.8 - 16
TOTAL		**82 - 135**

The upper bound of the transmission enhancement benefit reflects the improved control leverage of simultaneous P and Q modulation that adds $23 million to the present value of this benefit. As expected, with a 1-MWh SMES device, the spinning reserve and load-leveling benefits are relatively insignificant.

Recommendations

All transmission enhancement benefits evaluated in this study are specific to and conditioned by the 1999 heavy summer system conditions assumed in the analysis. Other system load and configuration conditions should be evaluated to confirm these results.

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[1] The "unit value" is a unitized value of each benefit.

[2] The present value is the value of the beneift over an expected 30 year life.

The combined modulation of real- and reactive-power, as well as steady-state reactive power supplied prior to the fault for voltage support, demonstrate considerable improvement in benefits for a SMES device located at Blythe. Furthermore, adjusting the series compensation on the Palo Verde-Devers line also improves performance. Additional investigation of these issues is needed to maximize the performance of SMES in this application. Also, engineering analysis of the PCS to include detailed modeling of the converter and investigation of the benefits associated with early modulation curtailment would be beneficial.

Future assessments of SMES spinning reserve and load-leveling benefits should employ an established chronological production cost model to confirm the simple scaling analysis used in this study to evaluate these benefits.

2

INTRODUCTION

Early in 1994, a study was launched to assess benefits of locating a SMES device on the San Diego Gas and Electric (SDG&E) site at Blythe, California. An adjunct to a larger project evaluating SMES transmission stability enhancement for several west-coast application scenarios, this study was administered by SDG&E, funded by the Electric Power Research Institute (EPRI), and performed by Battelle Northwest (BNW). The primary purpose of SMES evaluated in this study is to enhance the Southern California import capability; both simultaneous and non-simultaneous. Secondary benefits provided by SMES at this location were also assessed. This report documents Phase I and Phase II effort in this study.

SMES Background

Using the magnetic field created by current flowing in superconductive windings to store energy, SMES has the potential for performing a broad range of electric utility functions ranging from improving end use power quality to deferring thermal generation used to supply peaking power, such as combustion turbines. With the ability to provide real- or reactive-power modulation, SMES is an addition to the array of flexible ac transmission system (FACTS) devices available for transmission enhancement.

Bechtel/Lockheed Martin have designed a device known as SMES-1. This unit has a nominal energy storage capacity of 1 MWh and would typically be equipped with a power conditioning system (PCS) rated at 500 MW for about 20 seconds. The principal motivation for this study is the prospect that such a unit connected to the Palo Verde-Devers line near the SDG&E Blythe site can increase the Southern California import capability.

Study Objectives

The project was conducted in two phases. The first phase, Phase I, consisted of nine analytical tasks. These tasks investigated the optimal SMES size and modulation design for SMES at Blythe, and the potential improvement in East-of-River (EOR) and Southern California Import Transmission (SCIT) transfer capability. The specific objectives of these tasks are listed below:

Phase I Study Objectives

1. Establish base case conditions without SMES and verify stability limit.
2. Develop a SMES model for the Blythe site.
3. Review and validate base case conditions.
4. Identify transfer limits with SMES.
5. Evaluate SMES performance.
6. Determine the relationship between SMES size and transfer capability benefit.
7. Perform damping comparison of alternate sites.
8. Evaluate transfer capability increase for alternate sites.
9. Adjust Palo Verde-Blythe and Blythe-Devers series compensation to optimize benefits.

The Phase II efforts examined the effect of increasing the EOR transfer capability proposed by Southern California Edison (SCE), evaluated the multiple benefits provided by SMES at Blythe, and explored the combination of real- and reactive-power modulation. Phase II was divided into five major task with the following objectives:

Phase II Study Objectives

1. Perform additional contingency analyses.
2. Evaluate a higher initial transfer capability.
3. Assess multiple SMES benefits.
4. Evaluate P-Q modulation combinations.
5. Evaluate the performance of a 900-MW/1-MWh SMES unit.

Report Organization

Many tasks in this project were interrelated and/or extensions of the Phase I effort performed in Phase II. The coherence between topics could be lost if each task were reported separately. Therefore, the report groups related topics into three categories. Section 3 documents results relating to transmission stability enhancement. the other benefits provided by SMES at Blythe are discussed in Section 4 and a summary economic analysis is provided in Section 5. References are presented in Seciton 6. Appendix A gives line loadings for the 7000-MW EOR marginally-damped benchmark case. Power flow summaries of several cases associated with the 7365-MW EOR benchmark are listed in Appendix B.

3

TRANSMISSION STABILITY ENHANCEMENT

Simulations of the stability enhancement were performed using EPRI's Extended Transient/Midterm Stability Package (ETMSP) using a 5000-bus representation of the western North American power system developed by WSCC member utilities depicting 1999 heavy summer system load and configuration. The methodology and results of this analysis are given in this section.

Southern California Import Capability

For heavy power transfers from Arizona to California, one of the critical disturbances that results in electromechanical oscillations is a three-phase fault at the Palo Verde 500-kV bus followed by the loss of the Palo Verde-North Gila 500-kV line. This line, near the Colorado river, is one of the major tie lines between Arizona and Southern California. This is generally the limiting contingency when determining Southern California import capability, and is used to determine the ability of SMES to increase power transfer between Arizona and California in this analysis. Figure 2.1 shows the general structure of the transmission network in the southwestern portion of the system.

The Blythe site, located near the Colorado river, is close to the Palo Verde-Devers 500-kV line. This study assumes that a new 500-kV substation would be constructed at Blythe and looped into the Palo Verde-Devers 500-kV line. The existing Palo Verde-Devers line would be divided into Palo Verde-Blythe and Blythe-Devers segments with the addition of an approximately 5-mile double-circuit 500-kV line between the Blythe site and the existing transmission line.

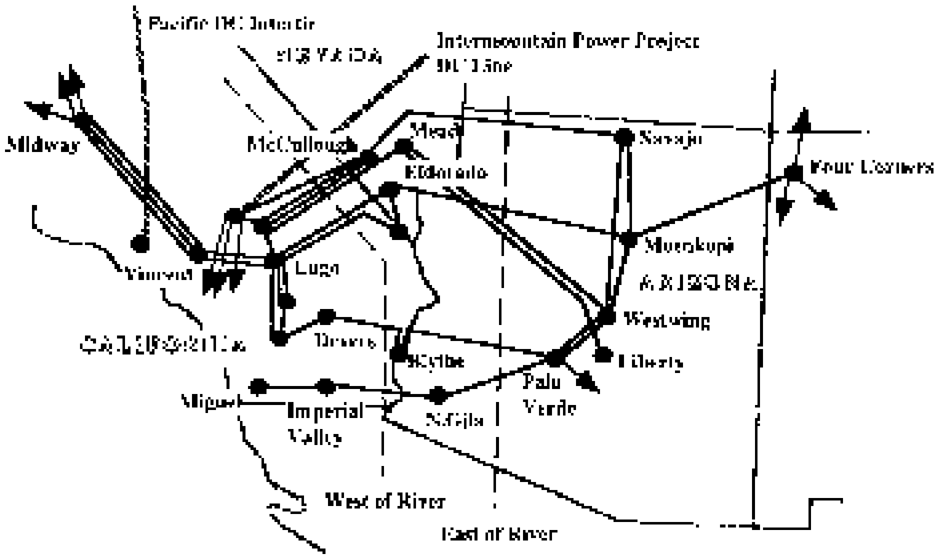

Figure 3-1 General Structure of the Regional Transmission Network and Location of Proposed SMES at Blythe

The stability limitations governing total available power imports into Southern California are represented by the SCIT Nomogram. This nomogram, which is updated periodically to reflect system conditions or changing configurations that impact system stability, is shown in Figure 3-2. The EOR transmission lines are generally heavily utilized due to the availability of less expensive coal-generated power from Arizona, New Mexico, and Utah. The power that can be brought from other areas, such as Northern California, the Northwest, and the Southern Nevada area (which complete the overall SCIT) is closely related to the level of imports in the EOR path.

The EOR path flow is the sum of the flows on the Navajo-McCullough, Moenkopi-Eldorado, Palo Verde-Devers, and Palo Verde-North Gila 500-kV lines, and the Liberty-Mead 345 kV line. At the present time, the non-simultaneous rating of the EOR path is 5700 MW. The Mead-Phoenix/Mead-Adelanto transmission project (MPP/MAP), scheduled for operation in April-May 1996, will add 1300 MW to EOR capacity.

In general terms, transmission capacity is determined by both thermal and stability restrictions. SMES can enhance the stability of the system; therefore, this study focuses on examining the system stability performance improvement. However, to realize these increases, thermal transfer constraints would also have to be increased. **No attempt was made in this study to identify methods that would resolve thermal limitations.**

SMES Model

To fully model SMES, the converters and their controls should be modeled in detail. For the purposes of this scoping study, however, a relatively simple analysis that uses real- or reactive-power injection is all that is necessary to evaluate SMES stability-enhancement benefits. The assumption is made that the converters themselves are responsive to the modulation controls, and deviations from the ideal response are negligible compared to the resolution the study is intended to provide.

The SMES power converter for transforming the dc power stored in the SMES coil to ac power exchanged with the grid, is assumed to provide four-quadrant power transfer, i.e., the ability to inject or withdraw both real or reactive power. Also, the power injection is assumed to be independent of the ac voltage.

The SMES model developed for this study uses a feature of ETMSP that allows sophisticated FACTS control devices to be analyzed in transmission stability planning models. These devices have a variety of attributes, the most important of which is a flexible means by which different controller designs can be developed and tested. The device interface with the network is modeled through special end-blocks.

The primary function of SMES analyzed in this study requires the injection of real power to provide modulation. No available end-block in ETMSP was available to model this interaction with the network. Therefore, modifications were made in ETMSP to model SMES real-power injection. The closest block available was a model for a resistive brake. This module was modified to change the nature of the current injection from constant impedance to constant power. Next, the limit constraining the device to exhibit only positive impedance was removed, allowing the new device to both inject and withdraw power from the network, both independent of the voltage. This module also can provide bi-directional reactive-power injection, also independent of voltage. Extensive testing of ETMSP was performed to ensure that the modified brake model provided satisfactory response.

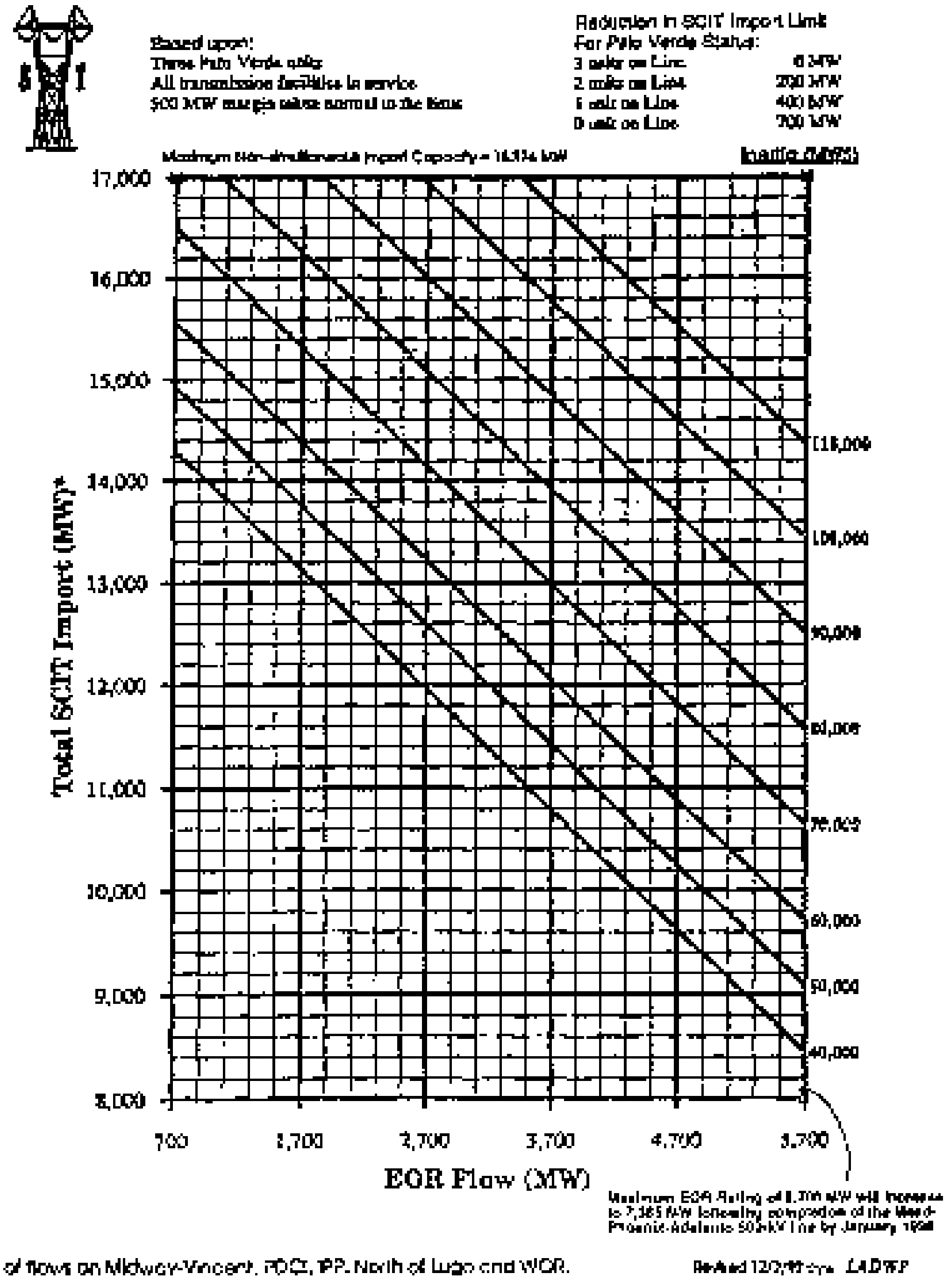

Figure 3-2 Current SCIT Nomogram (at the time that this study was originally performed)

SMES Control System Model

Feedback through a compensating controller is used to modulate the SMES real or reactive power. The block diagram for the modulation controller is shown in Figure 3-3. The design approach for the controller is based on advanced, but well established, small-signal stability control methodologies. Classical design techniques were used to select controller parameters that provide proper phasing and gain at the modulation frequency.

Prony analysis was used extensively in this study for designing the controller. Prony analysis is a technique of analyzing signals to determine modal, damping, phase, and magnitude information contained in the signal (Hauer et al. 1990) and is the basis for computer codes being developed by Battelle Northwest (Trudnowski 1994). To conduct a Prony analysis for a given case, a small power injection pulse is placed into the bus and the system response is simulated using ETMSP. The system's response is then analyzed using Prony resulting in the required modal information. This approach is described by Trudnowski et al. (1991).

The appropriate feedback signal is identified by comparing the residues of each of the candidate signals for relative observability for the mode to be controlled. Then the parameters of the compensating controller are determined. Frequency response and transfer-function identification based on Prony analysis are used to characterize the system from injection to output signal. Classical control techniques (e.g., root locus and frequency response analysis) are used to determine the proper feedback parameter settings. Control parameters are chosen to provide maximum damping to the principal oscillatory mode and to minimize any negative impact on other modes. Controllers designed in this study have a minimum 3dB gain margin.

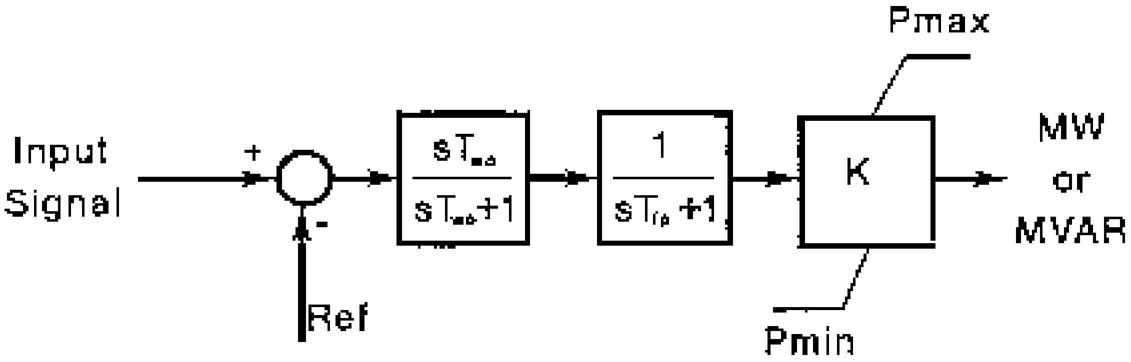

Figure 3-3 SMES Control Block Diagram

The marginally-damped case exhibits a strong 0.5-Hz mode in response to the Palo Verde-North Gila line outage contingency. Detailed simulation and modal analysis revealed that for this mode, machines in Southern California oscillate against those in the Arizona area. As expected,the oscillations are strongly observable in real-power flows and bus voltage angles. Also, 0.5-Hz swings occur heavily in the reactive line flows and bus voltage magnitudes. This mode appears to be very similar to the 0.67-Hz oscillatory mode present in the contemporary power system (Lee et al. 1994). Under heavier loading conditions and higher inertia, the frequency is somewhat less in the 1999 Heavy Summer model. Analysis showed that the mode damping is sensitive to the status of the Palo Verde-North Gila line, but the mode shape remains relatively constant. A second dominant mode observed at about 0.25 Hz is predominately a north-south mode in which Arizona and the LA Basin oscillate in phase with each other.

Independent EOR/WOR Increases Enabled by SMES Modulation

A marginally-damped benchmark loading condition was derived by incrementally adjusting WOR transmission while maintaining EOR and Midway-Vincent loadings of 7000 MW and 3000 MW, respectively. Figure 3-4 shows the comparison between the marginally-damped case and a case with an additional 10-MW WOR loading. Power line loadings for this case are given in Appendix A.

The minimum SMES power required to stabilize the system was determined by simulating the contingency with EOR or WOR flow increased above the marginally-damped benchmark case, with progressively less modulating power until an unstable response was observed. An example of this process is shown in Figure 3-5. Figure 3-6 gives the modulation output of the 400 MW SMES with EOR increased 400 MW.

The minimum SMES size needed for a stable response, and thus needed to obtain the given transmission enhancement benefit, are given in Table 3-1 for several levels of independent increases in EOR and WOR flow. Table 3-2 gives the same results for reactive modulation at Blythe, which requires different modulation control parameters.

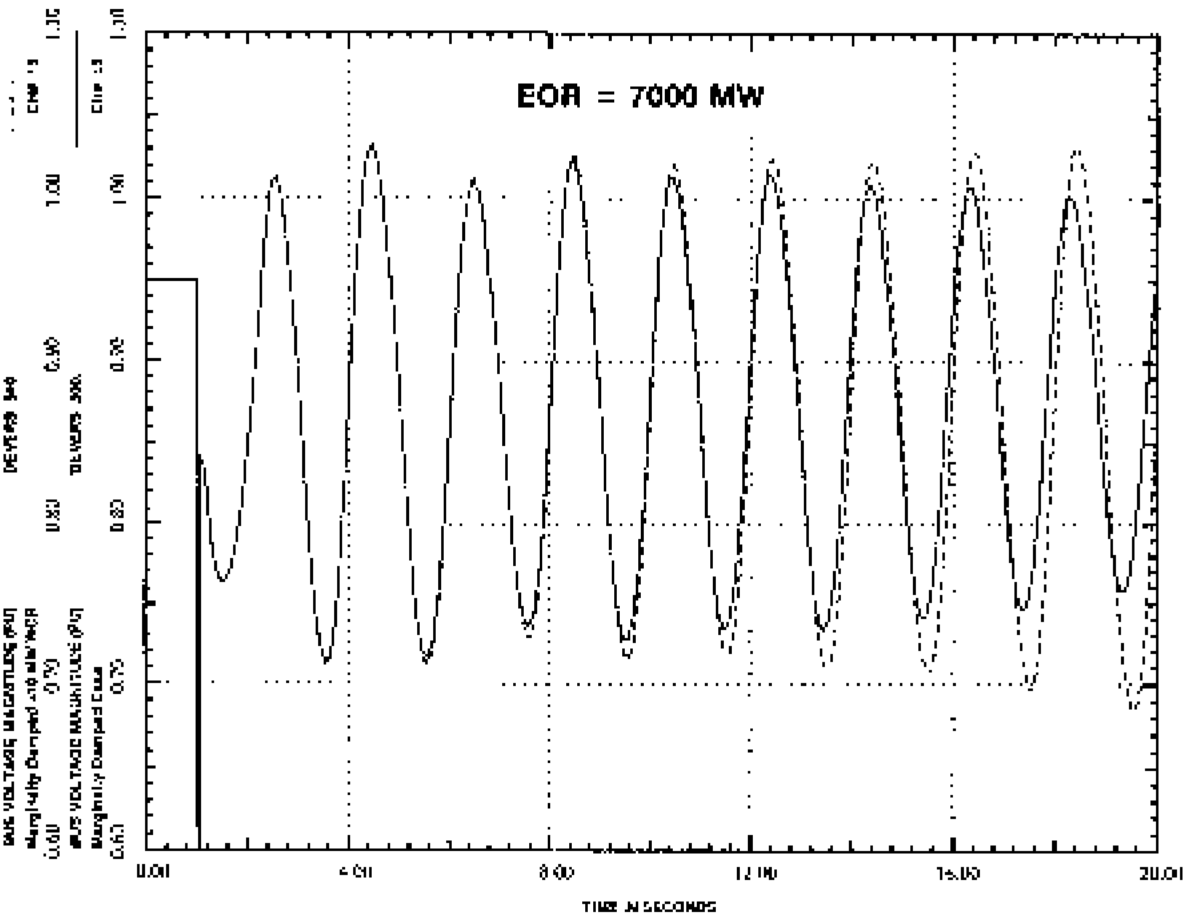

Figure 3-4 Demonstration of Marginal Damping for the Benchmark Loading Conditions without SMES

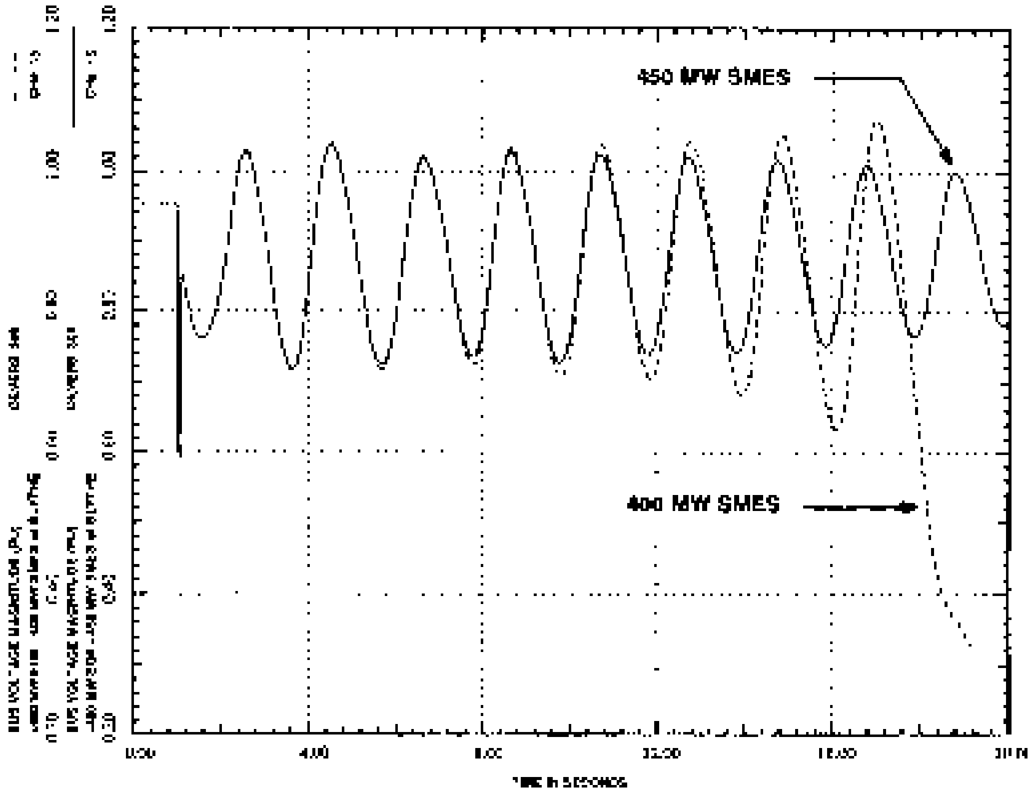

Figure 3-5 System Dynamic Response for Benchmark Loading Conditions +400 MW EOR with SMES Modulation at Blythe

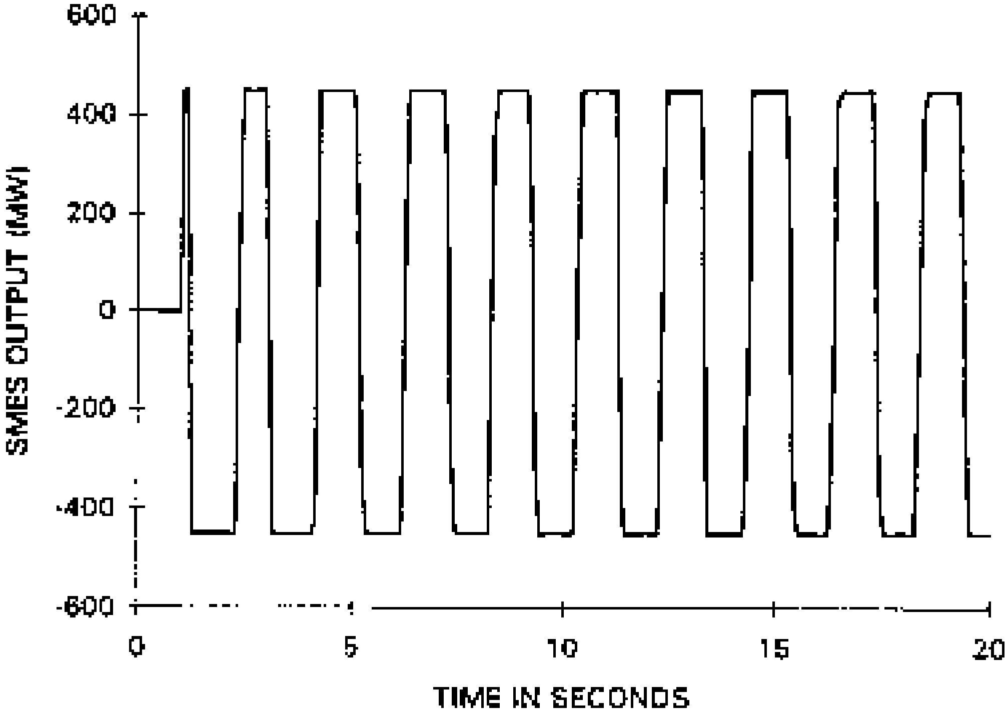

Figure 3-6 Plot of SMES Output for Benchmark Loading Conditions +400 MW EOR with 450 MW SMES Modulation at Blythe

Table 3-1
Real Power Modulation at Blythe

EOR Increase (MW)	SMES Rating Required (MW)
100	50
200	140
300	250
400	420
500	680

Table 3-2
Reactive Power Modulation at Blythe

EOR Increase (MW)	SMES Rating Required (MVAR)
400	80
500	100
600	120

Alternative Site Evaluation

Modulation controls were developed for real- and reactive-power modulation at Devers and Palo Verde to compare the relative leverage of controlling this disturbance at these locations. The minimum SMES size required for a stable response with a 400-MW EOR increase above the benchmark case is given in Table 3-3.

These results indicate that reactive modulation at Blythe has excellent control leverage for damping the predominant 0.5-Hz oscillatory mode, and thus enables an increase in the stability-constrained transmission capacity. Real-power modulation at this location, however, was found to exhibit poor leverage for controlling this mode. A comparison between Blythe and alternative locations indicates that reactive-power modulation at Blythe has superior leverage to other locations and modes of modulation investigated.

Table 3-3
Modulation Location Comparison to Increase EOR Transmission 400 MW

Location	**Minimum Modulation Size for Stable Response**	
	Real Power (MW)	**Reactive Power (MVAR)**
Blythe	420	80
Devers	120	120
Palo Verde	80	120

Series Compensation Sensitivity

Because Blythe is located midway along the Palo Verde-Devers line (near the equivalent center of the swing mode), the series compensation on either end of the line could be adjusted to optimize the effective electrical location for modulation. An analysis was performed to evaluate the effect of modulation control leverage with changes to the series compensation on the Palo Verde-Devers line. The sensitivity was performed by reducing the Palo Verde-Blythe and increasing the Blythe-Devers compensation by 10% for Case A; and vice versa for Case B, as shown in Table 3-4. For each case, a 1 second power injection pulse was applied at Blythe. Prony analysis was used to compute the normalized residue of the principal mode (0.53 Hz). This gives the relative controllability for each of these cases; roughly equivalent to relative modulation control leverage. Therefore, as indicated in the table, changing the series compensation as indicated for Case A improves the modulation control leverage by roughly 250%; Case B exhibits a 150% improvement. These results indicate that substantial improvement in control leverage could be obtained by moving series compensation from the Palo Verde to the Devers end of this line.

Table 3-4
Series Compensation Sensitivity

	Baseline	Case A	Case B
Series compensation at Palo Verde	18%	8%	18%
Series compensation at Devers	21%	21%	11%
Series compensation at Blythe (Devers line)		10%	
Series compensation at Blythe (Palo Verde line)			10%
Normalized residue amplitude of the 0.53 Hz mode for a real power pulse applied at Blythe	1.00	2.53	1.47

Additional Contingencies

The following five additional disturbances were analyzed: Palo Verde-Blythe; Blythe-Devers; Moenkopi-Eldorado; Navajo-McCullough; and Westwing-Mead. As shown by Figures 3-7 through 3-11, each of the disturbances are well damped at the benchmark loading conditions, and with an additional 400 MW applied to the EOR corridor. Therefore, this analysis confirmed that the Palo Verde-North Gila outage is the most limiting contingency for this case. Thus, a SMES facility providing modulation at Blythe to increase EOR flow by 400 MW will not be stability-limited by these five additional contingencies.

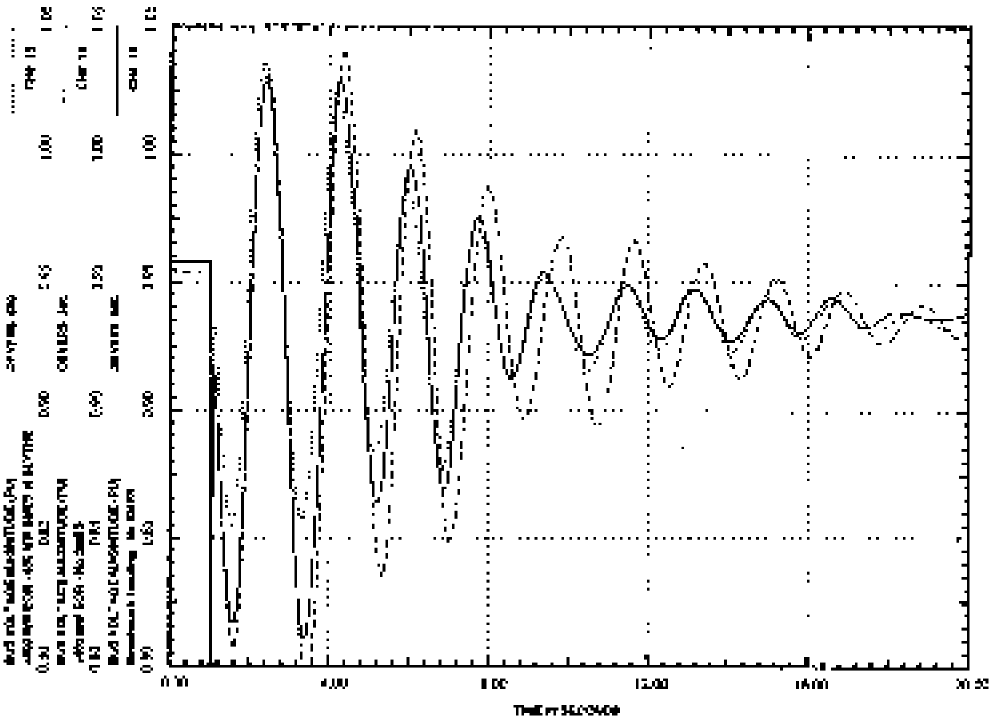

Figure 3-7 System Response to the Palo Verde-Blythe Line Outage Contingency

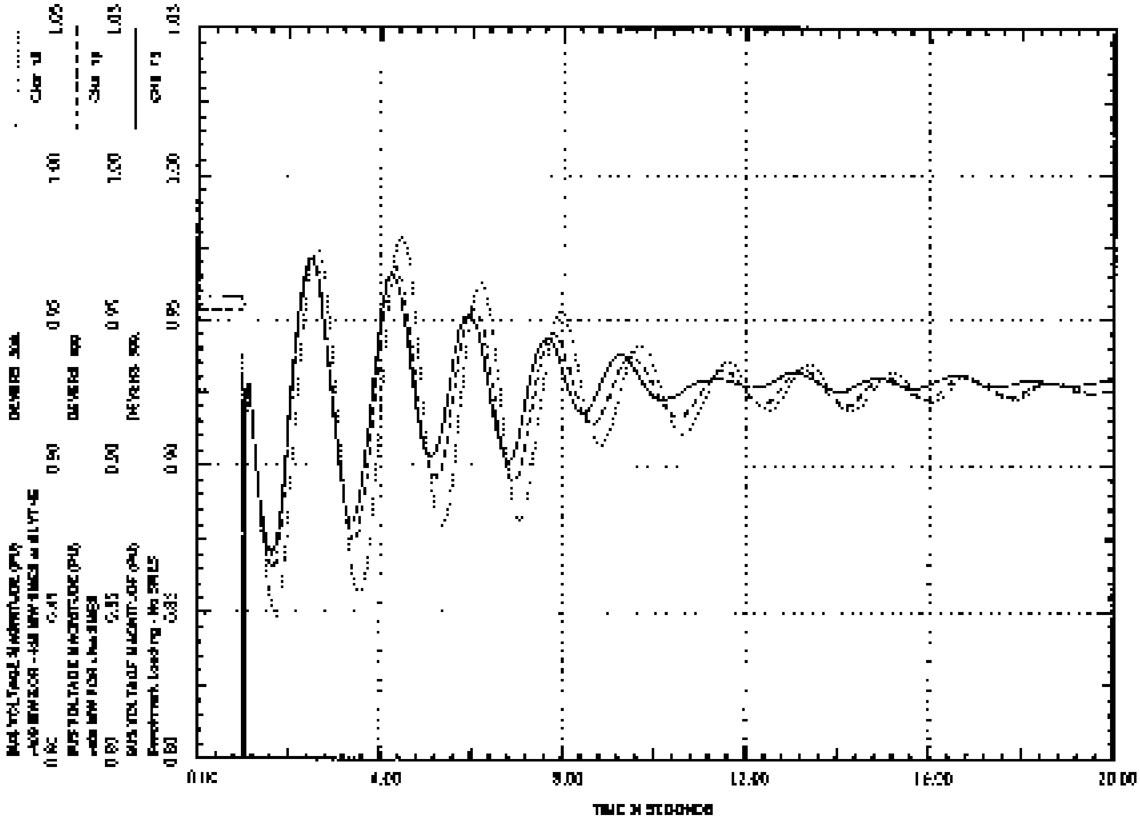

Figure 3-8 System Response to the Blythe-Devers Line Outage Contingency

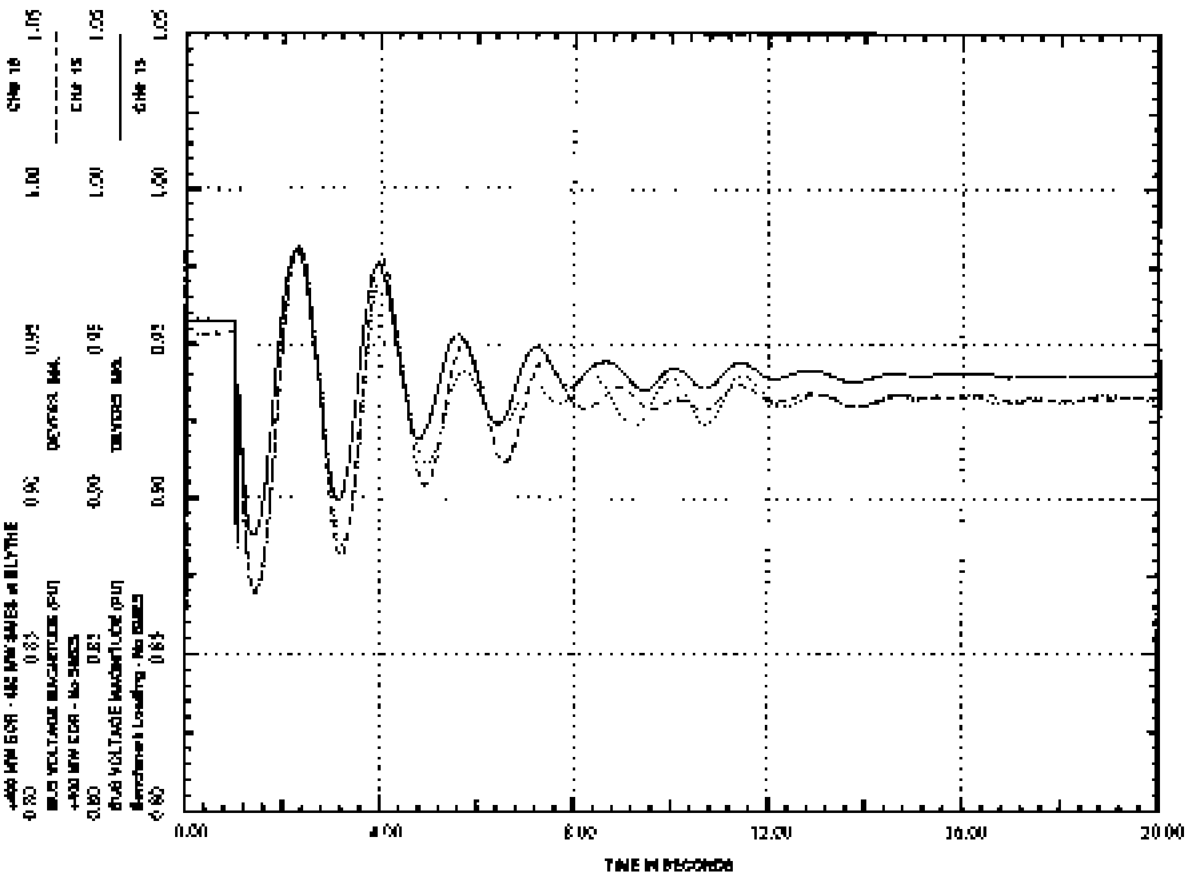

Figure 3-9 System Response to the Moenkopi-El Dorado Line Outage Contingency

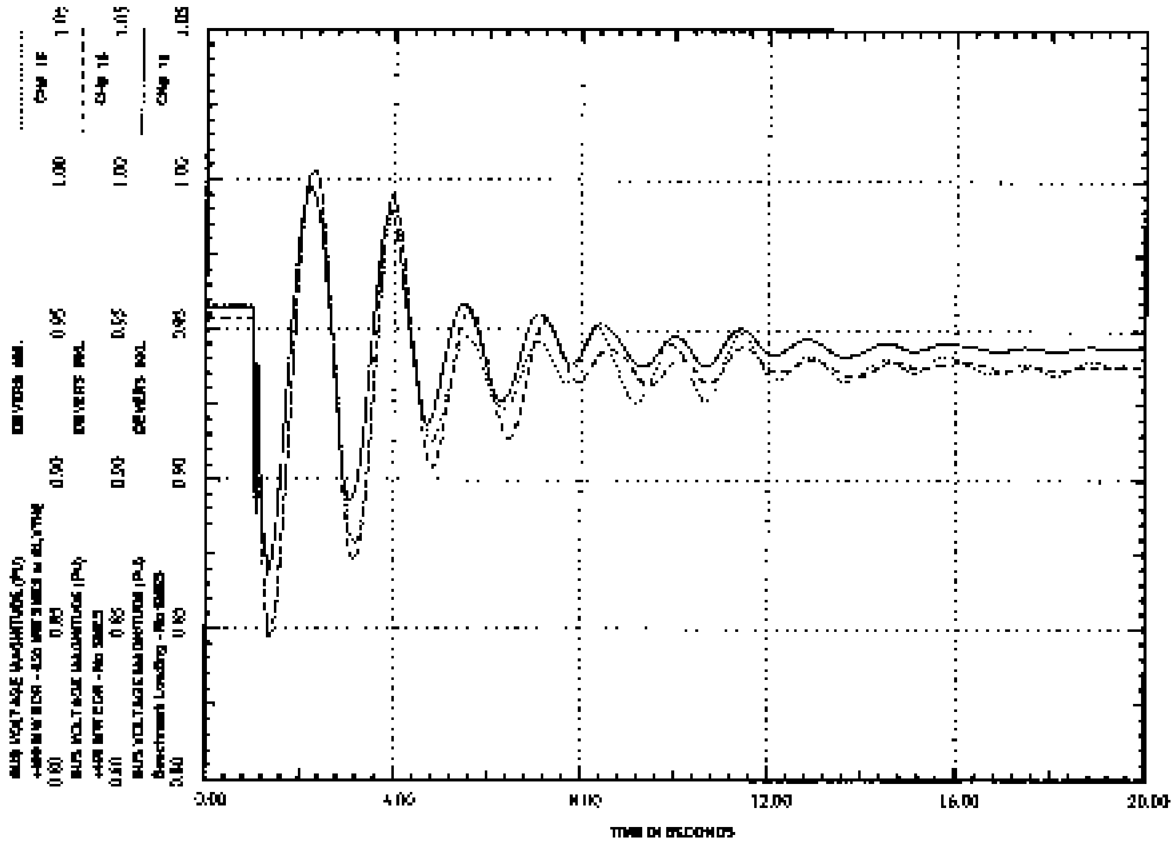

Figure 3-10 System Response to the Navajo-McCullough Line Outage Contingency

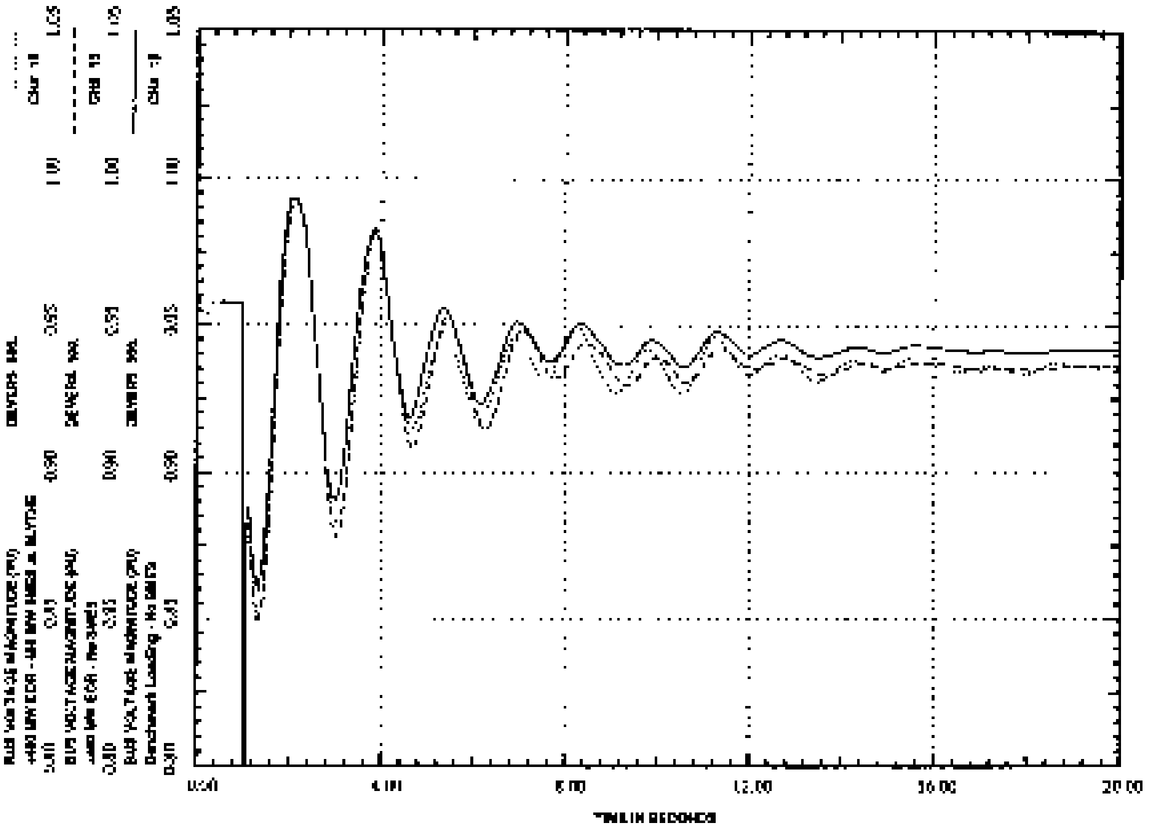

Figure 3-11 System Response to the Westwing-Mead Line Outage Contingency

SMES-Increased Import Capability with Enhanced EOR Rating

Studies performed by southwest utilities indicate that with the recent changes in the system and new thermal ratings for the series capacitors in the Moenkopi-Eldorado and Palo Verde-Devers 500-kV lines, the EOR path can accommodate an increase to 7365 MW by 1996. In this, and all subsequent sections of the report, the baseline loading of the EOR corridor is assumed to be 7365 MW without SMES.

While independent increases in EOR and WOR loadings could be used to determine the SMES-enabled increase in the SCIT Nomogram, a simultaneous increase in EOR and WOR loading is a more realistic scenario for increasing imports into Southern California. Because there is generally a fixed amount of generation resources available in the Southern Nevada area, EOR and WOR flows are closely related. For this reason, increases in EOR were evaluated by allowing EOR and WOR to be increased together, with Midway-Vincent loading reduced by a corresponding amount to maintain constant imports into Southern California (SCIT) for this set of analyses. This approach more closely resembles the present planning study methodology, and contrasts the approach taken in Phase I of the study **(reported in Section 2.4)** where increases in EOR would be offset by a decrease in WOR to hold SCIT constant.

A new benchmark case was established with the EOR lines loaded to 7365 MW. Special care was taken to ensure that none of the individual EOR lines were overloaded, which required generation rescheduling to reduce the flow on the Palo Verde-Blythe-Devers line. Another marginally-damped benchmark case, with EOR flow set at 7889 MW to account for a 7% stability margin, was established by adjusting Midway-Vincent flow in 50-MW increments (the marginal case is with the Midway-Vincent lines loaded to 1749 MW). Figure 3-12 shows the marginally-damped response of the benchmark case. Key power flows for this case are given in Appendix B. Additional work to revise the benchmark case was performed, including an updating of the dc line models, the use of more accurate line impedance parameters for the Palo Verde-Blythe and Blythe-Devers 500-kV lines, adoption of the latest version of IPFLOW (version 4), and removal of SDG&E's previously planned the Southbay repower project (500 MW), which was in the original basecase model.

Using similar methodology to that **described in Section 2.4**, several cases with line loadings in excess of the marginally-damped conditions were evaluated for both a 500 MVA and 900 MVA SMES unit providing modulation at Blythe. Both real and reactive-power modulation was evaluated, each of which requires different modulation control parameters. The results are given in Tables 3-5 and 3-6.

By evaluating the steady-state reactive output from SMES needed to support the voltage under heavily stressed conditions, it was found that substantial increases in both EOR and SCIT capacity could be obtained. For example, a case was shown to be stable with an EOR loading of 8664 MW (a 765-MW increase) and 400-MVAR pre-contingency steady-state reactive power support with 900-MVAR control modulation. Further analysis would be needed to more fully analyze strategies for combined steady-state and modulated reactive power output.

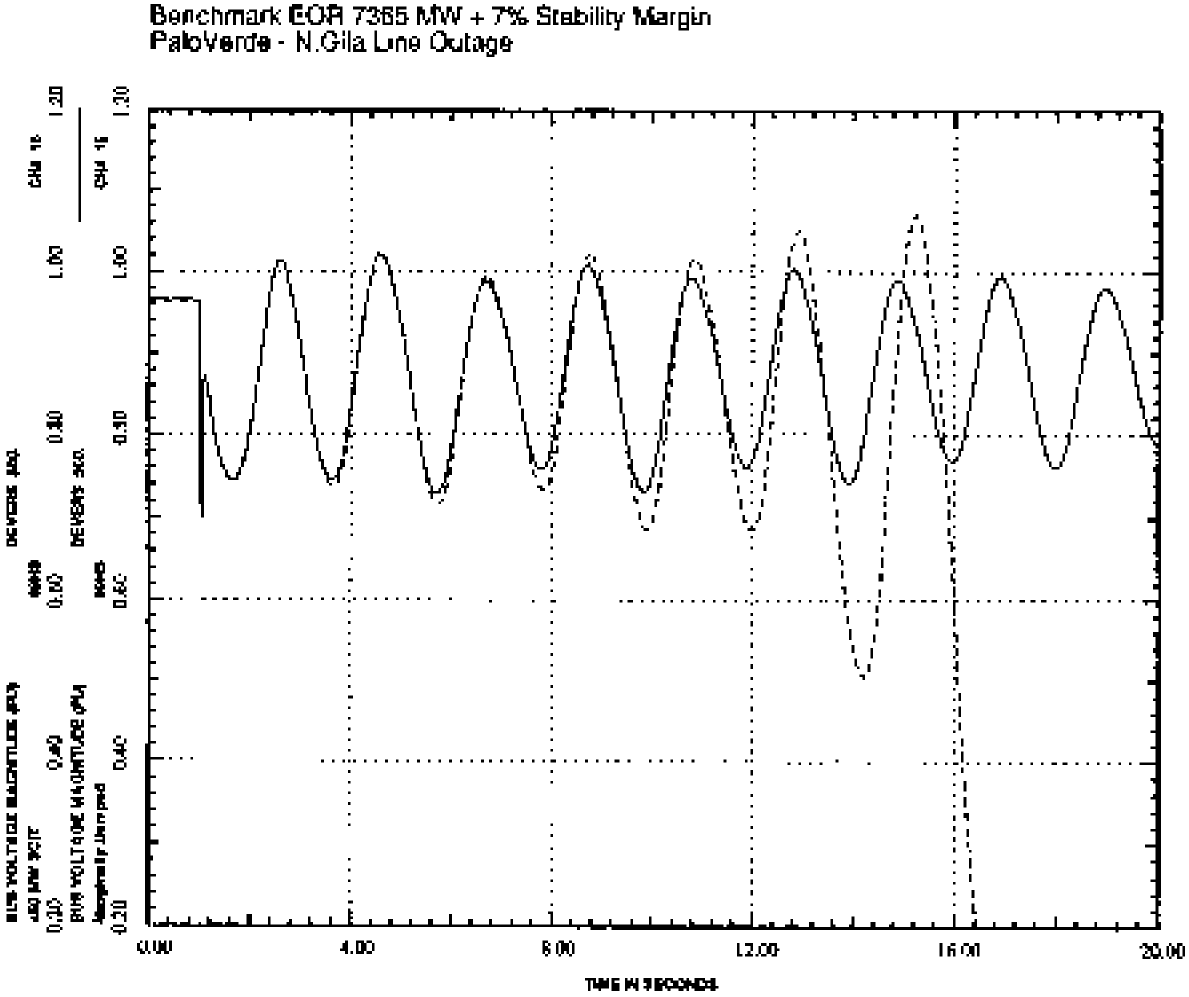

Figure 3-12 Demonstration of Marginal Damping for the Benchmark Loading Conditions

Table 3-5
Increasing the Non-Simultaneous Arizona-California Limit

SMES Converter Rating Located at Blythe	EOR Increase (MW)	
	Real-Power Modulation	Reactive-Power Modulation
500 MVA	300	> 511[1]
900 MVA	407	> 511[1]

Table 3-6
Increasing the Southern California Simultaneous Limit

SMES Converter Rating Located at Blythe	SCIT Increase (MW)	
	Real-Power Modulation	Reactive-Power Modulation
500 MVA	645	> 882[1]
900 MVA	829	> 882[1]

---

[1] When either the EOR corridor is loaded beyond 8400 MW (an increase in EOR of about 500 MW beyond the benchmark case stability limit) or Midway-Vincent greater than 2631 MW (an increase in SCIT of 882), the benchmark case fails to converge in the power flow solution. This is why upper-bounds for the reactive-modulation cases in these tables were not identified. This appears to be primarily due to poor voltage support in the region, which may be an artifact of the model used in this study or program solution.

Combined Real and Reactive-Power Modulation

As shown above, SMES can enhance increased power transfer capability by providing both real- and reactive-power modulation. This section describes an investigation to optimize simultaneous real- and reactive-power modulation.

The modulation of SMES real and reactive power to provide 400 MW of increased power transfer capability for the benchmark model was evaluated. The modulation cases evaluated included P only, Q only and P-Q combinations corresponding to SMES power angles of 30°, 45° and 60°. The controls were returned to optimize their simultaneous operation by performing a real-power pulse injection test with the reactive modulation controller active (closed-loop). Prony analysis and linear design techniques were then used to develop feedback compensation parameters.

The results of combined real- and reactive-power modulation are given in Table 3-7. A converter architecture is assumed where the relative real and reactive power capacity, or combinations thereof, are defined by a circle in the P/Q plane with the radius equal to the converter MVA rating. These results indicate that for the cases considered, a 60° P/Q angle provides the optimal control leverage, with a 1.33 MW increase in EOR loading per MVA of SMES available to provide modulation.

Table 3-7
Minimum SMES to Achieve 400 MW Increase in EOR Loading with Combined Real and Reactive-Power Modulation

Angle (Degrees)	**Relative P (MW/MVA)**	**Relative Q (MVAR/MVA)**	**Minimum SMES Rating Required (MVA)**
0	1.000	0.000	900
30	0.866	0.500	400
45	0.707	0.707	350
60	0.500	0.866	300
90	0.000	1.000	350

Reduced SMES Output Time

The impact of reducing the PCS power delivery time duration requirement to 10 seconds was investigated. The case with an additional 400-MW EOR was evaluated with the 60° P-Q modulation controls. When the 300-MVA modulation was turned off after 10 seconds, the system became unstable. However, with a 350-MVA modulation controller applied, the system remained marginally stable after the modulation controller had been turned off. These results are shown in Figure 3-13. Further engineering evaluation is required to determine the reduced energy storage requirements, potential cost savings and benefit trade offs by reducing the output time of the modulation controls.

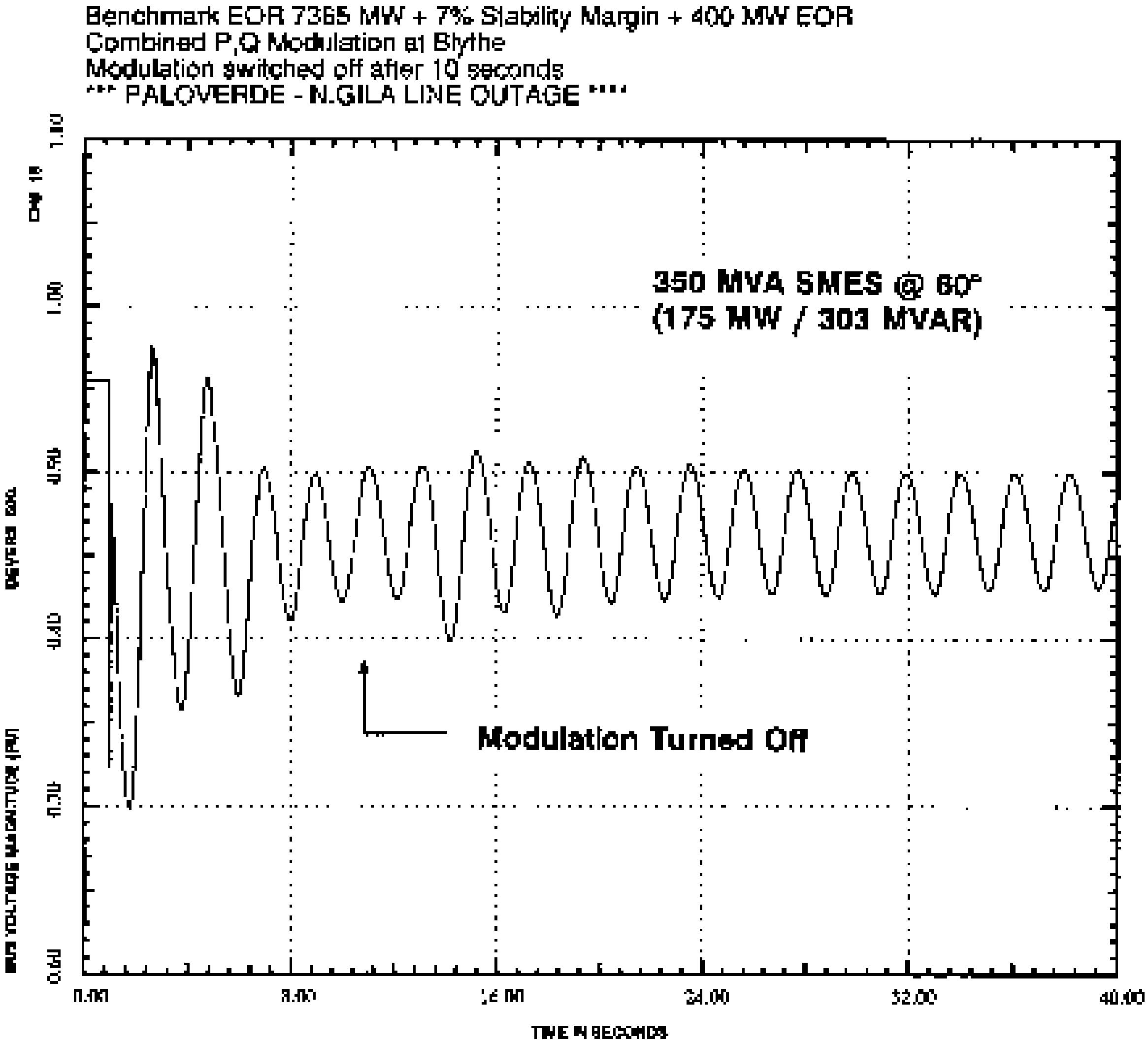

Figure 3-13 Impact of Switching Off Modulation Controls After 10 Seconds

4

OTHER BENEFITS OF SMES AT BLYTHE

The combined value of all benefits expected to accrue from a single SMES installation should be considered. The other benefits of a SMES facility located at Blythe evaluated in this study include voltage control, damping of subsynchronous resonance (SSR), tie-line control, spinning reserve, load-leveling, and underfrequency load-shedding.

Voltage Control

Voltage drop was assessed for several contingencies with EOR flow set to 7665 MW, a 300-MW increase over the 7365-MW baseline enabled by SMES modulation at Blythe (see Section 2). Based on guidance received from SDG&E planning staff, some modifications were made to out-of-date generation profiles and reactive power support contained in the planning model for this task.

The following single line outages were analyzed with two San Onofre units on-line:

- Imperial Valley-Miguel 500 kV and Imperial Valley-La Rosita 230 kV
- Blythe-Devers 500 kV
- Palo Verde-Blythe 500 kV
- Valley-Serrano 500 kV
- Moenkopi-Eldorado 500 kV
- Palo Verde-North Gila 500 kV
- Mira Loma-Lugo 500 kV #1 and #2
- Liberty-Mead 345 kV and Westwing-Mead 500 kV
- Marketplace-Adelanto 500 kV and McCullough-Victorville 500 kV

The following double line outages were analyzed with only one San Onofre unit on-line:

- Lugo-Serrano 500 kV and Mira Loma-Serrano 500 kV
- Imperial Valley-Miguel 500 kV and Imperial Valley-La Rosita 230 kV
- Ellis-Johanna 230 kV and Ellis-Santiago 230 kV

The percent voltage drop at select buses are shown in Table 4-1 for each of the contingencies listed above. Some of these contingencies led to voltage stability problems in the Southern California area when corrective operator action was not modeled. This was compensated with unscheduled reactive power dispatch at the Adelanto 500-kV bus to maintain a specified voltage (not less than 0.95 per-unit voltage). The Adelanto bus was chosen as a proxy and is not intended to indicate any preference in regard to support for voltage stability. The voltage, which resulted in the minimum unscheduled reactive-power dispatch, in some cases was greater than 0.95 per-unit. This process is similar to developing nose curves in voltage stability studies.

The limiting contingency for this planning model was determined to be the Imperial Valley - Miguel 500 kV and Imperial Valley - La Rosita 230 kV contingency with one San Onofre unit off-line. This case exhibited the most severe post-contingency voltages (largest voltage drops), and also required the greatest amount of unscheduled reactive power at the Adelanto 500-kV bus. Although none of the critical 230-kV buses monitored for each of the contingencies (as given in the previously indicated table) violate the 10% voltage deviation criterion, three buses in the Imperial Irrigation District (IID) area exceeded a 10% voltage drop for this contingency (Table4-2). It was found that 300-MVAR (in 50-MVAR) increments reactive-power support at Blythe is needed to satisfy the 10% voltage deviation criteria for these buses. The value of providing steady-state reactive power is approximately $25/kVAR (based on equivalent capacitor cost). Therefore, providing 300 MVAR at Blythe under the contingencies analyzed provides a benefit of about $325,000 for supporting voltage in the IID area.

A far greater voltage support benefit of SMES appears to be associated with augmenting voltage stability. Blythe was found to be an effective location to offset reactive power that would otherwise be required to support voltages in Southern California. In the limiting contingency, the loss of the Imperial Valley-Miguel and Imperial Valley-La Rosita lines with one San Onofre unit off-line, 300 MVAR of SMES reactive support at Blythe was found to enable a 278 MVAR reduction in unscheduled reactive power, which would otherwise be needed, a roughly 1:1 correlation. Therefore, an upper-bound for the voltage support benefit appears to be $25/kVAR benefit based on a nameplate SMES rating of 500 MVA, which is $12.5 million. Further analysis of this voltage collapse benefit is required, which was beyond the scope of this study.

Table 4-1
Two San Onofre Units On-Line

Critical 230 kV Bus Voltage Deviations (Percent)

Contingency	Imperial Valley	Miguel	Serrano	Chino	Devers	Lugo	Mead	Westwing
Baseline voltage magnitude (per unit)	1.006	.993	.976	.947	.948	.952	.996	1.018
Imperial Valley-Miguel Imperial Valley-LaRosita	2	-1	-5	-6	-10	-5	-4	-1
Blythe-Devers	-4	-2	-4	-5	-6	-5	-5	-1
Palo Verde-Blythe	-4	-2	-3	-4	-2	-4	-5	-1
Valley-Serrano	0	0	0	0	-3	0	0	0
Moenkopi-El Dorado	-1	0	0	0	-2	0	-1	-1
Palo Verde-North Gila	2	2	-4	-5	-9	-4	-4	-2
Mira Loma-Lugo #1, #2	-1	-1	-5	-7	-8	-2	-1	-1
Liberty-Mead Westwing-Mead	-1	-1	0	0	-2	0	-1	1
Marketplace-Adelanto McCullough-Victorville	-2	-1	-5	-6	-7	-7	-5	-2

Table 4-2
One San Onofre Unit On-Line

Critical 230 kV Bus Voltage Deviations (Percent)

Contingency	Imperial Valley	Miguel	Serrano	Chino	Devers	Lugo	Mead	Westwing
Baseline voltage magnitude (per unit)	1.002	.989	.975	.945	.948	.954	.998	1.018
Lugo-Serrano Mira Loma-Serrano	0	0	-3	-3	-4	-1	0	0
Imperial Valley-Miguel Imperial Valley-LaRosita	2	-1	-6	-7	-10	-4	-3	0
Ellis-Johanna Ellis-Santiago	-1	0	0	0	0	0	0	0

SSR Damping

This task addressed the potential benefits of SMES-1 as a mitigation device for Palo Verde related SSR with increased series compensation levels on the Palo Verde West 500 kV lines. Under current network topologies, SSR in the form of torsional interaction is a potential problem at one modal frequency while one or more units are lightly loaded at Palo Verde (Farmer 1988). Arizona Public Service has employed a protection scheme with type SSO relays on the Palo Verde units and operating procedures bypassing the capcitor bank at North Gila when loading falls below 200 MW on any Palo Verde unit.

Table 4-3
SMES Reactive Support to Maintain Voltage Deviation Within Ten Percent

	Critical Bus Voltage Deviation (Percent)		
Reactive Support Added at Blythe (MVAR)	**"AVE" 43" 92-kV Bus**	**"AVE 58" 92-kV Bus**	**"AVE 58" 161-kV Bus**
0	-11.3	-12.1	-10.5
50	-10.6	-11.6	-10.1
100	-10.0	-11.2	-9.8
150	-9.5	-10.9	
200		-10.5	
250		-10.2	
300		-9.9	

NOTE: The 10% voltage criterion can be met adding 5 MVAR and 8 MVAR shunt reactive support to the "AVE 42" and "AVE 58" 92-kV buses, respectively.

Prudence dictates that SSR protection countermeasures (for example, type SSO relays) be employed on susceptible generators regardless of whether various other countermeasures exist. The protection scheme should be coordinated with other countermeasures to provide a comprehensive SSR solution. For this reason, protection issues are not considered in the cost/benefit comparison. System modifications, supplementary generator controls, and filtering are considered alternatives to using SMES for SSR mitigation.

Shunt-connected SSR damping devices are well documented in the literature. SMES devices fall into this category. The third supplement to the IEEE SSR bibliography alone lists ten citations on various aspects of relationships between shunt-connected devices and turbo-generator SSR (IEEE 1991a). Many additional references exist in the IEEE bibliography, the first and second supplements to the bibliography, and valuable work subsequent to the third supplement. The bulk of the literature related to shunt-connected devices centers around SVC installations, but the only shunt-connected damping device known to have been employed for SSR mitigation is the Dynamic Stabilizer (Ramey et al. 1981).

Other electrical network modifications known to have been employed for SSR mitigation are blocking filters (IEEE 1992) and series devices designed to change the electrical behavior of the series capacitor itself (Hauer et al. 1995; Hingorani et al. 1987).

For the purpose of this study, it is appropriate to separate SSR countermeasures into two groups. The first group uses control strategies that can be called *passive* with respect to feedback of the basic modal SSR frequencies. The second group utilizes controllers that are *active* in the SSR modal frequency range. Devices in the two groups can be easily distinguished by observing modulation characteristics. Active devices modulate real or reactive power, or both, at SSR modal frequencies.

The aforementioned shunt devices (SVC, SMES, Dynamic Stabilizer, Braking Resistor) are active devices. Supplemental Excitation Damper Control (SEDC) is also an active device and has been suggested as an SSR countermeasure for Palo Verde (Farmer 1988). Blocking filters, NGH, TCSC, and turbine-generator (T-G) mechanical system modifications represent most of the practical passive SSR countermeasures. Passive countermeasures attempt to de-tune either the electrical network or the T-G system away from simultaneous resonance. For example, the TCSC firing control algorithm is designed to make the device appear as a short-circuit at SSR modal frequencies, yet highly capacitive at 60 Hz.

The distinction between active and passive devices is an important one in assessing the cost/benefit of a SMES on the Palo Verde-Devers line at Blythe. Active devices generally require more complexity in the controller software and are less immune to system uncertainties and ambiguities. Furthermore, failure of an active device can potentially leave the system in a state with high levels of energy present at an SSR resonance frequency. Passive devices are considered to have a higher inherent safety factor, which is reflected in the overall cost of the mitigation strategy.

It is assumed in this study that it may be desirable to increase the effective level of series compensation on the Palo Verde-Devers and Palo Verde - Miguel 500 kV lines to facilitate higher power flows. Comprehensive SSR studies, similar to those reported by Farmer (1988), must be completed when considering the capacitor upgrade, and it is likely that these studies will indicate an increased severity of SSR problems at Palo Verde. As was indicated above, the preponderance of literature suggests that a shunt device capable of modulating real or reactive power, such as SMES, could be made to be an effective SSR countermeasure in this case. Were the series compensation upgrade to take place without a SMES unit installed at Blythe, a variety of SSR countermeasures would be considered to mitigate the increased potential for SSR. Table 3.3 gives the approximate cost of selected devices for SSR mitigation for this case.

The benefit assigned to SMES for SSR mitigation can be argued to be the value of the least-cost alternative. The major source for error in this approach is the assumption, as described above, that protective and operational countermeasures used to compliment the primary mitigation device are equal in cost from among the choices. This may not be the case. However, based on this review, the SSR mitigation benefit assigned to SMES at Blythe as a conservative estimate is approximately $2 million, which is the cost of Supplemental Excitation Damper Control on the Palo Verde generators.

Because SEDC and SMES are both active devices, the calculated benefit does not involve errors associated with costing the active versus passive safety margin. This value of the safety margin was listed as $1 million. If ongoing studies show that series-connected SMES is a feasible option in this application, such a unit can be controlled with an SSR passive algorithm and the resulting SMES unit would be classified as a passive device with respect to SSR. Furthermore, such a device would be capable of supplying reactive power through the series connection, effectively turning the series-connected SMES into an equivalent series capacitor. In this case, a credit can be taken for the least-cost SSR countermeasure (SEDC @ $2M) plus the cost of capacitor upgrades ($5M) because SMES would also provide the series compensation. This scenario does not change the SSR benefit at $2 million, but it replaces the fixed series capacitor upgrade on the Palo Verde-Devers line.

Tie-Line Control

Automatic generator control (AGC) is a strategy to provide sufficient generation to meet the total load on a system in an economically optimum fashion. Units are committed to provide sufficient capacity and reserve margin to meet the load requirements. Economic dispatch is achieved by loading all of the plants such that the incremental variable cost of producing energy is minimized system-wide, a function of the heat rate, fuel cost, transmission losses, and variable operations and maintenance (O&M). Another important function of AGC is maintaining frequency and minimizing inadvertent energy transfers with neighboring power systems. AGC is performed by controlling the reference power settings of select generators to minimize the area control error (ACE). The ACE is computed from a combination of area frequency deviation and inadvertent tie-line flow at the area boundary.

The efficient utilization of generation resources can be significantly hindered because of constraints imposed by AGC, forcing the allocation of resources to deviate from the pure least-cost economic dispatch (Henderson et al. 1990). In some instances, this cost can be as high as thousands of dollars per hour when generators do not operate at their optimal economic loading because of the need to reserve a capacity margin for AGC.

Table 4-4
SSR Mitigation Devices

SSR Mitigation Devices	Base Cost ($M)	Cost of Additional Safety Controls ($M)[1]	Series Capacitance Cost ($M)[2]
Active Devices:			
SVC (300 MVAR)	30	0	0
Dynamic Stabilizer	25	0	0
Braking Resistor	6	0	0
SEDC	2	0	0
Passive Devices:			
Blocking Filters	18	-1	0
NGH	6	-1	0
TCSC	10	-1	-5

A SMES device could be used to relieve the burden of AGC requirements by pre-conditioning the ACE signal, allowing the units to extend their operating limits if necessary to operate at more optimal loading points. The continuous variation of the generator controls on AGC causes more wear and tear on governors, throttle valves, and prime movers. In addition to the benefit of releasing AGC capacity for economic dispatch, the reduced maintenance that would be required if the ACE were smoothed to eliminate the rapid response peaks is another important benefit SMES could provide.

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[1] "Cost of Additional Safety Controls" reflects the costs associated with protecting and operating a system reliant upon active SSR countermeasures as opposed to protecting and operating a system with passive SSR countermeasures. Since the reference countermeasure is a shunt SMES (an active device), costs associated with active devices are fixed at zero and the passive devices are discounted.

[2] "Cost of Series Capacitance" is the estimated cost of series capacitor upgrades on the Palo Verde-Devers Line. The TCSC is discounted by this fixed amount in order to make an equitable cost comparison between a shunt SMES and TCSC.

The SMES system would be used to respond to rapid power swings, while the remaining generators on control would respond to slower load variations.

Tie-line variations on SDG&E's system are subjected to almost constant variations of 20 MW. These spikes are brief, usually lasting no more than a few seconds, as the generator control settings are adjusted to meet the changing demand requirements. Between 0.5 and 2 MWh of SMES capacity was found sufficient to remove these spikes from the SDG&E tie-line variations for the period studied (about 1 hour).

A 30-MW regulation margin is required to provide sufficient tie-line and frequency control for the SDG&E system. By providing 30 MW of SMES capacity to satisfy the regulating margin requirement, 30 MW of generation capacity can be released for economic dispatch. An energy storage capacity of approximately 5 MWh is anticipated to be needed to provide this function (10-minute nominal capacity), although the actual energy storage requirement could be less based on actual operating practices. A rough order-of-magnitude estimate of this benefit is about $2.5 million annually, based on an average incremental cost difference of $10/MWh, which can be gained by releasing the regulation margin.

Spinning Reserve

The objective of this task was to estimate the ability of SMES-1 or a larger SMES unit to provide spinning reserve benefits on the SDG&E and/or SCE systems. A rigorous analysis of the spinning reserve benefit can only be provided by a chronological production cost model, such as EPRI's DYNASTORE code. This tool estimates the production cost savings achieved by the economic commitment and dispatch of SMES in combination with the generating resources on the system. The code computes the production cost savings and spinning reserve benefits of energy storage on an hour-by-hour basis. A rigorous assessment of these benefits cannot be duplicated by simple scaling.

Because in-depth computer modeling and analysis was not in the study scope, the following simple scaling assessment was undertaken to indicate the order-of-magnitude value of SMES spinning reserve benefits. The results of SMES analysis performed for Bonneville Power Administration (BPA) and the Public Service Company of New Mexico (PNM) were used as reference bases for this cursory assessment (De Steese et al. 1992; De Steese and Dagle 1994).

The California Power Pool spinning reserve entitlement is equal to 7% of the estimated or actual peak load on the system. From information supplied by SDG&E, the total peak planning load ranges from 3549 MW in the year 2000 to 4764 MW in 2013. The corresponding spinning reserve requirements are 248 MW and 333 MW, respectively. At these power levels, the nominal 1-MWh capacity of SMES-1 would satisfy the full system spinning reserve requirement for only 10 to 15 seconds. The 1-MWh capacity of SMES-1 could nominally provide 20 MW of spinning reserve for 3 minutes and conversely, 3 MW for 20 minutes.

An average cost saving of $66 would accrue for each additional hour of operation. Assuming four hours operation, five days a week, the annual value of savings determined on this basis would be about $68,000.

SMES units with larger storage capacity than SMES-1 were shown to provide significant spinning reserve benefits in both the BPA and PNM studies. The range of CT unit sizes in SDG&E's resource portfolio indicates that a SMES device rated between 16 and 26 MW with 1-hour storage capacity would provide a more significant spinning reserve benefit. While SMES could release the equivalent capacity of any unit from spinning reserve, the value of SMES would tend to be maximized when it is substituted for CT capacity. SMES in the 16- to 26-MW power range was credited with CT first hour start-up and operating cost savings between $917 and $1073 (referenced to costs of EAGT1 and NSGT1, respectively) together with cost savings between $500 and $612 for each additional hour of operation. As before, assuming four hours operation, five days a week, the annual value of savings determined on this basis would range from $594K to $756K.

A 150-MW, 1-hour SMES unit would be primarily a load-leveling device. Economic dispatch of such a unit would include optimizing its spinning reserve benefit. Estimating the spinning reserve benefit of this unit on the same basis as above (i.e., crediting SMES with avoided costs of operating equivalent CT capacity according to the SDG&E start priority list), indicates daily and annual savings of $20.5K and $5.34 million, respectively.

In Table 4-5, the present value (at the time of commissioning in 1994 dollars) of the annual spinning reserve benefits estimated above are expressed as a percentage of the sum of SMES capital costs and the present value of SMES O&M costs. Credit for the capital cost of the thermal plant deferred by SMES is not shown in Table 4-6 but, instead, is associated with the load-leveling benefit assessed in the Energy Storage for Load-Leveling section. **SMES capital and O&M costs, respectively, are taken from Equation 4.3 (page 4-17) and Figure 6.6-1 (Page 6-13) in the EPRI report "SMES Plant Costs: EPRI Estimate" (TR 103717**). Additional assumptions are a SMES plant life of 30 years and the SDG&E real discount rate is 6% (after inflation). With these assumptions, the present value multiplier is 13.76 times annual values.

Table 4-5
Comparison of Spinning Reserve Benefits and SMES Capital and O&M Costs

SMES Unit Capacity (MW/MWh)	Present Value ($M)			
	Spinning Reserve Benefit	Capital Cost	O&M Cost	Ratio of Spinning Reserve Benefit to Total Cost
16	8.2	60.9	6.9	0.12
26	10.4	73.5	8.9	0.13
150	73.5	178.607	19.3	0.37

A similar comparison using results of the PNM study show production cost saving from economic dispatch representing 43% and 49% for an 200 MW/1-hr and a 100-MW/1-hr SMES unit, respectively. The PNM results were gained using DYNASTORE and include spinning reserve and load-leveling benefits. In some cases the spinning reserve contribution may be the dominant benefit of the two. The 37% benefit/cost value shown in Table 3.4 for the 150-MW unit is comparable to the PNM study results and suggests that the approximating method used in the above analysis provides reasonable, order-of-magnitude estimates.

Energy Storage for Load-Leveling

The potential load-leveling benefit of SMES-1 (i.e., storing energy off-peak and returning energy and capacity on-peak) was assessed together with the long-term benefits of SMES with larger energy storage capacities. This benefit is realized when SMES gains credit for both converting low-cost energy into higher-value energy and its ability to defer the acquisition of high-cost generating resources. A simple basis for estimating the value of diurnal energy storage is to consider that SMES converts the value of energy from its off-peak to on-peak worth in one charge/discharge cycle per day. The value of off-peak energy was assumed to be 4 mill/kWh when discharged during peak periods.

With a nominal 1-MWh capacity, SMES-1 is considered too small to be credited with the ability to defer thermal plant acquisitions. Therefore, the nominal increase in value of the energy stored during each charge/discharge cycle is the principal load-leveling benefit .

Based on one cycle per day, five days a week, the annual load-leveling benefit of SMES-1 is $1,040 with a life-time present value of $14,300, ignoring round-trip energy losses. Thus, compared with other benefits of SMES-1, the load-leveling benefit is shown to be quite insignificant.

In both the BPA and PNM studies, cases where evaluated showing SMES has a large net present worth when it can replace the need to acquire combustion turbine units of similar capacity. The substitution of SMES for a planned CT acquisition has been validated by analysis using DYNASTORE in the BPA and PNM studies. Extrapolating from this experience suggests that SDG&E may benefit from installing 150 MW of SMES capacity in 2006 instead of the planned addition of a 150-MW GE Frame 7F GT.

For estimating purposes, a MW-for-MW substitution was assumed for the peaking capacity supplied by SMES. The SMES unit gains a $75 million credit (estimated at $500/kW) for the deferred capital cost of the 150-MW CT it replaces. This estimate may be conservative, however, as indicated in the PNM study, where a 100-MW SMES unit deferred acquisition of two CT's with a combined dispatchable power rating of 132 MW. By deferring O&M costs of the CT valued at $28/kW-yr, SMES gains additional credit of $4.2 million/yr with a present value of $57.8 million over the life of the unit.

A general indication of the BPA and PNM studies is that SMES units with a nominal 1-hour capacity are optimal. The energy dispatched by a 150-MW/1-hour device would be 150 MWh reduced by the SMES round trip efficiency of 0.95. The resulting increase in energy value is $570/cycle. If, as assumed above, SMES is dispatched in this manner 260 days per year, the annual benefit would be $148 thousand with a present value of $2.04 million over a 30-year SMES life. This benefit would be in addition to the spinning reserve benefit estimated in the Energy Storage for Load Leveling section. Load-leveling benefits and costs are summarized in Table 4-6. A 20-MWh unit was assessed similarly and added for comparison. The deferred thermal capacity capital savings provided by the 20-MWh unit were estimated at $715/kW. A similar opportunity could be realized by installing a second SMES unit to defer a 150-MW CT acquisition in 2010.

With the addition of spinning reserve benefit estimated at about $9 million, the cost of the 20-MW SMES unit still exceeds the value of benefits by a large margin. In contrast, when benefits are totaled for the 150-MW case, including spinning reserve, load-leveling, and the deferral of thermal plant capital and O&M, total benefit present value ($208 million) exceeds the present value of SMES costs ($198 million) by $10 million. A similar opportunity could be realized by installing a second SMES unit to defer a 150-MW CT acquisition in 2010.

Table 4-6
Comparison of SMES Load-Leveling Benefits and Capital and O&M Costs

Present Value of Benefits ($M)	**20 MW/20 Mwh SMES**	**150 MW/150 MWh SMES**
Load-leveling energy value added	0.3	2.0
Deferred thermal capacity capital cost savings	14.3	75.0
Displaced thermal capacity annual O&M cost savings	7.7	57.8
Total Benefits	**22.3**	**134.9**
Present Value of Costs ($M)	**20 MW/20 MwWh SMES**	**150 MW/150 Mwh SMES**
Capital construction	66.2	178.6
Annual O&M	8.3	19.3
Total Costs	**74.5**	**197.9**

In the PNM study, benefits provided by 1-hour SMES units ranging in power between 100 MW and 400 MW indicate, by interpolation, that a 150-MW SMES unit would enable production cost and thermal plant deferral benefits of about $200 million. In the present study, the equivalent benefits provided by a unit of this size are approximately $208 million. Thus, while the above results are in good agreement from an order-of-magnitude perspective, they should be confirmed by analysis using a production cost model.

Underfrequency Load-Shedding

The double line loss south of Table Mountain with NE/SE separation was simulated. This case represents false tripping of the islanding scheme, and although the probability is low, it gives an estimate of the SMES benefit for an underfrequency condition. The simulated contingency caused underfrequency load-shedding of 3892 MW to occur. A steady-state, 500-MW SMES power step injected 0.5 seconds after fault inception provides a basis for evaluating the SMES-enabled load-shedding reduction potential. The total system load-shedding in this case is reduced to 3637 MW, a reduction of approximately 250 MW.

Real power injection is an effective method to offset underfrequency load-shedding because it reduces the mismatch between load and supply capability of the system after the disturbance. An evaluation of the modulation controls developed for the transmission enhancement aspects of this study was performed to determine if additional load-shedding reduction could be obtained. For this case, no reduction in load-shedding was observed. However, additional load- shedding is anticipated with a controller specifically tuned for this disturbance. It is estimated that SMES-1 with an appropriately designed control algorithm could provide a 500 MW load-shedding reduction for this or similar types of contingencies. Estimates of underfrequency load-shedding benefits for SMES-1 located at Blythe are given in Table 4-7.

Table 4-7
Underfrequency Load Shedding Benefit of SMES-1

	Lower Bound	**Upper Bound**
Estimated cost of underfrequency load shedding[1]	$8.02/kW	$11.34/kW
Load shedding reduction potential[2]	250 MW	500 MW
Benefit per occurrence	$2.0 million	$5.7 million
Average time between occurrences[3]	10 years	5 years
Present value of Benefit[4]	$2.8 million	$16.0 million

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[1] A value of $4.69/kW plus $6.65/Kwh is indicated as the average cost of a service interruption of all industrial plants in the IEEE Gold Book (IEEE 1991b). The lower-bound estimate uses an average outage duration of 30 minutes while the upper bound assumes one hour outages.

[2] The observed reduction in load shedding from simulated step-response power injection at Blythe gives the basis for the lower-bound estimate. The upper-bound reduction could be obtained from SMES controls optimized to reduce load shedding.

[3] Average time between contingencies of a similar nature where significant underfrequency load shedding occurs. This lower bound represents a conservative estimate based on historical data.

[4] Present value = (Benefit per occurrence) $\sum (1+ i)^{-n}$ For $n = T/2, 3T/2, 5T/2, \ldots, n \leq 30$
where i = real discount rate T = average period between occurrences (years)

5

ECONOMIC SUMMARY

The total benefit value of SMES at Blythe can be estimated by combining the benefits evaluated in **Sections 2 and 3**. For the purposes of this study, the benefit value of SMES-enabled transmission enhancement (increased Arizona - California transfer capability) was assumed to be $10,000/MW-year (based on SDG&E production cost analysis). This value, recommended by SDG&E, represents the annual worth of adding transmission capacity to the EOR system for increased economy purchases. It may also be interpreted as potential revenue gained from power sales enabled by SMES at times when the transmission system would be otherwise constrained. This assumption is also conservative (i.e., tends to under-value SMES) when considered in the emerging arena of utility restructuring, and the potential increase in retail wheeling and power marketing. All of these trends may increase the utilization and, hence, the value of a SMES-enabled transmission capability.

Table 5.1 summarizes SMES-1 benefits at Blythe evaluated in terms of their unit value and present value. As reported in previous sections, some benefits are estimated as a range between upper and lower bounds. The lower bound of transmission enhancement is 500 MW. This is based on analytical results showing a 1 MW/MVAR control leverage provided by 500 MVAR of SMES reactive-power modulation at Blythe. The corresponding upper bound is 667 MW provided by leverage increased to 1.33 MW/MVA (see Section 2.6) by combining real- and reactive-power modulation. The unit value of the transmission benefit has a range from $5 million to $6.7 million annually. The present worth of this and other annual or intermittent benefits are estimated on the basis of a 6% real discount rate and 30-year equipment life. The tie-line control value is scaled proportionally to SMES storage capacity from the $2.5 million annual value estimated in **Section 3.3** for a 5-MWh device.

Table 5-1
Summary of SMES-1 (500 MVA, 1 MWh) Benefits at Blythe

Benefit	Unit Value ($M)	Present Value ($M)
Transmission Enhancement/yr	5 - 6.7	69 - 92
Voltage Control (capital)	0.3 - 12.5	0.3 - 12.5
SSR Damping (capital)	2 - 7	2 - 7
Tie Line Control/yr	0.5	6.9
Spinning Reserve/yr	0.07	0.94
Load Leveling/yr	0.001	0.014
Underfrequency Load Shedding/occurrence	2 - 5.7	2.8 - 16
TOTAL		**82-135**

Summing benefit values shown in Table 5-1 indicates that the estimated present value of SMES at Blythe is between $82 million and $135 million. The lower and most conservative bound of this range is equal to the $82-million capital cost of a first-of-a-kind SMES-1 unit estimated by Bechtel in correspondence with SDG&E; twice the $41 million cost estimated for an nth-of-a-kind device. The upper bound of total benefit value provides a net present value of $53 and $94 million for the first-of-a-kind and nth-of-a-kind SMES-1 device, respectively.

6

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A

BENCHMARK POWER FLOW SUMMARY

West of the Colorado River		**MW**	**MVAR**
EL DORADO 500.	LUGO 500.1	1053.06	143.70
EL DORADO 230.	LUGO 230.S	80.54	-7.23
EL DORADO 230.	LUGO 230.N	80.66	-7.23
MEAD 230.	VICTORVL 287.1	165.14	8.42
MIRAGE 230.	DEVERS 230.1	106.98	24.27
MCCULLGH 500.	VICTORVL 500.1	929.38	70.65
MCCULLGH 500.	VICTORVL 500.2	919.49	-86.77
MOHAVE 500.	LUGO 500.1	1105.62	200.20
MARKETPL 500.	ADELANTO 500.2	960.48	-94.16
N. GILA 500.	IMPRLVLY 5001	1347.85	15.32
PALOVRDE 500.	BLYTHE 500.1	1896.51	736.53
EL CENTRO 230	IMPRLVLY 2301	-23.29	2.01
COACHELV 230	MIRAGE 230.1	203.09	45.38

NOTE: ALL FLOWS MEASURED AT “FROM” BUS

East of the Colorado River		**MW**	**MVAR**
NAVAJO 500.	MCCULLGH 500.1	1416.18	161.56
PALOVRDE 500.	N. GILA 500.1	1152.25	243.71
MOENKOPI 500.	EL DORADO 500.1	1744.10	81.19
PALOVERDE 500.	BLYTHE 500.1	1896.51	736.53
LIBERTY 345.	MEAD 345.1	377.36	-70.71
WESTWGPS 500.	MEAD 500.1	419.99	22.74
North of Lugo		**MW**	**MVAR**
KRAMER 230.	LUGO 230.1	433.31	61.75
KRAMER 230.	LUGO 230.2	433.31	61.75
VICTOR 230.	LUGO 230.1	-50.25	24.02
VICTOR 230.	LUGO 230.2	-50.25	24.02
Northeast-Southest Boundary Breakpoint:		**MW**	**MVAR**
SIGURDPS 230	GLENCANY 230.1	129.42	-10.41
PINTO PS 345	FOURCORN 345.1	175.74	-23.60
SHIP PS 345.	SHIPROCK 345.1	108.38	35.49
SANJN PS 345.	SAN JUAN 345.1	107.82	19.48

NOTE: ALL FLOWS MEASURED AT “FROM” BUS

Northeast - Northwest		**MW**	**MVAR**
BURKE 115	THOMSON 1151	-21.82	17.66
ELMO 115	KALISPEL 1151	-2.46	-16.30
HOT SPR 230	RATTLE S 2301	51.37	7.43
HOT SPR 230	OVANDO 2302	-4.71	-8.64
TAFT 500	GARRISON 5001	-399.13	-43.99
TAFT 500	GARRISON 5002	-398.96	-44.14
ENTERPRS 230	HELLSCYN 2301	-70.80	-17.39
HARNEY 115	HINES 1381	-12.14	8.57
ROUNDUP 230	LAGRANDE 2301	57.07	-17.22
LOLO 230	OXBOW 2301	256.95	-26.06
MIDPOINT 500	MIDPOINT 3451	-495.31	133.49
Northwest - California		**MW**	**MVAR**
MALIN 500	ROUND MT 500.1	1463.23	-73.14
MALIN 500	ROUND MT 500.2	1476.87	-92.00
CAPTJACK 500	OLINDA 500.1	1638.63	-125.96
DELTA 115	CASCADE 115.1	71.25	-32.11

NOTE: ALL FLOWS MEASURED AT “FROM” BUS

N. CALIFORNIA - S. CALIFORNIA		**MW**	**MVAR**
MIDWAY 500.	VINCENT 500.1	969.48	84.23
MIDWAY 500.	VINCENT 500.2	976.29	83.28
MIDWAY 500.	VINCENT 500.3	1054.44	102.45
NEVADA - N. CALIFORNIA		**MW**	**MVAR**
DRUM 115.	SUMMIT 1 1201	5.10	5.30
DRUM 115.	SUMMIT 2 1201	-6.43	7.76
SPAULDNG60.0	SUMMIT 3 601	2.60	-3.17
UTAH - S. NEVADA		**MW**	**MVAR**
HA PS 345	REDBUTTE 3451	0300.02	-23.12
Pacific DC Intertie	**AT CELILO:**	3002.64	1560.52
IPP DC Line	**AT INTERMTX:**	1916.72	981.78

NOTE: ALL FLOWS MEASURED AT “FROM” BUS

B

POWER FLOW SUMMARY TABLE

CASE	BASE - 1	BASE - 2	SMES - A	SMES - B	SMES - Br
EOR (MW)	7364	7899	7914	8198	8411
WOR (MW)	8885	9438	9451	9772	10005
M-V (MW)	3330	1749	2383	1397	1151
N. LUGO (MW)	476	478	477	479	479
SCIT (MW)	17609	16585	17230	16568	16554
PV-Dev (MW)	1692	1821	1821	1898	1947
PV-NG (MW)	1298	1331	1379	1378	1415
Moe-EL (MW)	1422	1626	1611	1709	1771
Nv-McC (MW)	1311	1371	1360	1440	1495
Lib-Md (MW)	441	449	441	472	483
WW-Md (MW)	1300	1300	1302	1300	1300
Lugo 230 kV	0.925	0.940	0.925	0.934	0.919
Devers 230 kV	0.926	0.933	0.919	0.922	0.902
Kyrene 230 kV	1.001	1.003	0.999	1.004	0.999
Mead 230 kV	0.987	0.986	0.976	0.978	0.962
Westwng 230 kV	1.014	1.015	1.010	1.014	1.004

LEGEND

Base - 1	EOR = 7365 MW
Base - 2	EOR = 7365 + 7% stability margin
SMES - A	500 MW SMES modulation at Blythe enabling 645 MW SCIT increase
SMES - B	500 MW SMES modulation at Blythe enabling 300 MW EOR increase
SMES - Br	500 MVAR SMES modulation at Blythe enabling 512 MW EOR increase

Southern California Inertia = 127,080 MWs