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Wide-Area Energy Storage and Management System to Balance Intermittent Resources in the Bonneville Power Administration and California ISO Control Areas

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Bonneville Power Administration
under Contract DE-AC05-76RL01830
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Abstract

The entire project addresses the issue of mitigating additional intermittency and fast ramps that occur at higher penetration of intermittent resources, including wind generation, in the Bonneville Power Administration (BPA) and the California Independent System Operator (California ISO) control areas. The proposed Wide Area Energy Storage and Management System (WAEMS) will address the additional regulation requirement through the energy exchange between the participating control areas and through the use of energy storage and other generation resources. For the BPA and California ISO control centers, the new regulation service will look no different comparing with the traditional regulation resources. The proposed project will benefit the regulation service in these service areas, regardless of the actual degree of penetration of the intermittent resources in the regions.

The project develops principles, algorithms, market integration rules, functional design and technical specifications for the WAEMS system. The project is sponsored by BPA and supported in kind by California ISO, Beacon Power Corporation, and the California Energy Commission (CEC).

This report provides a summary of results obtained in the first phase of the project. These tasks addressed in Phase 1 are as follow:

- Evaluate and compare energy storage options. Review the world experience. Identify top three technologies that can meet the needs of this project.

- Design and evaluate configurations and integration schemes of the energy storage, generation resources, their combinations, and other options. Identify the most promising configurations and their benefits.

- Analyze technical and market compatibility of the proposed integration schemes with the existing regulation and load following systems at BPA and California ISO.

- Collect data needed for experiments at BPA and California ISO.

- Develop algorithms for the energy storage and generation control. Implement them as MATLAB™ codes.

- Conduct experiments using the MATLAB™ model and collected data.

- Carry out the cost benefit analysis based on simulation results.

- Provide a summary of results and recommendations to BPA on continuation of the project.

The main results obtained in Phase 1 are as follow:

- Based on the developed set of selection criteria, an extensive literature review, and an analysis of the worldwide industrial experience, the most suitable energy storage technologies have been identified for the project. They include flywheel energy storage devices (ESDs), pumped or conventional hydro power plants, and sodium sulfur or nickel cadmium batteries.

- Using a developed set of requirements and an analysis of various configurations, a preferred WAEMS service architecture has been selected. A configuration with two ESDs was elected as the main variant: an aggregate of a flywheel ESD and a pumped storage (or a conventional hydro power plant). The one-ESD configuration can be also used as a first step toward the two-ESD configuration, or as an alternative architecture. The aggregate will form the WAEMS, which is vertically integrated with the BPA and the California ISO automatic generation control (AGC) systems. Elements of the WAEMS can be located in different control areas. Dynamic schedules will be employed to distribute the aggregate's power output among the participating control areas. BPA's and California ISO's conventional regulation signals will be used to control the WAEMS. WAEMS control algorithms will be designed to mimic behavior of conventional regulating unit and to coordinate the control functions of aggregated ESDs.

- Technical and market compatibility of the proposed WAEMS integration schemes have been analyzed. BPA and California ISO business practices, operating procedures, AGC systems, requirements for ancillary services, scheduling and load balancing processes, market designs, operating reserve and regulation procurement procedures, ancillary service rates and market clearing prices have been analyzed. Results of these comprehensive analyses are provided in the report. It has been found that the proposed architecture of the WAEMS is fully compatible with the current BPA and California ISO systems without changes.

- A new optimization-based control algorithm implemented as MATLAB™ codes has been developed and thoroughly tested. The algorithm provides an excellent regulation signal following capability, helps to maintain the desired state of charge (SOC) on the flywheel ESD and prevent violations, and keeps the hydro (pumped storage) power output close to the most efficient operating point.

- A hydro power plant regulation model has been built and implemented in MATLAB™ codes. The Beacon Power Corporation flywheel ESD model has been coded in MATLAB™. An integrated model was composed, including the control algorithm, hydro power plant regulation model, and the flywheel ESD model.

- To eliminate potential operating transfer capability (OTC) violations on the California Oregon Intertie (COI), several measures have been proposed. These measures include disaggregating the regulation service when the COI power flow reaches the limit, providing a unidirectional service during the high load periods (regulation down service in BPA service area, and regulation up service in California), and others. These options will be more comprehensively examined at the subsequent phase of this work.

- An experimental data set that includes 36 days of 4-second data for the BPA and the California ISO control areas in the year 2006 has been collected. Because of the limited data availability, a decision was made to substitute unavailable real regulation signals by the Area Control Error (ACE) signals for the purposes of Phase 1.

- Simulations have been conducted to demonstrate feasibility and to evaluate the performance of the proposed models. The aggregated hydro power plant model and flywheel ESD model provide a robust and accurate regulation service, help to keep the flywheel's SOC within the available energy limits, and keep the hydro power (pumped hydro) plant's output very close to the most efficient operating point.

- An analysis of potential reductions in the regulation procurement caused by the integrated regulation service provided for BPA and California ISO has been done. It was shown that the WAEMS service could help to reduce the regulation requirement in these control areas by about 30% compared to a traditional regulation service with the same total regulation capacity.

- A cost benefit analysis has been conducted for hydro power (pumped hydro) plants, flywheel ESDs, and lead acid and sodium sulfur batteries. The hydro power (or pumped storage) plant and the flywheel ESD will ensure high net present values (NPV) in both control areas under all analyzed financing options (i.e., BPA financed, California ISO utility financed, and California ISO private financed developments). The NPV results were comparable for these two technologies. Although, for the hydro power plant capital cost of $1,000/kW, the hydro power technology gives a better NPV than the flywheel technology: from $12.5 to $97 million. The flywheel ESD option provides rather close, but less beneficial, results based on the capital cost of $30 million for a 20 MW ESD: from $5.5 to $84.4 million. Nevertheless, both technologies should be considered as competitive based on the uncertainty in the capital cost of hydro power plants and additional considerations, such as siting and scalability issues, environmental benefits and so on. The battery storage technology has a negative NPV because of the cycling capability/degree of discharge issues (except for the sodium sulfur technology under the California utility financing option).

- Recommendation has been made to BPA and California ISO to continue the project into Phase 2. A statement of work has been suggested for Phase 2. Work in Phase 2 should include physical experiments with the flywheel ESD and other technologies using real BPA and California ISO regulation signals.

Summary

This project develops principles, algorithms, market integration rules, functional design and technical specification for the Wide Area Energy Storage and Management System (WAEMS), helping to cope with the wind generation resources intermittency and unexpected fast ramps by recycling the excess energy, controlling other generation, and inter-area exchanging the energy imbalance between Bonneville Power Administration (BPA) and California ISO control areas. The project provides a cost-benefit analysis and develops a business model for an investment-based practical deployment of such a system.

The project is sponsored by BPA and supported in kind by California ISO, Beacon Power Corporation, and California Energy Commission (CEC).

This report covers the first phase of the project. The tasks addressed in Phase 1 are as follow:

- Evaluate and compare available energy storage options. Review the world experience. Identify top three technologies that can meet the needs of this project.

- Design and evaluate configurations and integration schemes of the energy storage, generation resources, their combinations, and other options. Identify the most promising configurations and their benefits.

- Analyze technical and market compatibility of the proposed integration schemes with the existing regulation and load following systems at BPA and California ISO.

- Collect data needed for experiments at BPA and California ISO.

- Develop algorithms for the energy storage and generation control. Implement them as MATLAB™ codes.

- Conduct experiments using the MATLAB™ model and collected data.

- Carry out the cost benefit analysis based on simulation results.

- Provide a summary of results and recommendations for possible continuation of the project.

The project work was organized in four Stage Gates. The following work has been done and results have been obtained in Phase 1.

- Use of specific trade names and brands is for research purposes only and does not constitute an endorsement of these products.

Stage Gate 1: Evaluate Different Energy Storage Configurations and Identify Top Technologies That Meet the Needs of This Project

Objectives. Evaluate and compare different energy storage configuration options and participating load / distributed generation control schemes. Identify top three technologies that would meet the needs of this project. Provide review of the world experience.

Approach/Section Criteria. The following selection criteria were applied to select the technologies best suitable for the project:

- Ability to frequently change power output (or store and deliver energy) over a wide range at least several times over a 10-minute interval, preferably, several times over 1 minute.

- Ramp rate (the technology should be able to respond to control signals, i.e., automatic generation control (AGC) signals, changing every 4 seconds).

- Response delay time (the lesser is the better).

- Duration (the technology should be able to provide rated power for 15 - 60 minutes).

- Resource potential to be scaled to achieve needed energy and capacity.

- Lifetime.

- Maturity of the technology.

- Industrial use experience for regulation/frequency control.

- Cost.

- Energy efficiency and power density.
- Environmental impacts.
- Ability to provide other ancillary services.
- Ease of siting.

The highest absolute priority was given to the technical characteristics of the energy storage technologies that allow them to perform regulation services. The rest of the characteristics listed above was used to distinguish between the technologies that are capable to follow regulation signals. The cost-benefit analysis was applied to make a final selection of candidate technologies.

The report compares principal features of 12 generically distinguishable storage technologies based on these selection criteria and an extensive literature review and an analysis of the worldwide industrial experience. Analyzed characteristics included the ease of siting, environmental impacts, cyclic capability, life cycle, power capacity, energy capacity, response speed, duration, self discharging characteristics, maintenance cost, storage, capacity cost, weight, round trip energy efficiency, and existing industrial experience and applications. The battery storage technologies were additionally analyzed based on their cycling capability as a function of the depth of discharge (DOD). The cyclic duty of battery and required DOD influence the battery life. The Figure S-1 compares the cost of some of the battery technologies based on the required cycling capability/DOD and one year lifetime.

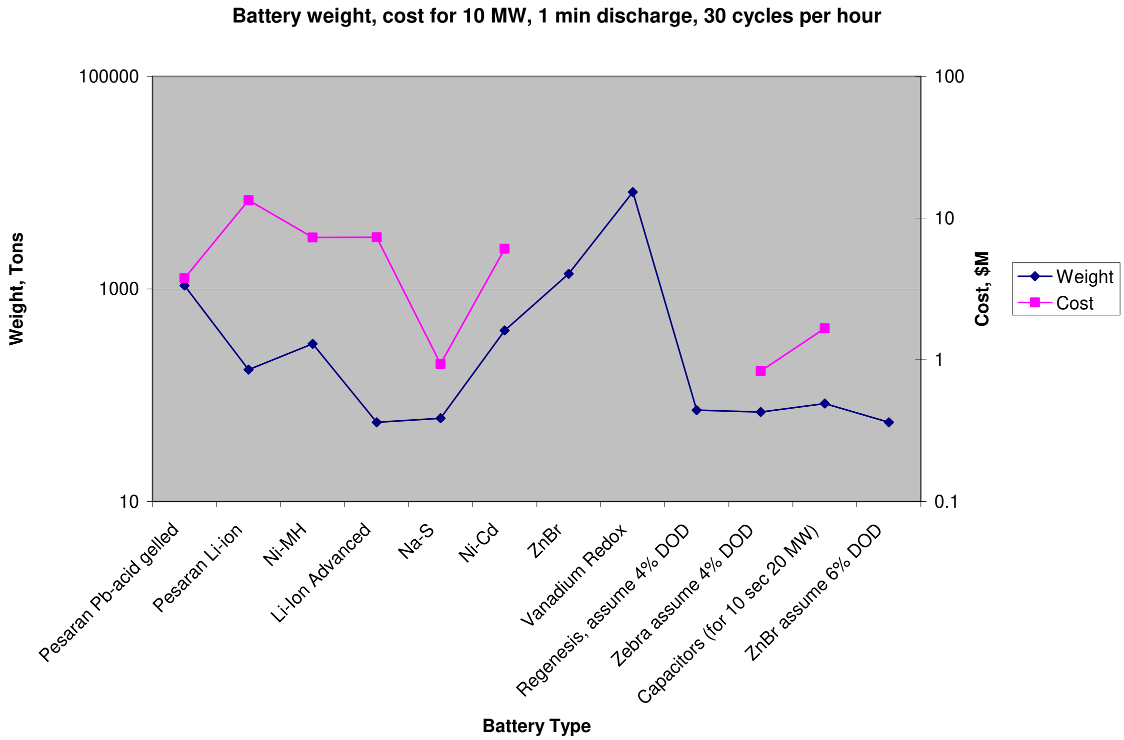


Figure S-1 Comparison of the cost and weight characteristics of some battery technologies

The selection process resulted in the selection of flywheels, pumped hydro power plants (or conventional hydro power plants) and sodium sulfur (or nickel cadmium) batteries for detailed evaluation in the following stage of the study including the cost benefit analysis.

Selected Energy Storage Technologies.

Flywheel ESD. This is an established modular technology that has a proven growth potential to utility. Flywheel energy storage is a "green" technology that has long cycle life and is insensitive to the depth of discharge. In addition, other strong positive values of the technology include high peak power capacity without overheating concerns, high round trip energy efficiency, rapid response, ability to provide other ancillary services because of power electronic interface with the grid and ability to site wherever needed. A 100-kW, 25-kWh, scale-power Smart Energy Matrix (SEM) unit comprised of Beacon Power® flywheels has been built, installed and is currently operating at Pacific Gas and Electric's (PG&E) Distributed Utility Integration Test (DUIT) facility in San Ramon, California. A 20-MW frequency regulation plant comprising 200 high-speed, high-energy flywheels is currently under design by Beacon Power under a contract with the DOE. The plant will provide 20 megawatts of up and down regulation (a 40-megawatt swing).

Pumped or Conventional Hydro Power Plant. This technology is the most developed and practiced utility option. Although a conventional hydro power plant is not an energy storage facility, it remains a very perspective regulation resource and is a selected candidate technology for this project. The major difficulties are siting and environmental impacts of the two requisite reservoirs. The practical use of hydro power resources for wide-area regulation depends on the availability of one of the existing hydro power plants for this service. Pumped hydro power plants can provide both power regulation and energy storage services. Examples can be found in California, where some pumped storage power plants provide both AGC regulation and intraday energy storage capabilities. In the regulation mode, pumped storage units are following AGC signals by changing their MW output around the preferred operating points. In this mode, the plants may be capable of providing the maximum ramp rate almost equal to their full capacity in 1 minute. This would be a sufficiently fast response for achieving the objectives of this project. In this respect, the pumped energy storage can be used similarly to the regulation of conventional hydro power plants. A transition from the pumping to generation mode takes minutes, and of course this would not be an acceptable response time for regulation purposes. The energy storage mode could be used to provide intraday services for the wind generation projects and for BPA and California ISO, such as helping to follow the schedules, optimizing the daily production schedules, and addressing the over-generation problem.

Sodium Sulfur (NaS) Batteries. Sodium sulfur batteries have been employed in power systems for more than 20 projects in Japan and worldwide. Compared with other leading battery technologies, NaS batteries have attractive energy density (over four times that of lead-acid battery), and low capital, a long cycle capability (2500 plus cycles upon reasonable depth of discharge) and millisecond response with full charge and discharge. Therefore, they have a good potential for regulation application. This technology has high cell DC efficiency (up to 89%), no self discharge, minimal maintenance and long life (up to 15 years). NaS batteries are made of abundant low cost materials that are suitable for high volume mass production. Modular fabrication yields potentially high power and energy capability, and also reduces the construction intervals. However, some technical issues, particularly those related to the containment of the liquid electrodes (corrosion of the electrode containers and brittle glass seals), still need to be properly addressed. The NaS technology has been implemented as utility energy storage in Japan (up to 64 MWh). NaS batteries have demonstrated their ability to improve power quality, emergency power supply and stabilization of renewable power resources from kW to MW level in utility substations. For example, NaS batteries are used in a substation update demonstration project at Charleston, Virginia by American Electric Power (AEP). The batteries could generate up to 1.2 MW power for up to 7 hours, easing the strain of overloaded substation. AEP was also expecting to deliver 6-MW NaS battery systems in 2008.

Nickel Cadmium (NiCd) Batteries. Compared with lead-acid batteries, NiCd batteries have higher energy density and are more temperature tolerant. For the purpose of regulation, NiCd batteries have an important feature of being tolerant to deep discharges and storage during the discharged state. The drawbacks lie in their higher costs and the need for advanced battery monitoring during charge and discharge. An application of Ni-Cd batteries is the Golden Valley Electric Association BESS (battery energy storage system) project in Alaska. The batteries were supplied by Saft, and power electronics by Asea Brown Boveri Inc. (ABB). This system is designed to provide 26 MW for 15 minutes or a full 40 MW for 7 minutes.

Eliminated Options.

The following options were eliminated from further immediate consideration because they exhibit various significant disadvantages or technological immaturity despite possessing potential advantages that may warrant reinvestigation over the longer term. This is particularly true of several evolving battery options.

- Superconducting magnetic energy storage.
- Compressed air energy storage.
- Demand side management.
- Super capacitors.
- Lead acid batteries.
- Nickel metal hydride batteries.
- Lithium ion batteries.
- Zebra batteries.
- Flow batteries.
- Metal air batteries.
- Plug-in hybrid electric vehicles.

Stage Gate 2: Design and Evaluate Different Configurations/ Integration Schemes of the Energy Storage. Identify the Most Promising Configurations and Their Benefits

Objectives. Design and evaluate different configurations and integration schemes of the energy storage, participating load and distributed generation including the ones shown in this proposal, their combinations, and other options. Identify the most promising configurations and their benefits.

Requirements. The preferred regulation service architecture should meet the following requirements:

- Overall efficiency of the solution (minimum total regulation capacity required).
- Compatibility with the existing regulation systems and markets (minimum changes).
- Minimum technical difficulty of implementation.
- Minimum cost for BPA and California ISO.

Considerations. Several considerations of the preferred architecture can be distinguished:

- The maximum value of the regulation service as well as the ESD-based balancing service is achieved when it is addressing to multiple intermittent resources distributed over a large geographical area.
- The efficiency of the regulation service is increasing if it addresses the load intermittency and uninstructed deviations of conventional generators concurrently with the intermittent renewable resources.
- The strategic choice to be made is between the horizontal scheme for balancing intermittent resources (the direct integration of regulation service providers with particular renewable energy projects or groups of projects) and the vertical scheme (indirect integration via the BPA and California ISO EMS or wide area EMS). Although the horizontal scheme has its own merits and cannot be eliminated from consideration, the vertical scheme provides better overall system wide efficiency because it addresses multiple sources of intermittency altogether rather than addressing them one by one.
- The architecture with two different types of regulation devices, for instance the flywheel ESD and pumped storage (or a conventional hydro unit), gives more flexibility and maximizes the value of the wide area EMS comparing with the architecture that employs only one ESD. Participation of a pumped storage or conventional hydro unit in the wide area EMS will help to effectively double the flywheel's regulation range and help to continuously maintain the required flywheel's state of charge. The flywheel ESD in its turn could help to minimize the regulation stress posed on the hydro generation unit.
- To provide a smooth integration of the wide area EMS into the BPA and California ISO systems, the regulation service characteristics and integration requirements should be very similar to the ones that are currently used in these service areas.
- Participation of a pumped storage or conventional hydro units in the wide area EMS is justified if they are existing units. Capital cost considerations and other difficulties may be unfavorable if a new hydro power plant is considered.
- California Oregon Intertie (COI)'s operating transfer capability (OTC) should be included into the project's design.
- Area control error (ACE) and conventional units' regulation signals are prime candidates for the control signal used to control the wide area EMS.
- An important additional feature is that ESDs are employed to provide additional services such as static VAR control, frequency response, and the others. This could help to justify the ESD's cost.

<u>Selected Configuration</u>.

- Configuration with two ESDs: flywheel and pumped storage (or conventional hydro) as shown in the Figure S-2.

- One ESD configuration can be also used (as the first step toward the two-ESD configuration or as an alternative configuration).
- Vertical configuration that would integrate the wide area EMS with the BPA and California ISO AGC systems.
- BPA's and California ISO ACE and "conventional regulation unit" signals will be used to control the wide area EMS
- Dynamic schedules will be used to incorporate the ESD regulation into the corresponding neighboring control area AGC system.
- Control algorithms will be designed to mimic behavior of a conventional unit of regulation and to coordinate the control functions of participating ESDs.

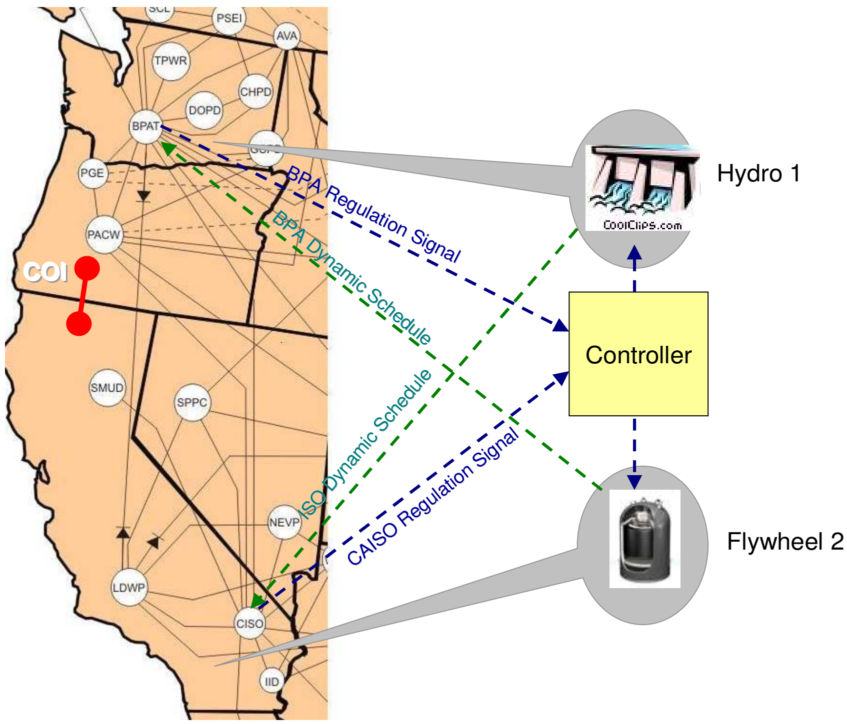


Figure S-2 Configuration of the Wide Area EMS system

Stage Gate 3: Analyze Technical and Market Compatibility of the Proposed Integration Schemes with BPA and California ISO Systems

Objectives. Analyze technical and market compatibility of the proposed integration schemes with the existing regulation and load following systems at BPA and California ISO and identify potential minimum changes if they are required. Identify the requirements for energy storage devices to participate ancillary services in the two control areas, from both technical and business point of view. Analyze the compatibility of the Wide Area Energy Storage and Management System (WAEMS) configuration selected in State Gate 2 with the existing practices, and identify potential minimum changes if needed.

Provide reference information on system operation procedures for the simulation and control algorithm design in Stage Gate 4.

Work Done. The work conducted in this stage gate included an in-depth analysis of relevant aspects of the BPA and California ISO systems. This analysis included the following target points:

- Compatibility with ancillary service operating procedures.
- California ISO's and BPA's AGC systems information and analysis.
- Compatibility with the AGC systems.
- Technical requirements for providing ancillary services.
- Scheduling and load balancing processes in BPA and California ISO systems.
- Load following and regulation processes.
- California ISO market processes and timelines.
- Changes expected under the new California ISO market design (MRTU).
- BPA and California ISO operating reserve standards.
- California ISO regulation procurement procedure.
- Effects of limited ramp rates on ancillary service procurement at California ISO.
- BPA and California ISO ancillary service rates.

It has been found that the proposed architecture of the WAEMS is fully compatible with the current BPA and California ISO systems without changes.

BPA ancillary service rates are energy based. The estimated benefit of energy storage in the BPA service area is the sum of:

Service 10 - hourly scheduling, system control and dispatch (0.59 mills/kWh).
Service 12 - regulation and frequency response (0.33 mills/kWh).
Service 14/15 - operating reserves - spinning and supplemental (7.93 mills/kWh).

California ISO regulation prices are capacity based. This means that the regulating units bid a part of their capacity into the market, and if they are accepted, they are paid the market clearing price (MCP). The average California ISO regulation price in 2006 was $18/MW ($17 for regulation down and $19 for regulation up). Figure S-3 shows the weekly weighted average ancillary service prices from April 2007 to September 2007. The regulation up price reaches $40/MW in May and exceeds $30/MW in May and June. The regulation down price reaches $20/MW in the mid of September.

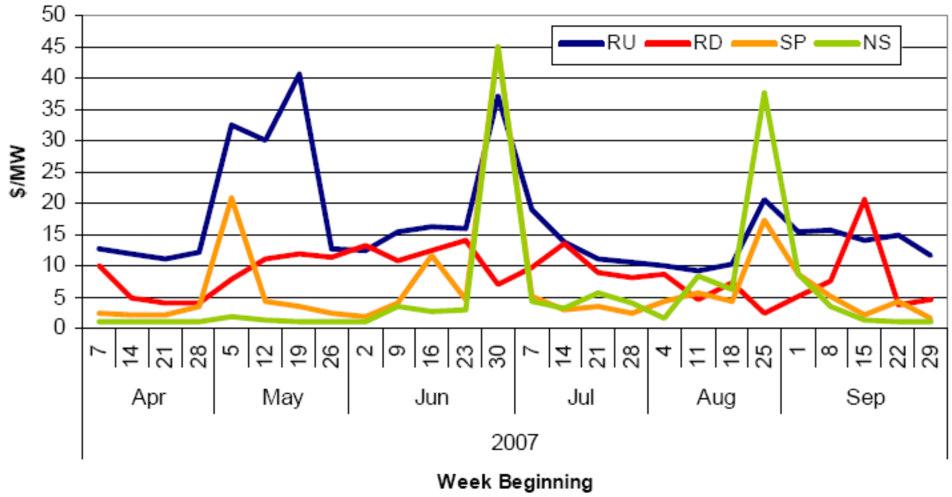


Figure S-3 California ISO's weekly weighted average ancillary service prices (RU – regulation up; RD – regulation down; SP – spinning reserve, and NS – non-spinning reserve prices)

Stage Gate 4: Develop Algorithms and Conduct Experiments Using MATLAB Model. Carry Out Cost Benefit Analysis.

Objectives.

- Develop initial algorithms for the energy storage control. Implement them as MATLAB codes.
- Collect and preprocess data needed for experiments from BPA and California ISO.
- Conduct experiments using the MATLAB models and collected data.
- Carry out the cost benefit analysis based on simulation results.
- Evaluate changes that are needed for the San Ramon prototype flywheel ESD (if any).
- Provide a summary of results and recommendations for BPA on continuation of the project. Write and submit Phase 1 Report.

Data Sets Used. Because of the limited availability of BPA data, a decision has been made to use the BPA and California ISO ACE signals as a substitute for the real regulation signals. A total of 36 days of 4-second data have been pulled out from the California ISO PI Historian. The analyzed period is the year of 2006 including the 1st, the 15th, and the 30th days of each month except February. In February, the 28th day of the month has been used instead of the 30th day used for the other months. The ACE data from each control area was scaled down to fit into the ±20 MW range of change.

Hydro Power Plant Model. The developed hydro power plant model is shown in Figure S-4. The model includes: delay block simulating the delay in the plant's response to the changing regulation signal, dead band element, first order plant response model, error range simulating deviations of the actual plant response from the load setting, and limiting element restricting the maximum and minimum regulation output provided by the plant.

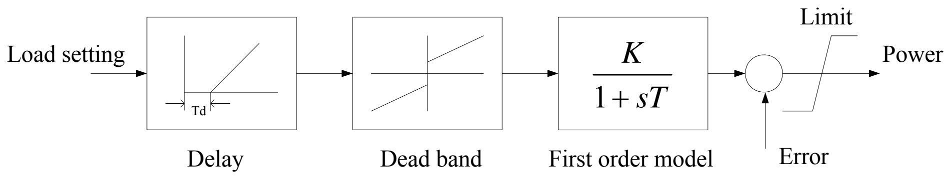


Figure S-4 Hydro power plant model

Flywheel Model. The flywheel model was initially developed and supplied by Beacon Power Corporation, and it has been converted to a MATLAB model by PNNL. The model incorporates charging and discharging losses, floating losses and auxiliary power, as shown in Figure S-5.

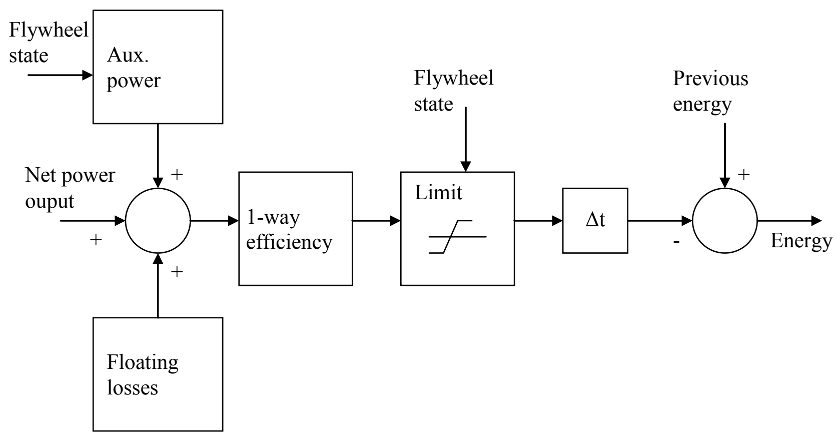


Figure S-5 Flywheel model

Integrated Model. The integrated model is modeled using a MATLAB model, consisting of three parts: control algorithm, hydro plant model, and flywheel model. The regulation signal is a sum of regulation signals received from the BPA and California ISO AGC systems. The control algorithm distributes that signal between the flywheel energy storage and hydro power plant depending on their current states and system constraints. The varying flywheel and hydro power plant outputs are required to match the regulation signal. Dynamic scheduling is used to distribute a part of the outputs into the neighboring control area.

Treatment of COI Limits. To eliminate potential OTC violations on the COI, several measures have been proposed. They include disaggregating the regulation service during periods when the COI power flow reaches the limit, providing a unidirectional service during the high load periods (regulation down service in BPA service area, and regulation up service in California), and others. These options will be more comprehensively examined at the subsequent Phase of this work.

Control Algorithm. The developed control algorithm seeks to find an optimal trade-off between the state of charge of the flywheel and the hydro power output related to the efficiency of the hydro power plant. The relative weights of these two objectives have a significant influence on system behavior. By changing the relative weights, the system can be designed to allow either the flywheel or the hydro take a relatively larger share of the regulation task.

Simulation Results.

The original regulation signal (a sum of regulation signals from BPA and California ISO) is scaled in the range of total regulation capacity of the flywheel – hydro aggregate. Table S-1 shows the models' parameter settings used in the simulations.

Table S-1 Parameter Settings

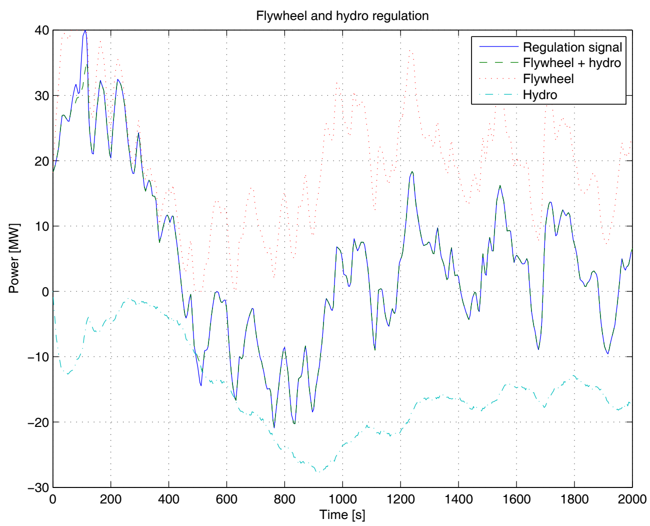
No.	Parameters	Minimum	Maximum
1	Hydro regulation capacity, MW	-40	0
2	Total hydro capacity, MW	+100	+400
3	Flywheel power, MW	-20	+20
4	Flywheel energy, MWh	0	+5
5	Total regulation capacity to system, MW	-40	+40
6	Hydro power plant efficient point, MW	316.8 (=400*0.8*0.99)	323.2 (=400*0.8*1.01)

The hydro power plant efficient operation point is assumed to be at 80% of the plant maximum capacity, allowing ±1% deviation.

Parameter Settings. The settings of model parameters shown in Table S-1 are an example of an asymmetrical task distribution, where the hydro plant delivers down regulation and the flywheel up regulation. The regulation task may be divided differently, e.g., symmetrically. To obtain 40 MW regulation up from the flywheel, the actual range of [-20, +20] MW from the flywheel has been offset +20 MW in the simulations. It may be practically obtained by simply purchasing +20 MW constant generation, scheduled to be absorbed by the flywheel (because the regulation output is a deviation from a scheduled setpoint, i.e., if the scheduled setpoint is -20 MW, an output of 0 MW is actually +20 MW of regulation). For the symmetrical parameter setting scenario, the minimum and maximum hydro regulation capacities are -20 MW and +20 MW, respectively.

Simulation Cases. Two simulation cases were used. In these cases, the relative weights of the hydro power to the flywheel ESD in the objective cost functions were different. The first case uses a proportion of weight of hydro to flywheel of 5:1, and 10:1 in the second case. Two situations are considered in each of the cases. In these two situations, the difference lies in the flywheel energy offset point. In the first situation, the flywheel energy offset point is located at the middle point of flywheel energy range. In the second situation, the flywheel energy offset point is located at the 90% of the flywheel energy range, close to the maximum energy point.

Simulation Results. Some simulation results are presented in the following three figures for the one directional flywheel and hydro regulation case, where the flywheel energy offset point is located at the middle of energy range, flywheel weight is set to 1, and hydro power plant is set to 5.



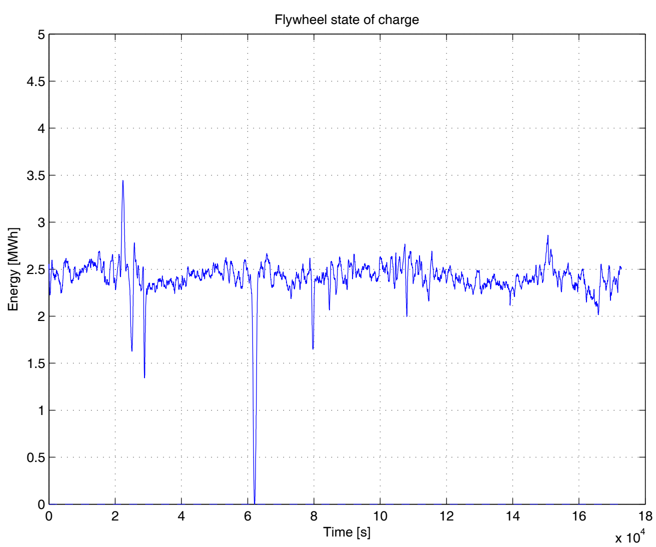
Comments

The flywheel-hydro aggregate follows the regulation signal exactly.

The flywheel provides regulation up service. The hydro power plant provides regulation down service.

The flywheel takes most of the regulation task in terms of variability of regulation. Less stress is posed on the hydro unit.

Figure S-6 Flywheel and hydro regulation

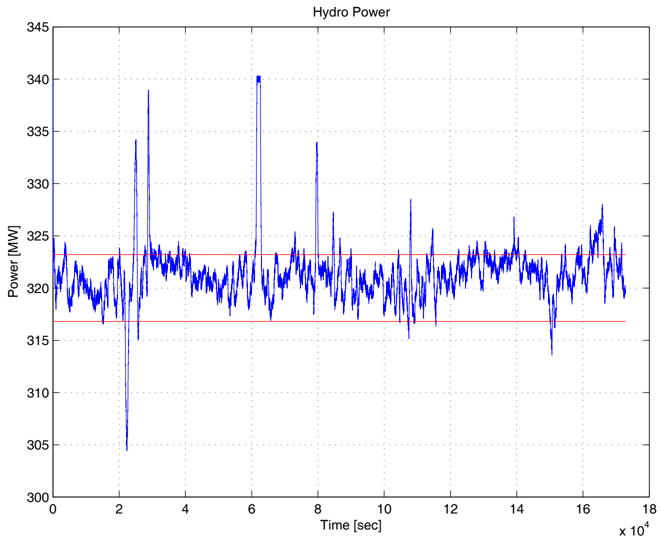


Comments

The flywheel's energy is kept close to the midpoint. The hydro power plant helps to make this happen.

At some points within the 48 hour interval, the flywheel energy reaches its minimum.

Figure S-7 Flywheel state of charge



Comments

It is seen that the flywheel helps to keep the hydro plant output close to the desired ±1% range most of the time.

Figure S-8 Hydro power

Discussion on Simulation Results.

- Simulation results clearly demonstrate feasibility and efficiency of the proposed WAEMS. The aggregated hydro power plant and ESD provide a robust and accurate regulation service.
- The flywheel energy storage can be tuned to make the hydro power plant regulation curve smoother. This will help to minimize the wearing and tearing problem on the participating hydro power plant.
- It has been shown that the flywheel helps to keep the hydro power plant output closer to the most efficient operating point. By a proper selection of the hydro and flywheel weight factors in the cost function, the hydro power plant operating point can be kept within the ±1% deviation range from the most efficient point most of the time.
- The hydro power plant is capable of holding the flywheel's state of charge closer to the selected level whenever it is possible and prevent failures in following the regulation requirement when the flywheel exhausts its energy regulation range.
- By selecting the weights in the cost function, the aggregate can be tuned to use the entire regulation range of the flywheel, and minimize the regulation stress posed on the participating hydro power plant.
- The flywheel energy storage can compensate for the regulation inaccuracies caused by the response delay, dead zone, and deviation characteristics of the hydro power plant.
- Both asymmetrical (where the flywheel energy storage provides regulation up, and the hydro power plant provide regulation down services) and symmetrical (where the flywheel and the hydro power plant provide bi-directional regulation services) are feasible. There are no noticeable differences in the flywheel energy storage and hydro power plant performance in these two approaches.

- By a proper selection of the flywheel's energy offset, the flywheel energy can be adjusted to efficiently use the entire available energy range and minimize the number of violations. This energy offset adjustment does not noticeably alter the flywheel and hydro power plant performance.

Benefits of Wide Area Regulation Service. An analysis of potential reductions in the regulation procurement caused by the integrated regulation service provided for BPA and California ISO has been done. It was shown that the WAEMS service could help to reduce the regulation requirement in these control areas by about 30% comparing with a traditional regulation service with the same total regulation capacity.

Cost Benefit Analysis Results. A cost benefit analysis has been conducted for hydro power (pumped hydro) plants, flywheel ESDs, and for lead acid and sodium sulfur batteries – see Table S-2.

Table S-2 Cost Benefit Analysis Results

Storage System	BPA Financed	California ISO Utility Financed	California ISO Private Financed
Flywheel			
Capital Cost ($M)	30	30	30
Annual Benefit ($M)	3.83	15.88	15.88
Annual Cost ($M)	3.46	5.97	7.86
Benefit/Cost	1.11	2.66	2.02
NPV ($M)	+5.5	+84.4	+68.3
Pumped Hydro			
Capital Cost ($M)	20	20	20
Annual Benefit ($M)	3.83	15.88	15.88
Annual Cost ($M)	2.99	4.49	5.75
Benefit/Cost	1.28	3.54	2.76
NPV ($M)	+12.5	+97	+86.2
Lead Acid Battery			
Capital Cost ($M)	226	226	226
Annual Benefit ($M)	3.83	15.88	15.88
Annual Cost ($M)	38.90	56.39	-
Benefit/Cost	0.1	0.28	-
NPV ($M)	-520	-340	-
Sodium Sulfur Battery			
Capital Cost ($M)	56	56	56
Annual Benefit ($M)	3.83	15.88	15.88
Annual Cost ($M)	9.82	14.24	17.77
Benefit/Cost	0.39	1.12	0.89
NPV ($M)	-110	+14	-16

The hydro power (or pumped storage) plant and the flywheel ESD will ensure high net present values (NPV) in both control areas under all analyzed financing options (i.e., BPA financed, California ISO utility financed, and California ISO private financed developments). The NPV results were comparable for these two technologies. Although, for the hydro power plant capital cost of $1,000/kW, the hydro power technology gives a better NPV than the flywheel technology: from $12.5 to $97 million. The flywheel ESD option provides rather close, but less beneficial, results based on the capital cost of $30 million for a 20 MW ESD: from $5.5 to $84.4 million. Nevertheless, both technologies should be considered as competitive based on the uncertainty in the hydro power plant capital cost and additional considerations, such as siting and scalability issues, environmental benefits, and others. The battery storage technologies have negative NPV because of the cycling capability/degree of discharge issues (except for the sodium sulfur technology under the California utility financing option). It is important to stress that this conclusion concerns only possible applications of the battery energy storage technologies for regulation purposes only. Other power system applications could be still cost effective for these technologies. Future progress with these and other energy storage technologies as well as changes of the regulation prices could lead to some different selections of the most suitable energy storage devices.

Recommendations for Phase 2. Recommendation has been made to BPA and California ISO to continue the project into Phase 2. A statement of work has been suggested for Phase 2. The main work in Phase 2 should be physical experiments with the flywheel ESD and other technologies using real BPA and California ISO regulation signals.

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Glossary

Abbreviation	Term	Meaning
AB	Annual Benefit	The annual benefit of storage options was estimated as the product of the annual sum of the energy exchanges in MWh they achieve with the grid and the value in $/MWh these transactions are worth.
ABB	Asea Brown Boveri Inc.	ABB in the United States is a technology-based provider of power and automation products, systems, solutions, and services.
AC	Annual Levelized Cost	Annual levelized cost converts the life cycle cost to a series of equal amounts throughout the economic plant life expressed in $/year.
AC	Alternating Current	Alternating current (AC) is a type of electrical current, in which the direction of the flow of electrons switches back and forth at regular intervals or cycles.
ACE	Area Control Error	Area control error (ACE) is the difference between scheduled and actual electrical generation within a control area on the power grid, taking frequency bias into account.
ADI	ACE Diversity Interchange Program	ADI enables participating control area operators to share control burden and relax control requirements through the ACE sharing.
AEP	American Electric Power	A U.S. electric utility.
AGC	Automatic Generation Control	Generation equipment that automatically responds to signals from the EMS control in real time to control the power output of electric generators within a prescribed area in response to a change in system frequency, tie line loading, or the relation of these to each other, so as to maintain the target system frequency and/or the established interchange with other areas within the predetermined limits.
APEL	Applied Process Engineering Laboratory	APEL is an Eastern Washington technology business startup center with engineering and manufacturing scale space, as well as wet labs, bio labs, and electronic laboratories. Prototypes or pilot plants can be tested and initial manufacturing conducted using APEL's utilities, services, and permits. APEL supplies process and hood-off gas connections, compressed air, vacuum, water, and power. APEL also has air & water discharge permits, and flammable storage permits.
AR	Area Requirement	Control area regulation requirement calculated in an AGC system.
AS	Ancillary Services	Ancillary services are those services necessary to support the transmission of energy from resources to loads while maintaining, reliable operation of the transmission provider's transmission system in accordance with good utility practice.
ASMP	Ancillary Service Marginal Price	Market clearing price for ancillary services.
B&W	Babcock and Wilcox Company	An international provider of energy products and services.
BASE	Beta-Alumina Solid Electrolyte	Electrolyte used in sodium sulfur batteries.
BESS	Battery Energy Storage System	Energy storage that used batteries.
BPA	Bonneville Power Administration	A U.S. government electric utility in the Pacific Northwest.
CAES	Compressed Air Energy Storage	With this technology, energy is stored mechanically by compressing air. When the air is expanded again, energy is released to the grid.
CAISO	California Independent System Operator Corp.	Independent system operator controlling most of the California electric power system.
CAP	Capital Cost	Capital costs are costs incurred on the purchase of land, buildings, construction and equipment to be used in the production of goods or the rendering of services.
CEC	California Energy Commission	The California Energy Commission is the state's primary energy policy and planning agency.
COI	California Oregon Intertie	The California – Oregon Intertie (COI) is also referred to as WECC Qualified Transfer Path 66 and comprises three 500 kV transmission lines, which are operated as a single path. These transmission lines include the California – Oregon Transmission Project's (COTP) Captain Jack – Olinda 500 kV line and the Malin – Round Mountain #1 and #2 500 kV lines (also known as the Pacific AC Intertie (PACI)). Combined, COI has a normal rating of 4800 MW North-to-South and 3675 MW South-to-North. COI has firm scheduling limitations each operating season determined by BPA's Standing Order #306 (COI/PDCI – North of John Day Nomogram Operation.
---	Control Area	An electric power system or combination of electric power systems to which a common automatic control scheme is applied in order to: (1) match, at all times, the power output of the generators within the electric power system(s) and capacity and energy purchased from entities outside the electric power system(s), with the load in the electric power system(s); (2) maintain, within the limits of good utility practice, scheduled interchange with other control areas; (3) maintain the frequency of the electric power system(s) within reasonable limits in accordance with good utility practice; and (4) provide sufficient generating capacity to maintain operating reserves in accordance with good utility practice.
COTP	California – Oregon Transmission Project	See COI

CPS	Control Performance Standard	Control performance standards established by NERC for balancing authorities (control areas). Currently, two CPS are enforced: CPS1 and CPS2.
---	Cycling Life (Cycling Capacity)	How many charge/discharge cycles the battery can endure before it loses its ability to hold a useful charge.
DAM	Day Ahead Market	The market for energy for the following day, or more specifically, the market for energy 24 hours in advance of a given time in any day.
DC	Direct Current	Direct current (DC) is a type of electrical current, in which the direction of the flow of electrons remains the same..
DER	Distributed Energy Resources	Distributed energy resources (DER) refers to technologies which can be used to provide energy close to the energy consumer (load). These technologies including small power generators, energy storage units, interconnection and power control technologies, and combined heat and power technologies.
DOD	Depth of Discharge	The amount of energy that has been removed from a battery (or battery pack). Usually expressed as a percentage of the total capacity of the battery.
DOE	Department of Energy	U.S. Department of Energy
DOT	Dispatch Operating Target	Desired generation used in the California ISO real time dispatch system.
DSM	Demand Side Management	Demand side management is the process of managing the consumption of energy, generally to optimize available and planned generation resources.
DUIT	Distributed Utility Integration Test	The Distributed Utility Integration Test (DUIT) is the first full-scale, integration test of commercial-grade, utility grid interactive distributed energy resources (DER) in the United States. DERs are small modular generation and storage devices such as fuel cells, microturbines, photovoltaics and batteries that can be integrated into the utility electric system. Ref.: http://www.dua1.com/DUIT
ECN	Energy Communications Network	Dedicated shared, high-reliability, and high bandwidth communications network established by the California ISO for subscribers to California ISO connectivity as well as for connectivity among the subscribers.
EMS	Energy Management System	A computer control system used by electric utility dispatchers to monitor the real time performance of the various elements of an electric system and to control generation and transmission facilities.
ESD	Energy Storage Device	An energy storage connected to the electric power system.
GFA	Grid Friendly™ Appliances	Electrical devices are considered grid friendly if they operate in a manner that supports electrical power grid reliability.
GridWise™	---	GridWise™ Alliance is a consortium of public and private stakeholders who are aligned around a shared vision. A vision of an electric system that integrates the infrastructure, processes, devices, information and market structure so that energy can be generated, distributed, and consumed more efficiently and cost effectively; thereby achieving a more resilient, secure and reliable energy system. The Alliance members recognize that emerging energy and information technologies have the potential to radically improve the efficient use of the nation's energy system. The Alliance and its members advocate change locally, regionally, and nationally to promote new policies and technology solutions that move us closer to this vision.
HASP	Hour Ahead Scheduling Process	The hour ahead scheduling process is a process for trading hourly energy and ancillary services based on bids submitted up to 75 minutes ahead of a trading hour.
IFM	Integrated Forward Market	The integrated forward market (IFM) at California ISO is a market for trading Energy and Ancillary Ser-vices for each hour of the next Trading Day.
IPP	Independent Power Producer	A producer of electrical energy which is not a public utility but which makes electric energy available for sale to utilities or the general public
LMP	Locational Marginal Price	The market clearing marginal price for energy at the location the energy is delivered or received.
MATLAB	---	MATLAB is a numerical computing environment and programming language.
MCP	Market Clearing Price	The price at which supply equals demand.
MPM	Market Power Mitigation	Procedures for mitigation of local market power exercised by generator merchants. The MPM at California ISO performs the local market power mitigation test to determine whether bids submitted allow the exercise of market power based on specific criteria.
MRTU	Market Redesign and Technology Upgrade	New market design currently under development at the California ISO.
NAESB	North American Energy Standards Board	The North American Energy Standards Board (NAESB) serves as an industry forum for the development and promotion of standards, which will lead to a seamless marketplace for wholesale and retail natural gas and electricity, as recognized by its customers, business community, participants, and regulatory entities.
NERC	North America Electric Reliability Corporation	NERC's mission is to improve the reliability and security of the bulk power system in North America. To achieve that, NERC develops and enforces reliability standards; monitors the bulk power system; assesses future adequacy; audits owners, operators, and users for preparedness; and educates and trains industry personnel. NERC is a self-regulatory organization that relies on the diverse and collective expertise of industry participants. As the Electric Reliability Organization, NERC is subject to audit by the U.S. Federal Energy Regulatory Commission and governmental authorities in Canada.
NPV	Net Present Value	Net present value is the difference between the present value of cash inflows and the present value of cash outflows. NPV compares the value of a dollar today to the value of that same dollar in the future, taking inflation and returns into account.

NWPP	Northwest Power Pool	NWPP serves as a forum in the electrical industry for reliability and operational adequacy issues in the U.S. Northwest.
O&M	Operations and Maintenence	---
OASIS	Open Access Same-Time Information System	A web-based information system linking individual transmission owner OASIS websites that list available capacity on specific transmission lines.
OTC	Operating Transfer Capability	The OTC is the maximum amount of actual power that can be transferred over direct or parallel transmission elements comprising: • An interconnection from one transmission operator area to another transmission operator area; or • A transfer path within a transmission operator area.
PACI	Pacific AC Intertie	See COI.
PBL	Power Business Line	A division at BPA.
PDCI	The Pacific DC Intertie	The Pacific DC Intertie (also called Path 65) is an electric power transmission line that transmits electricity from the Pacific Northwest to the Los Angeles area using high voltage direct current.
PG&E	Pacific Gas and Electric	Investor owned electric utility in California.
PHEV	Plug-in Hybrid Electric Vehicle	A plug-in hybrid vehicle is an hybrid electric vehicle with the ability to recharge its energy storage system with electricity from the electric utility grid.
PI	Process Information System	A database developed by OSI Soft Company for storing large amounts of time domain data.
PNNL	Pacific Northwest National Laboratory	U.S. Department of Energy Laboratory located in the Pacific Northwest. The Laboratory is runn by Battelle Memorial Institution.
POP	Preferred Operating Point	In the California ISO system, the POP is the generation loading at which an AGC unit has pre-scheduled its energy from the energy markets.
PSB	Polysulfide Bromide Battery	A sort of Redox battery.
Redox	Reduction-Oxidation	In Redox (reduction-oxidation) flow batteries, all chemicals that actively take part in the electro-chemical energy conversion are dissolved in the electrolyte.
RF	Recovery Factor	Capital recovery factor also called fixed charge rate
RPS	Renewable Portfolio Standard	Renewable portfolio standards (RPS) are state policies mandating a state to generate a percent of its electricity from renewable sources. Each state has a choice of how to fulfill this mandate using a combination of renewable energy sources, including wind, solar, biomass, geothermal, or other renewable sources.
RIG	Remote Intelligent Gateway	The remote intelligent gateway (RIG) is a system for collection and transmission of data between generators' sites and other monitoring and supervisory control sites.
RMR	Reliability Must Run	RMR generation is generation the California ISO determines is required to be on line to meet applicable reliability criteria requirements. This includes: i) generation constrained online to meet NERC and WECC reliability criteria for interconnected systems operation; ii) generation needed to meet load demand in constrained areas; and iii) generation needed to be operated to provide voltage or security support of the California ISO or a local area.
RRD	Reliability Requirement Determination	The RRD process allows California ISO to identify RMR requirements for RMR units.
RT	Real Time	---
RTCD	Real Time Contingency Dispatch	The RTCD function executes upon California ISO operator action, usually following a generation or transmission system contingency. The RTCD execution is for a single 10-minute interval and includes all contingency only operating reserves in the optimization process. California ISO real time contingency dispatch (RTCD) is executed manually.
RTD	Real Time Dispatch	Generation dispatch conducted in real time.
RTED	Real Time Economic Dispatch	Real time economic dispatch (RTED) is a market for trading imbalance energy and dispatching ancillary services at regular intervals.
RTID	Real time Interval Dispatch	Real time interval dispatch (RTID) is the normal mode of RTED. It runs automatically every 5 min, at the middle of each 5-min interval of each hour.
RTM	Real Time Market	Real time market (RTM) at California ISO is a market for trading energy and ancillary services in real time.
RTMD	RealTime Manual Dispatch	The real time manual dispatch (RTMD) is executed manually and it has a single 5-min interval.
RTPD	Real Time Pre-Dispatch	The real time pre-dispatch (RTPD) is a market for committing resources and for selling ancillary services at 15-min intervals.
RTU	Remote Terminal Unit	In SCADA systems, an RTU is a device installed at a remote location that collects data, codes the data into a format that is transmittable and transmits the data back to a central station, or master. An RTU also collects information from the master device and implements processes that are directed by the master. RTUs are equipped with input channels for sensing or metering, output channels for control, indication or alarms and a communications port.
RTUC	Real Time Unit Commitment	RTUC looks out between four and seven 15-minute intervals to ensure there is sufficient capacity to meet the demand. RTUC commits and de-commits short start units and procures additional AS.
RUC	Residual Unit Commitment	The RUC process provides a reliability backstop for the California ISO to commit additional units in order to meet its reliability requirements. The California ISO performs a day-ahead and hour-ahead RUC process immediately after the day-ahead or hour-ahead IFM has run and feasible final schedules are established. In the event that these markets close with supplies offered below the California ISO's load forecast, the RUC process will commit additional resources to ensure that on-line capacity is available in real time.

SC	Security Coordinator	Scheduling coordinators (SCs) submit balanced schedules to the California ISO and provide settlement-ready meter data.
SCADA	Supervisory Control and Data Acquisition	A computer system for gathering and analyzing real time data. SCADA systems are used to monitor and control a plant or equipment.
SDG&E	San Diego Gas and Electric	An investor owned electric utility in California.
SEM	Smart Energy Matrix	Beacon Power Corporation Trade Mark for the 20 MW frequency regulation plant currently under design.
SMES	Superconducting Magnetic Energy Storage	In a superconducting magnetic energy storage, the energy is stored in the magnetic field of a superconducting coil.
SOC	State of Charge	State of charge (SOC) is the ESD's level of charge, usually expressed as a percentage of full.
SOW	Statement of Work	The purpose of a SOW is to detail the work requirements for projects and programs that have deliverables and/or services performed.
SRS	Supplemental Regulation Service	A method of providing regulation service in which the balancing authority providing the regulation service receives a signal representing all or a portion of the other balancing authority's ACE.
STD	Standard Deviation	Standard deviation is a measure of the spread of a random variable.
STUC	Short Term Unit Commitment	STUC is a reliability function for committing short and medium start units to meet the California ISO forecast of California ISO demand. The STUC function is performed hourly, in conjunction with RTUC and looks ahead three hours beyond the trading hour, at 15-minute intervals.
TBL	Transmission Business Line	A division within BPA.
TSO	Transmission System Operator	Transmission system operator (TSO) refers to the operator that transmits electrical power from generation plants to the regional or local electricity distribution operators.
UPS	Uninterruptable Power System	UPS is a device which maintains a continuous supply of electric power to connected equipment by supplying power from a separate source when utility power is not available.
VRB	Vanadium Redox Battery	A sort of Redox battery.
WAEMS	Wide Area Energy Storage and Management System	The system which is under development in this project.
WECC	Western Electricity Coordinating Council	WECC is responsible for coordinating and promoting electric system reliability in the Western Interconnection. WECC supports efficient competitive power markets, assure open and non-discriminatory transmission access among members, provide a forum for resolving transmission access disputes, and provide an environment for coordinating the operating and planning activities of its members as set forth in the WECC Bylaws.
WG	Wind Generation	---
Zebra	Zeolite Battery Research Africa Project	An evolution of NaS battery.

Contents

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1. Project Objectives

The project's technology area, goals, and plan are as follow.

1.1 Technology Area Investigated in the Project

The project targets the issue of mitigating the additional intermittency and fast ramps that occur at higher penetration of intermittent generation resources (including wind generation) in the Bonneville Power Administration (BPA) and California Independent System Operator (California ISO) control areas. The proposed wide area energy storage and management system will address the additional intermittency through the exchange of intermittent energy between the participating control areas, the use of energy storage, dispatchable load, and distributed generation resources. For the BPA and California ISO control centers, the new regulation service will look no different when compared to existing regulation resources. It should be stressed that the proposed project will start benefiting the regulation service and load following demand in these two service areas, regardless of the actual degree of penetration of the intermittent generation resources in the region.

1.2 Overall Goals of the Project

Develop principles, algorithms, market integration rules, functional design and technical specification for an energy storage system to help coping with the wind generation resources intermittency and unexpected fast ramps by recycling the excess energy, controlling dispatchable load and distributed generation, and inter-area exchanging the excess energy between the BPA and California ISO control areas. Provide a cost-benefit analysis and develop a business model for an investment-based practical deployment of such a system.

2. Phase 1 Project Plan and Stage Gates

The project plan for Phase 1 is given in detail in Table 2-1.

Table 2-1 Project Plan and Task Distribution of Each Stage Gate for Phase 1

STAGE GATES	TASKS		DELIVERABLES	DATES
Stage Gate 1	1.1	Evaluate and compare different energy storage configuration options and participating load / distributed generation control schemes. Identify top three technologies that would meet the needs of this project. Provide review of the world experience. Justify the use of the flywheel SEM or alternate energy resources, if something appears to be better as the energy storage device to be used in this project. If the flywheels prove to be the best technology, then this technology will be further used in this study.	A brief summary report and response to BPA's further inquiries.	06/12/07 through 07/16/07
Stage Gate 2	1.2	Design and evaluate different configurations/ integration schemes of the energy storage, participating load and distributed generation, including the ones shown in this report, their combinations, and other options. Identify the most promising configurations and their benefits.	A brief summary report and response to BPA's further inquiries.	06/12/07 through 07/17/07
Stage Gate 3	1.3	Analyze technical and market compatibility of the proposed integration schemes with the existing regulation and load following systems at BPA and California ISO and identify potential minimum changes if they are required.	A brief summary report and response to BPA's further inquiries.	07/18/07 through 07/31/07
	1.4	Develop initial algorithms for the energy storage, distributed generation and load control. Implement them as MATLAB™ codes.	---	
	1.5	Collect and preprocess data needed for experiments from the BPA and the California ISO.	---	
	1.6	Conduct experiments using the MATLAB™ model and collected data.	---	
	1.7	Carry out the cost benefit analysis based on simulation results.	---	
	1.8	Evaluate changes that are needed for the San Ramon prototype SEM (if any).	---	
Stage Gate 4	1.9	Provide a summary of results and recommendations for BPA on continuation of the project. Write and submit Phase 1 Report.	- Phase 1 Summary Report including results of Tasks 1.1-1.9. - Description of the methodology used in Task 1.6. - MATLAB codes. - Recommendations for BPA on a continuation of the project. - Provide BPA with the proposed SOW and budget for Phase 2. - Presentation of results and follow up discussion with BPA.	08/01/07 through 09/28/07

3. Stage Gate 1: Evaluate Different Energy Storage Configurations and Identify Top Technologies That Meet the Needs of This Project

The Stage Gate 1 report summarizes the utility-scale energy storage technology options against acceptance criteria that could enable a larger reliance on intermittent energy resources including wind power in the BPA service area specifically and, more generally, across the Western Interconnection.

3.1 Stage Gate 1 Objectives

Evaluate and compare different energy storage configuration options and participating load / distributed generation control schemes. Identify top three technologies that would meet the needs of this project. Provide review of the world experience.

3.2 Why Energy Storage is Needed

As the magnitude of the power provided by intermittent renewable resources grows, it will become increasingly difficult to seamlessly dispatch this energy into the grid. Equipping the grid with additional bulk energy storage capacity will help to balance the output of intermittent sources and also provide a resource that may be independently dispatched to assist the grid in supporting load and maintaining stable operation.

3.3 Approach/Section Criteria

The following selection criteria were applied:

- Ability to frequently change power output (or store and deliver energy) over a wide range at least several times over a 10-minute interval, preferably, several times over 1 minute.
- Ramp rate (the technology should be able to respond to control signals, i.e., AGC signals, changing every 4 seconds).
- Response delay time (the less, the better)
- Duration (able to provide rated power for 15 up to 60 minutes)
- Resource potential to be scaled to achieve needed energy and capacity
- Lifetime.
- Maturity of the technology.
- Industrial use experience for regulation/frequency control.
- Cost.

- Energy efficiency and power density.
- Environmental impacts.
- Ability to provide other ancillary services.
- Ease of siting.

The highest absolute priority was given to the technical characteristics of the energy storage technologies that allow them to perform regulation services. The rest of the characteristics listed above was used to distinguish between the technologies that are capable to follow regulation signals. The cost-benefit analysis was applied to make a final selection of candidate technologies.

There are 13 key criteria listed here and even more features of potential candidates are considered in Tables 3-1 and 3-2. Besides power and energy constraints, the specialty of regulation application requires fast response (AGC signal could change every 4 seconds), long cyclic life (need to activate multiple times every minute) and competitive ramp rate (ancillary market). The candidate could also have more credits for high energy density, low maintenance, long life and low cost. Industrial application demonstrations, ease of siting, and ability to provide other types of services are also practical concerns for utilities.

3.4 Principal Results

Table 3-1 and Table 3-4 compare principal features of 12 generically distinguishable storage options, acknowledging that there are many more derivatives that differ in detail and/or have somewhat different performance. The generic categories comprise flywheels, superconductive magnetic energy storage (SMES), pumped hydro-storage, compressed air energy storage (CAES), super capacitors, several electrochemical battery types, and demand-side control.

The selection process resulted in the selection of flywheels, pumped hydro power plants (or conventional hydro power plants) and sodium sulfur (or nickel cadmium) batteries for detailed evaluation in the following stage of the study. Each of the latter technologies has been commercialized and has generated a record of operational experience that minimizes the risk of scaled–up application.

3.5 Technology Screening Considerations

The following summarizes the primary considerations that guided this selection.

3.5.1 Selected Energy Storage Technologies

Flywheel ESD

This is an established modular technology that has a proven growth potential to utility-scale with no significant "show-stopper" reservations. The flywheel energy storage is a "green" technology that has long cycle life insensitive to the depth of discharge. Besides, high peak power capacity without overheating concerns, high round trip energy efficiency, rapid response, ability to provide other ancillary services because of power electronic interface with the grid and ability to site wherever needed are strong positive values of the technology.

A 100-kW, 25-kWh, scale-power Smart Energy Matrix (SEM) unit – comprised of Beacon Power® flywheels, ancillary electronics and communications and control software – has been built, installed and is currently operating on the California Independent System Operator grid at PG&E's DUIT facility in San Ramon, California. A 20-MW frequency regulation plant comprising 200 high-speed, high-energy flywheels is currently under design by Beacon Power under a contract with the DOE. The plant will be able to provide 20 MW of "up and down" regulation – equal to a 40-MW swing [42].

Pumped or Conventional Hydro Power Plant

This technology is the most developed and practiced utility storage option. The major difficulties are siting and environmental impacts of the two requisite reservoirs. As a possible feasible alternative for the pump hydro storage, a conventional hydro power plant could provide regulation service addressed by this project. The practical use of hydro power resources for wide-area regulation most likely depends on the availability of one of the existing hydro power plants for this service.

Pumped hydro power plant can provide both power regulation and energy storage services. Examples can be found in California, where some pumped storage power plants provide both AGC regulation and intraday energy storage capabilities. In the regulation mode, pumped storage units are following an AGC signal by changing their MW output around the preferred operating points. In this mode, the plants may be capable of providing the maximum ramp rate almost equal to their full capacity in 1 minute. This would be a sufficiently fast response for the purposes of this project. In this respect, the pumped energy storage can be used similarly to the use of conventional hydro power plants for regulation. A transition from the pumping to generation mode takes minutes, and of course this would not be an acceptable response time for the regulation purposes. The energy storage mode could be used to provide intraday services for the wind generation projects and for BPA and California ISO to help in following the schedules, optimizing the daily production schedules and addressing the over-generation problem.

Sodium Sulfur (NaS) Batteries

Sodium sulfur batteries have been employed in power systems for more than 20 projects in Japan and worldwide since the 1980s. Compared with other battery technologies, NaS batteries have attractive energy density (over four times that of lead-acid battery) and low capital cost. They also have a long cycle capability (2500 plus cycles upon reasonable depth of discharge) and millisecond response with full charge and discharge, which have a good potential for regulation application.

The technology is highly efficient by having a high cell DC efficiency (up to 89%), no self discharge, minimal maintenance and long life (up to 15 years). NaS batteries are made of abundant low cost materials which are suitable for high volume mass production. Modular fabrication yields potentially high power and energy capability which also reduces the construction intervals.

The NaS battery, like most other electrochemical batteries, basically consists of two electrodes separated by an electrolyte. However, unlike most other batteries, the electrodes are liquid and the electrolyte solid. The anode is molten sodium (Na), the cathode molten sulfur (S) and the electrolyte a beta-alumina (β''-alumina) solid electrolyte (BASE). The beta-alumina in combination with a mobile sodium ion (Na^+) transports sodium ions very well, while retaining all other liquids as well as electrons. During discharge, sodium ions at the anode migrate through the electrolyte to the cathode. The remaining electrons, being unable to pass through the electrolyte, travel outside the battery, resulting in an electric current. At the cathode, the sodium ions and the electrons recombine with sulfur and form sodium polysulfide (Na_2S_x). The NaS battery is usually cylindrical with the anode contained in the center of a BASE cylinder, and the cathode contained between the BASE cylinder and another larger cylinder, that also forms the battery's outer casing. To keep the electrodes liquid and the BASE at its optimal operating point the battery is operated at a temperature about 250^{o}C -300^{o}C.

The NaS battery has a long cycle life, attractive energy density and a good scaling potential to power system applications. However, there are some technical issues that still need to be properly addressed, particularly related to the containment of the liquid electrodes (corrosion of the electrode containers and brittle glass seals). Although implemented as utility energy storage in Japan (up to 64 MWh), the technology is considered immature for application within this project.

The NaS batteries have demonstrated their ability on improving power quality, emergency power supply and stabilization of renewable power resources from kW to MW level on utility substations. For example, they are used in a substation update demonstration project at Charleston, Virginia, by AEP. The batteries could generate up to 1.2 megawatt power for up to 7 hours, easing the strain of overloaded substation. AEP was also expecting to a delivery of 6-MW NaS battery systems in 2008.

Nickel-Cadmium (Ni-Cd) Batteries

The nickel-cadmium battery is another electrochemical battery type, with a widespread use in portable consumer electronics. It is like the lead-acid battery an electrochemical cell, based on the conversion of cadmium (Cd) to cadmium hydroxide ($Cd(OH)_2$) at the anode and nickel oxyhydroxide (NiOOH) to nickel hydroxide ($Ni(OH)_2$) at the cathode. The electrolyte is not consumed by the process and is commonly an aqueous solution of potassium hydroxide (KOH). Compared with the lead-acid battery, the Ni-Cd battery has higher energy density and is more temperature tolerant. For the purpose of regulation, it has the important feature of being tolerant to deep discharges, and storage during the discharged state. Drawbacks are higher costs and the need for advanced battery monitoring during charge and discharge.

An application of Ni-Cd batteries is the Golden Valley Electric Association BESS (Battery energy storage system) [40] project in Alaska. Batteries were supplied by SAFT, Power electronics by ABB. This system, commissioned in December 2003, was designed to provide 26 MW for 15 minutes or a full 40 MW for 7 minutes.

3.5.2 Eliminated Options

The following options were eliminated from further immediate consideration because they exhibit various significant disadvantages or technological immaturity despite possessing potential advantages that may warrant reinvestigation over the longer term. This is particularly true of several evolving battery options that, with both further technical development and accumulated operating experience, may be eventually preferable to the above noted conventional choices.

Superconducting Magnetic Energy Storage (SMES)

In a SMES, the energy is stored in the magnetic field of a superconducting coil. The coil must be kept at a very low temperature to maintain its superconducting capability. Advantages include an extremely short response time as well as high efficiency (the superconducting coil itself is theoretically lossless, but the conversion from AC to DC and back implies losses, as does the continuous cooling of the coil).

Applications of SMES are able to provide high power, very fast, but usually for very short periods (seconds). It has scaling potential to about 1 MWh capacity without serious siting restrictions, but the exposure of the surroundings to the magnetic field must be considered. Besides, the immaturity of the large-scale SMES systems capable of bulk storage is a major disadvantage.

Compressed Air Energy Storage (CAES)

This is an established energy storage technology in grid operation since the late 1970s. With this technology, energy is stored mechanically by compressing air. When the air is expanded again, energy is released to the grid. If the heat that develops during compression is conserved, this mechanical process is theoretically 100% efficient. However, in large-scale systems, that is not likely to be the case. Furthermore, combined with the losses occurring during the conversion from electrical to mechanical energy and back, the round-trip efficiency is very low. Other disadvantages include slow response and fewer environmentally acceptable siting opportunities.

Demand-side Management (DSM)

Demand-side management offers benefits similar to those of other energy storage technologies using end-use thermal storage and other means of load reduction or deferral. While demand-side management has been applied successfully for over 25 years, it was not selected as an option in the present study. Current utility DSM program shows that it does not routinely provide the amount or quality of load control equivalent to the value offered by dispatchable energy storage options, although it shows promise for doing so in the future. Therefore, demand-side management is considered to be still an immature tool for immediate usage. It has been demonstrated in the Olympic Peninsula Project [83] by PNNL that a DSM system with the help of grid friendly appliances (GFA) shows advantages on mitigation wind power penetration. The DSM system along with GFA would be promising to be used for regulation control. The potentials of DSM would be further explored in future work.

Super Capacitors

Superior to most conventional battery systems in speed of response and cycle life, super capacitors are a developing technology that is not yet applicable for the storage requirements of electric utility-scale operations.

Like traditional dielectric capacitors, the super capacitor (or ultra capacitor) stores energy by physically separating negative and positive charges. The energy density of super capacitors is, however, much higher than that of traditional capacitors as a result of a modified internal capacitor structure. The short charge and discharge time (fractions of seconds) known from traditional capacitors is partially maintained (few seconds), as well as the very long cycle life (potentially 100,000s of cycles). Accordingly, the super capacitor is said to gap the bridge between batteries and capacitors in terms of energy density and response time. Super capacitors are a rapidly developing technology and a strong research effort in continuously improving the energy density.

Current applications typically take place in combination with batteries or other storage or power supplies, in situations where a low average, but high pulse, power is needed. An example is cars, where the use of super capacitors can decrease the needed battery size or in buses, where the capacitors store braking energy and release it during acceleration.

The technology is not yet considered applicable for the storage requirements of power system regulation or other large-scale electric storage operations.

Lead-Acid Batteries

As a well developed advanced battery technology, lead-acid battery systems are easily sited and have been employed in multi-megawatt level assemblies for load leveling and grid stabilization. Compared with other advanced battery technologies, they have shallow depth of discharge, lower energy density and higher capital cost, which limit their application on regulation services.

The lead-acid battery has an evolutionary development history of over 100 years, and is currently well-known to everyone because of its widespread use in cars and trucks. It is an electrochemical battery, based on lead electrodes submerged in sulfuric acid. When the battery is discharged, lead (Pb) is converted to lead sulfate ($PbSO_4$) at the anode (releasing two electrons), and lead oxide (PbO_2) to lead sulfate ($PbSO_4$) at the cathode (absorbing two electrons). The process is theoretically reversible, but a layer of non-convertible lead sulfate tends to build up at the electrodes during cycling. This problem is particularly significant if the battery is left in a discharged state for long periods. Other problems with this technology include corrosion of the electrodes and the shedding of active material from the electrode as a result of volume change of the material during deep discharge. The technology is relatively inexpensive and easily sited, and has been employed in multi-megawatt assembles for load leveling and grid stabilization.

The largest demonstration for electric utility applications in the United States is a 20-MW/18-MWh plant in San Juan, Puerto Rico, providing spinning reserve, frequency control, and voltage control.

Nickel Metal Hydride Batteries

The nickel metal hydride (Ni-MH) battery is a variant of the Ni-Cd battery, having an alloy of various rare metals as the anode instead of cadmium. It shares many advantages with the Ni-Cd battery including robustness to deep discharges and a long cycle life. In addition, it has a higher energy density than Ni-Cd batteries, but on the other hand, a slightly larger internal resistance.

Application of Ni-MH batteries is widespread in consumer electronics, replacing the Ni-Cd as the preferred substitute of alkaline cells in cameras and toys, etc. On the kW scale, it is found in most hybrid electric vehicles currently on the market. However, operating experience on the MW scale for electric utility storage is not currently present.

Lithium-Ion Batteries

With high energy density and long cycle life, lithium-ion batteries are increasingly becoming the workhorse battery in portable consumer electronics but are not yet suitable for bulk power storage at the utility scale.

The lithium-ion battery is like nickel and lead-acid batteries based on an electrochemical process, but unlike these batteries, the electrolyte is non-aqueous. The battery consists of two electrodes, both containing lithium, submerged in an electrolyte, which is a lithium salt in an organic solvent, e.g., ether. The anode is usually graphite (LiC_6) and the cathode cobalt oxide ($LiCoO_2$). During discharge, lithium ions (Li^+) migrate from the anode, through the electrolyte, to the cathode. An electron similarly moves from the anode to the cathode, outside the battery, creating an electric current.

Some critical drawbacks, however, limit the application of lithium-ion batteries. In the charged state, the battery is inherently unsafe and extremely sensitive to over-temperature, over-charge and internal pressure built-up. This means that advanced monitoring equipments and safety precautions are needed. Additional drawbacks for power system applications are the intolerance to deep discharges, and the relatively rapid, cycling-independent reduction of capacity with aging.

Zebra Batteries

The Zebra battery (whose name originates from the Zeolite Battery Research Africa Project) is an evolution of the NaS battery. Like the NaS battery, it has a molten sodium anode and a beta-alumina solid electrolyte, but the cathode is molten sodium chloraluminate impregnated in porous nickel chloride structures ($NiCl_2$). Additionally, the mechanical design is somewhat different from that of the NaS battery, with the cathode in the center and the anode around it, separated by the electrolyte. The basic principle of operation is the same as for the NaS battery, i.e., sodium ions migrate from the anode to the cathode, resulting in surplus electrons at the anode, that in turn generate an electric current when they travel to the cathode outside the battery. At the cathode, sodium ions and electrons react with the nickel chloride ($NiCl_2$) to form nickel (Ni) and sodium chloride (NaCl).

Some of the corrosion problems with NaS batteries are mitigated by the Zebra design. However, until now, maturing technology has mainly been focused on special applications such as electric vehicles and submarines, where the energy density is of high concern. Future has to be shown, if this technology is to be mature for electric utility applications.

Flow Batteries

Having very attractive energy, power, cost and scaling potentials, flow battery technologies are still in the process of maturation at the utility scale. They have not yet been established well enough in the U.S. to be selected for the present evaluation.

Unlike traditional electrochemical batteries, flow batteries are a series type of batteries with a continuous replacement of one or more liquid electrolytes. Additional electrolyte is stored outside the battery in tanks, and is pumped through the battery cell during operation.

In Redox (reduction-oxidation) flow batteries, e.g., the vanadium Redox battery (VRB) and the polysulfide bromide battery (PSB or Regenesys), all chemicals that actively take part in the electrochemical energy conversion are dissolved in the electrolyte. It means that no deposit of material takes place within the battery cell during charging and discharging. Therefore, the energy capacity is determined only by the size of the electrolyte tanks, whereas the power capacity is determined by the cell and the pumping capacity. This stringent separation of power and energy capacity configuration is one of the major advantages of the Redox batteries.

In contrast, the hybrid flow batteries, e.g., the zinc bromine (ZnBr) batteries, are based on processes, where material is deposited as solids within the cell during charging or discharging. The consequence is a correlation of power and energy capacity as known from most other batteries, even though some variations are still possible.

Common advantages of flow batteries are long cycle life, short response time and a symmetrical charge/discharge rate, making them suitable for power system applications. Particularly, the vanadium Redox battery technology seems to be promising. But, present installations are mostly test sites or demonstration projects, and the maturity of the technology is, therefore, not considered sufficiently well proven.

Metal-Air Batteries

With high energy density as its principal asset, the metal-air battery technology does not have a manufacturing base that is well enough developed to be a candidate for utility-scale operations. The drawbacks for power system applications are severe, and include complicated recharging (many types are not electrically rechargeable but must have active material replaced), low power output, and poor cycle life.

Advanced Batteries

Many of the battery technologies described above are currently under development to improve their power and energy density characteristics, cycle life and costs, and/or to mitigate some other specific problems. Such improved battery types include gelled lead-acid batteries, and advanced variants of the lithium-ion and nickel batteries. Although these efforts may result in better storage options in the future, the lack of operating experience with these technologies is considered a critical drawback for their use in this project.

Plug-in Hybrid Electric Vehicles (PHEV)

Plug-in hybrid electric vehicles are vehicles that are equipped with a battery of a significant size. Special electronic equipment could allow the grid to utilize this battery while the vehicle is parked. The advantage of this approach is that the battery resource otherwise left unused is utilized when needed by the electric utility. However, this is a strongly dispersed resource that requires a complicated information infrastructure to be developed to control the battery charge/discharge process. Besides, the technology is still at its early stage, and it is not presently available for a commercial application.

Table 3-1 Energy Storage Technology Attribute Summary

	Flywheel	SMES	Pumped Storage	CAES	Super Capacitor	Lead-Acid	NaS	Flow Battery	Li-ion	Ni-Cd	Metal Air	Demand Control
Advantages	High power capacity; short access time; long life time; low maintenance effort; high efficiency; small environmental impact.	High power capacity; short access time; long life time; high efficiency	Very high energy and power capacity; moderate access time; long life time;	Very high energy and power capacity; long life time;	High efficiency; Long life cycle	High power capacity; low volume energy density; low capital cost; long life time	Very high energy and power capacity; high energy density; high efficiency; long life time	Very high energy and power capacity; long life time	Short access time; high energy density; high efficiency	Short access time; high energy density; high efficiency	Very high energy density	Huge potential capacity, fast response
Disadvantages	Low energy density	Low energy density; high production cost; potential adverse health impact	Special site requirements; adverse impact on environment; moderate efficiency	Low efficiency; adverse environmental impact; low efficiency	Low energy density; few power system applications	Low efficiency; potential adverse environmental impact	Production cost; safety concerns	Low energy density; low efficiency	No large energy market application so because of technical and cost issues	Cycling and safety control required	Few rechargeable batteries available	Cost

Table 3-2 Energy Storage Technology Features

	Flywheel	SMES	Pumped Storage	CAES	Super Capacitor	Lead-Acid	NaS	Flow Battery	Li-ion	Ni-Cd	Metal Air	Demand Control
Ease of Siting	Required rated floor to load machine (200 lb / ft^2)	Large area requirement (100-mile diameter for GWh storage)	Large body of water or large variation in height	Specific underground geological characteristics required	No specific restrictions	No specific restrictions	No specific restrictions	No specific restrictions	No specific restrictions	No specific restrictions	No specific restrictions	Requires identification of existing controllable load, distributed loads for aggregation.
Environmental Impact	Green technology	Possible adverse health impact due to extensive magnetic field [4]	Adverse impacts on environment both upstream and downstream	Adverse environmental impact, similar as conventional power plants	Environmentally friendly	Potential lead pollution	Made of inexpensive and non-toxic material	Environmentally friendly	Made of toxic material and requires recycling and safety control	Made of toxic heavy metal, should be under recycling and safety control	Environmentally benign	Environmentally friendly, green, may accompany energy conservation.
Cyclic Capability	Over hundreds of thousands cycles [27]	Several 1000	No limitations within the life cycle.	No limitations within the life cycle	1 million >10000 [37]	Thousand cycles for 2-5% discharge; 300-500 [35] with deep discharge	Long	> 13000 [17]	1200 cycles[1]	2000 cycles [1]	Few hundred cycles [7]	Good. Depends on application.

[1] The cyclic capability of the batteries is changing depending on the depth of discharge (DOD). Higher rate of DOD tends to reduce their capability.

	Flywheel	SMES	Pumped Storage	CAES	Super Ca-pacitor	Lead-Acid	NaS	Flow Battery	Li-ion	Ni-Cd	Metal Air	Demand Con-trol
Life Cycle	20 year	> 20 year	40 year	30 year	40 year	15 – 20 year (5-10 yr for each cell	15 year	10 year [6]	Limited	Limited	Designed for multi-year operation	5 – 15 years
Power Capacity	25 MW	3 kW	100 – 4000 MW [12]	25-3000 MW [12]	Up to 250 kW	Up to 500kW [12]	1 MW	100kW-10 MW	Up to 500 kW	Up to 500 kW		Multiple MW for commercial or aggregated, distributed loads.
Energy capacity [18]	2.5 MWh	10 MWh	500 M–15GWh	200M – 10GWh [12]	10 kWh	100 MWh	1 MWh	1-100 MWh	Up to 100 MWh	Up to 100 MWh		Depends on application. Capacity decays over minutes to hours. Multiple MWh.
Response speed[2]	ms	ms	Seconds to 1 - 3 minutes	9 minutes full, or 6 minutes emergency start	< 1 minute	Instantaneous discharge	ms	Under half a millisecond for a 100% load change	Instantaneous discharge; depth charge reduce life cycle	Instantaneous discharge		Seconds to about 30 minutes

[2] Response speed shows how fast the units could be in terms of releasing power into system.

	Flywheel	SMES	Pumped Storage	CAES	Super Capacitor	Lead-Acid	NaS	Flow Battery	Li-ion	Ni-Cd	Metal Air	Demand Control
Duration	Full power for 15 minutes	High power for several seconds	Rated power for long time	Rated power for long time	Rated power for seconds up to several minutes	Rated power for a few seconds up to a couple of hours	Rated power for hours, very high power for minutes	Rated power for long time	1 – 8 hr	1 – 8 hr		Seconds – 4 hours
Self discharging	1 - 10 % / h	Cooling power	low evaporation	--	10 % / day	40 % per year [9]	No	Not significant	5 – 10 % per month	25% per month		Not directly applicable. Value is deferred (thermal) storage, deferred load.
Maintenance cost / MWh [22]	$4	$1	$4	$3	$5	--	--	--	--	--	--	Variable. Up to $3K per year for residential programs.
Storage Cost/kWh	$300 [31] (100 MW project)	$275	$10	$1 [31] (300 MW project)	$100 (300 MW project)	--	--	--	--	--	--	$50 - $200K

	Flywheel	SMES	Pumped Storage	CAES	Super Capacitor	Lead-Acid	NaS	Flow Battery	Li-ion	Ni-Cd	Metal Air	Demand Control
Capacity cost/kW[3]	$150 (100 MW project) [31]	$975 (1000 MW project)	$900-1490 (500-2000 MW project) $1000	$425-625 (25-300MW project)	$120 (100 MW project)	$120 (10 MW project)	-	-	-	-	-	-
Cost of 20 hrs storage/kW	$6200 [31] (100 MW project)	-	$1100	$460 (300MW project)	$6100 (100 MW project)	$2100 (10 MW project)	-	-	-	-	-	-
Weight / MWh	3000 kg	10 kg	3000 kg	2.5 kg	10000 kg	30 - 40 Wh/kg	See Table 3-4	See Table 3-4	See Table 3-4	See Table 3-4	See Table 3-4-	Not applicable

[3] Power conversion system costs vary according to different companies' quotes. The range is from $80-320/kW for area control and frequency regulation purposes, which is not included in the capital cost here. The value would be reduced along with technology development.

	Flywheel	SMES	Pumped Storage	CAES	Super Capacitor	Lead-Acid	NaS	Flow Battery	Li-ion	Ni-Cd	Metal Air	Demand Control
Round Trip Energy Efficiency , % (w/o power electronics)[4]	85 - 90	90-95	70 - 85	70+	95	75	89 - 92	70 - 75	96	70 - 90	50	Not directly applicable. Value is deferred (thermal) storage, deferred load.

[4] Typical power loss on power conversion systems is between 1% and 3%, and it varies for different manufacturers. Usually it works more efficient for full load condition than half load[32].

Table 3-3 Known Energy Storage Technology Application Examples

	Flywheel	SMES	Pumped Storage	CAES	Super Capacitor	Lead-Acid	NaS	Flow Battery	Li-ion	Ni-Cd	Metal Air	Demand Control
Power System Operational Experience	Fuji Electric, Tokyo, Japan; Darwin wind farm, Power-Corp, Darwin, Australia; Frequency regulation plant, CA	Anchorage, Alaska project (31.5 MVA and 0.5 MWH), operation from April 2000 to now [21]; Tacoma - BPA 1983 10 MW; San Diego Gas and Electric Study 550 MW, 1 sec.	Too many to list them all [23]	Huntorf, Germany, 290 MW since 1978; and McIntosh, Alabama, 110 MW since 1991	Most application on public transportation [25]	Chino, Ca, 40 MWh from 1988; Helco, Hawaii, 15 MWh from 1993; Prepa, Puerto Rico, 15 MWh from 1994; and Vernon, CA, 4.5 MWh from 1995 Use in a PHEV with a storage capacity of 8 kWh	A 6 MWh system has been installed at Tsunashima, Japan	A 1.5MW UPS system in a semiconductor fabrication plant in Japan; A 275 kW output balancer in use on a wind power project in the Tomari Wind Hills of Hokkaido; A 200 kW, 800 kWh output leveler in use at the Huxley Hill Wind Farm on King Island, Tasmania; A 250 kW, 2 MWh load leveler in use at Castle Valley, Utah; and 12 MWh flow battery is also to be installed at the Sorne Hill wind farm, Ireland [16]		1. Fairbanks, Alaska, 40 MW for 6 to 7 minutes or 25 MW for 15 minutes		Numerous examples from 1970s and later.
Technology Maturity	Limited commercial	Commercial	Commercial	Commercial	Commercial	Limited commercial	Limited commercial	Limited commercial	Commercial (not in power applications)	Commercial (not in power applications)	Commercial (not in power applications)	Commercial products exist for control of residential loads.

	Flywheel	SMES	Pumped Storage	CAES	Super Capacitor	Lead-Acid	NaS	Flow Battery	Li-ion	Ni-Cd	Metal Air	Demand Control
Plant Startup Time	--	3 - 4 years	6 - 8 years	2 - 3 years	4 – 6 years	--	--	3 - 4 years	--	--	--	1 – 2 years
Developers	Beacon Power; Active Power, Inc; AFS Trinity Power; Piller Gmb; and Urenco Power Technologies Limited, AC Propulsion	Babcock and Wilcox (B&W); Superconductivity, Inc, Intermagnetics General Corporation, American Superconductor Corporation	MWH	CAES Development company; Ridge Energy Storage, Dresser-Rand Company	SAFT; NESS; ESMA; Power; Cache(Maxwell); ELIT; and Powresystem Co.	GNB Industrial Power/Exide; Delco; East Penn; Teledyne; Optima Batteries; Winston Salem; JCI Battery Group; Trojan; and Crown Battery	NGK	VRB power systems, Inc.; Reliable Power; Pinnacle; Sumitomo Electric Industries, Ltd; and Cellennium Company limited	SAFT and HITACHI	SAFT	EVionyx; AER Energy Resources; Metallic Power; Chem Tek; Power Zinc; Electric Fuel; Alupower; Aluminum Power; and Zoxy Energy Systems	Residential: Cannon, Comverge, Concurrent, Itron, ESCO, and many others. Small comm.: Echelon, Site Controls, Cimetrics, EnerNOC, Silver Spring, Inc., Tridium, and many others.
Possible Applications	Frequency control; generation reserve, transition supply to long-term backup supply	Short duration energy storage (improve power quality), transition supply to long-term backup supply	Frequency control; generation reserve	Shaving peak, black start capability, load leveling, frequency voltage control	Short term power supply, public transportation	Shaving peak, generation reserve, UPS	Shaving peak, generation reserve, UPS	Relatively large (1 kW - many MW) stationary applications	--	Black start, emergency power supply	Stationary applications, UPS	Peak load management, regulation, voltage support, distributed dump loads

	Flywheel	SMES	Pumped Storage	CAES	Super Ca-pacitor	Lead-Acid	NaS	Flow Battery	Li-ion	Ni-Cd	Metal Air	Demand Control
Other Services	Voltage support, regulation	Voltage support, regulation			Voltage support, regulation	Voltage support, regulation	Voltage support, regulation	Voltage support, regula-tion	Voltage support, regulation	Voltage support, regulation		Voltage support by distributed capacitors. Regulation, load following

Table 3-4 Comparison of Different Technologies Subject to Potential Regulation Requirements [38]

Battery category	Battery name	DOD	Battery Energy, MWh*	Charging rate for 10 MW, hrs	Wh/kg	Wh/Liter	Weight, Tons	Volume, kL	$/kWh	Cost, $M	W/kg actual	Comments
Lead-Acid Battery	Pesaran Pb-acid Gelled (Lead-Acid)	1.24	26.9	2.69	25		1075		140	3.76	18.6	Too heavy
Lithium-Ion Battery	Pesaran Li-ion	2.74	12.2	1.22	70		174		1100	13.38	115.1	Very costly, available only to 10 kW
	Li-Ion Advanced	5.00	6.7	0.67	120		56		1100	7.33	360.0	Lightweight, available to 10 kW
Nickel Metal Hydride Battery	Ni-MH	2.74	12.2	1.22	40		304		600	7.30	65.8	Available to 2 MW
Sodium Sulfur Battery	Na-S	5.00	6.7	0.67	110	367	61	18	140	0.93	330.0	Lightweight, high temperature.
Evolution of NaS Battery	Zebra assume 4% DOD	4.00	8.3	0.83	120	154	69	54	100	0.83	288.0	Beta R&D claims this can be used for load leveling up to 10 MWh energy
Nickel-Cadmium Battery	Ni-Cd	2.74	12.2	1.22	30		406		500	6.08	49.3	Heavy - Alaska project - 26 MW, 14.5 MWh SAFT Ni-Cd battery
Flow Battery	ZnBr	0.24	138.9	13.89	100		1389				14.4	Too heavy. Available to 5 MW. Need more data at shallow DOD
	ZnBr Assume 6% DOD	6.00	5.6		100		56				360.0	
	Vanadium Redox	0.24	138.9	13.89	17		8170		380-600 [39]		2.4	Too heavy. Need more data at shallow DOD Intended for up to 5 kW
	Regenesis, Assume 4% DOD	6.00	5.6	0.56	77		72				277.2	120 MWh 15 MW flow battery
	Super Capacitors		0.3		4		83		5000	1.67	240.0	

In Table 3-4, we assume that the energy demand, which we need to cycle and which determines the required depth of discharge (DOD), corresponds to 10 MW power output supplied for 1 minute. Therefore, the full cycle (charge/discharge) will be 2 minutes. Those assumptions lead to the following model: (1) The battery is forced to cycle 30 times each hour; (2) Being in service for 1 year requires 262,800 full cycles (repeated charges and discharges). The DOD of each battery is determined based on Figure 3-1. Note that batteries are kept at a shallow DOD to obtain a longer cyclic capability.

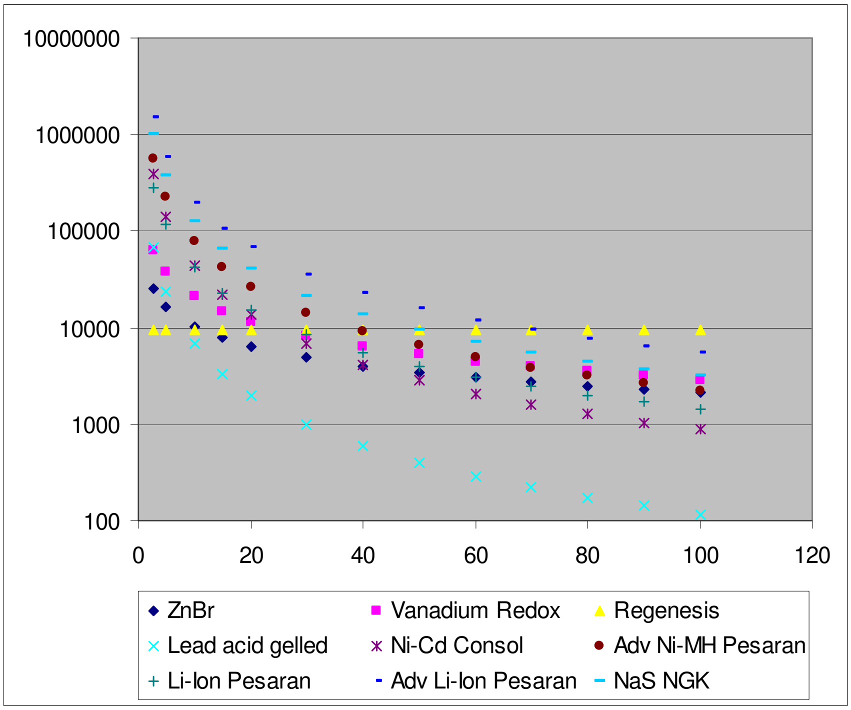

Figure 3-1 Lifetime cyclic capability (cycles/lifetime, vertical axis) vs. the percent depth of discharge (horizontal axis) of different battery technologies [38]

Figure 3-1 gives an estimate of the total number of cycles relating to the depth of discharge (DOD). The total number of cycles is reduced along with the DOD being increased. To be able to satisfy the cyclic requirement for regulation services under the conditions assumed above, the battery should work at a low DOD. More detailed information is given in Table 3-4 (in the column under "DOD"). To increase the number of cycles that a battery can withstand, the total required battery energy capacity and the number of batteries in the ESD should be expanded based on this consideration. For instance, a 26.88 MWh energy capacity will be needed for the lead-acid batteries.

The capital costs per KWh of competing battery technology have been provided by Dr. V. Viswanathan [38]. The same source also gives energy density information. The capital cost and weight information for the competing battery technologies are compared in Figure 3-2.

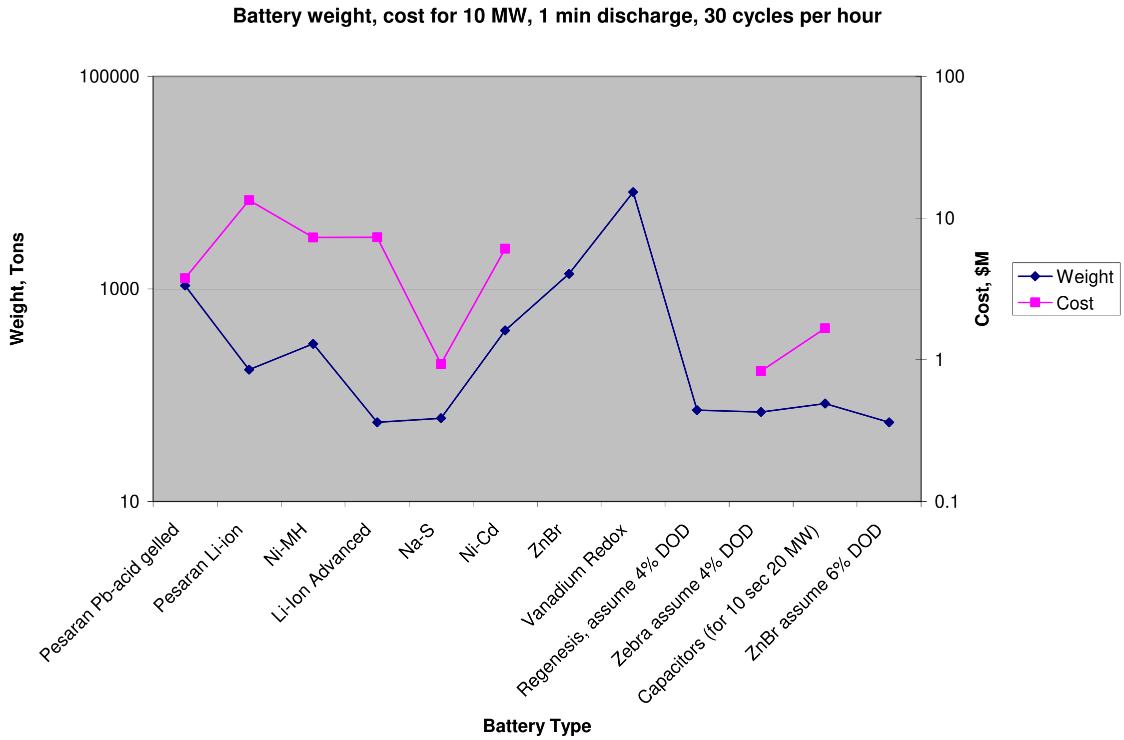

Figure 3-2 Cost and weight comparison of advanced battery technologies

Based on available information, it is clear that, among other types of batteries, NaS batteries have the lowest capital cost.

4 Stage Gate 2: Design and Evaluate Different Configurations and Integration Schemes of the Energy Storage. Identify the Most Promising Configurations and Their Benefits.

This section summarizes the effort to analyze, compare and select system architecture options, to optimize the grid-connected value of energy storage devices (ESDs) and to enable a larger reliance on wind power in the BPA and California ISO service areas. References [3]-[40] were used to collect information on currently available energy storage technology options.

4.1 Stage Gate 2 Objective (in Phase 1)

Design and evaluate different configurations and integration schemes of energy storage, participating load and distributed generation, their combinations, and other options. Identify the most promising configurations and their benefits.

4.2 Why the System Architecture is Important

There are various possible approaches to providing regulation services and integrating energy storage devices (ESDs) into the grid that have different implications on system operations, markets, asset utilization, overall efficiency and value added. The wind power resource in the area served by the Western Interconnection is approaching a magnitude that, because of its intermittency, will be increasingly difficult to dispatch without causing noticeable additional stress to the grid. The effectiveness of regulation services in mitigating this stress varies depending on various factors including the size of the area covered, number of ESDs, the number and diversity of intermittent resources included, the dispatch authority and others. The effort briefly reported here compares advantages and disadvantages of different architectures and identifies one or more preferred configurations.

4.3 Architecture and Comparison Criteria

Table 4-1 compares distinguishable architectures for providing regulation services by incorporating energy storage into the grid. The preferred regulation service architecture should meet the following requirements (four minimums rule):

- The overall efficiency of the solution (Minimum total regulation capacity required).

- Compatibility with the existing regulation systems and markets (Minimum changes).
- Minimum technical difficulty of implementation.
- Minimum cost for BPA and California ISO.

Several considerations of the preferred architecture can be discussed:

- The maximum value of the regulation service, as well as the ESD-based balancing service, is achieved when it is addresses multiple intermittent resources distributed over a large geographical area.
- The efficiency of the regulation service is increasing if it addresses the load intermittency and uninstructed deviations of conventional generators concurrently with the intermittent renewable resources.
- The strategic choice to be made is between the horizontal scheme for balancing intermittent resources (the direct integration of regulation service providers with particular renewable energy projects or groups of projects) and the vertical scheme (indirect integration via the BPA EMS or wide area EMS). Although the horizontal scheme has its own merits and cannot be eliminated from consideration, the vertical scheme provides better overall efficiency by addressing multiple sources of intermittency altogether rather than addressing them one by one.
- The architecture with two different types of regulation devices, for instance the flywheel ESD and pumped storage (or a conventional hydro unit), gives more flexibility and maximizes the value of the wide area EMS compared to the architecture that employs only one ESD. Participation of a pumped storage or conventional hydro unit in the wide area EMS will help to effectively double the flywheel's regulation range and help to continuously maintain the required flywheel's state of charge. The flywheel ESD, in turn, could help to minimize the regulation stress posed on the hydro generation unit.
- To provide a smooth integration of the wide area EMS into the BPA and California ISO systems, the regulation service characteristics and integration requirements should be very similar to the ones that are currently used in these service areas.
- Participation of a pumped storage or conventional hydro units in the Wide Area EMS is justified if they are existing units. Capital cost considerations and other difficulties will be most likely unfavorable if a new hydro power plant is considered.
- Limited California Oregon Intertie operating transfer capability (OTC) should be addressed in the project's design.
- ACE and conventional units' regulation signals are prime candidates for the control signal used to control the wide area EMS.
- An important additional feature is that ESDs are employed to provide additional services such as static VAR control, frequency response, and the others. This could help to justify the ESD's cost.

Table 4-1 Architecture Table

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
1. Main Grid Integration Principle of the ESD	1.1 Horizontal Integration	1.1.1 Direct integration with a wind farm or a group of wind farms	Decentralized regulation and other ancillary services potential for BPA and California ISO	Low efficiency solution for the regulation and load following problems comparing to the integration on control area and interconnection levels	- No cost for BPA or California ISO potentially - Lesser regulation procurements on the BPA and California ISO levels. - Minimum system impact intermittent resource will be created - Energy may be stored and sold by the producer when it is most needed - Increased autonomy on the part of the power producer in use of the asset - Potential to address local problems, e.g., voltage support and stability - Frequency response can be provided on the wind farm level - Fault ride through capability can be provided - Ramp limiting option can be provided on the resource level - A solutions that could potentially lead to building a distributed energy storage resource in these control areas	- Valuable regulation resource may be unavailable for the direct BPA control - An expensive solution that needs to be justified in terms of the benefits for the society - There is no market for decentralized regulation and many other potential ancillary services, e.g., frequency response, voltage support, stability support, etc. - Higher WG production cost and wind energy price	Might be an efficient solution on the wind farm level if the ESD provides multiple services, and these services are supported by incentives, or are paid by the utilities or BPA , or help the WG to be compliant with mandatory requirements (most of these conditions is currently in place). Low efficiency solution in terms of regulation and load following due to selective treatment of one isolated intermittent resource	Paid by wind farm(s). The investment needs justification on the power producer's level	Some wind generation projects in California consider building a horizontally integrated energy storage (batteries)

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
		1.1.2 Integration Through a Utility/Scheduling Coordinator	More accurate energy schedules can be provided to BPA and California ISO	Relatively low efficiency solution for the regulation problems comparing to the integration on control area and interconnection levels	-No cost for BPA or California ISO potentially - Lesser regulation and load following capacity procurements on the BPA and California ISO levels. - Cost sharing opportunities for the utilities and wind projects - Less uninstructed deviations from the schedules - Energy may be stored and sold when it is most needed - More efficient dispatches of utility resources can be achieved - Decentralized regulation and other ancillary services potential for BPA and California ISO - Potential additional black start capabilities	- Collective use of the ESD by multiple projects could introduce conflicts over responsibility in scheduling, maintenance, and other aspects of asset utilization - Valuable ESD regulation resource may be unavailable for the direct BPA control	Might be an efficient solution helping to provide more accurate energy schedules and follow these schedules in real time. Relatively low efficiency solution in terms of regulation and load due to selective treatment of just one system generation region	Collectively paid by utilities and wind farms	- Some utilities in the Pacific Northwest express interest to energy storage options

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
	1.2 Vertical Integration	1.2.1 Separate Integration Through the BPA or California ISO Control Center (through the AGC system) **= Existing System**	Efficient solution for the regulation problem within a particular control area	Energy storage may have some unusual characteristics (limited stored energy, necessity to maintain certain state of charge, fast response) that would require a partial redesign of the BPA and California ISO AGC systems.	- Freedom of location; e.g., the energy storage resource can be located in a less congested area - Regulation is an established service with existing rules and markets - 1 MW of fast regulation can replace up to 2 MW of slower thermal regulation resources (2005 CEC study) - Energy storage can potentially minimize the stress posed on the other units on regulation under a smart control - Energy storage can be involved in multiple functions on the control area level, e.g. providing stability control, frequency response, and others.	- More regulation procurement will be needed on the BPA and California ISO levels comparing with the horizontal integration approach - Multiple intermittent resources with less accurate schedules must be dealt with on the BPA and California ISO levels	Efficient solution collectively addressing multiple sources of intermittency distributed over a control area	Additional regulation costs are paid by the utilities (ultimately, by the loads).	---

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
		1.2.2 Simultaneous Integration With Both BPA and California ISO Control Centers (Wide-Area Integration)	Most efficient solution collectively addressing multiple sources of intermittency distributed over a large geographical area	Complexity of hardware and software solutions on the ESD level	- BPA and California ISO will not be forced to change their operating procedures and AGC/ market systems if the project architecture is right - Creates a more competitive market for regulation services with the potential reduction of the market prices for regulation - Potential expansion of this solution to a wider geographical area, e.g., to the Pacific Northwest	- Need to find investors and resources willing to provide this service - Need to develop new complicated technical solutions, energy management schemes, and control algorithms - Transmission constraints may limit the opportunities for the wide-area regulation service - Additional inter-area telemetry system - Potential opposition from the local providers of the regulation services in Control Areas	Most efficient solution collectively addressing multiple sources of intermittency distributed over a large geographical area	Paid by utilities, IPPs, or other investors and project developers willing to provide regulation service for BPA and California ISO	---
2. Number and Types of ESDs	2.1 One ESD in BPA Area	2.1.1 One Flywheel ESD (or one lead acid /Ni-Cd battery ESD)	A proven solution already implemented in Alaska (NiCd battery ESD) and tested in California (Beacon Power (flywheel ESD)	Effective regulation capacity can be limited by the limited energy storage capacity of flywheels and battery ESDs	-Flywheel or battery ESDs can provide a variety of additional ancillary services (both local and wide area) - Fast response opens the opportunities for developing new more efficient AGC algorithms - Flywheel or battery ESD could help to minimize the stress posed on the conventional units on regulation	- Potential inability to follow the regulation signals due to the limited energy storage capability - Control algorithms need to be developed on the control area or ESD level to obey energy storage constraints - A business case needs to be created for potential investors/project developers	Not the most efficient solution because of the effective regulation range limited by energy considerations and the necessity to provide two-way regulation service	The cost, depending on the ESD size can be $30 million or more. Could be paid by a utility, IPP or external investor.	- Beacon Power and Alaskan experience should be studied.

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
		2.1.2 One pumped hydro storage ESD or conventional hydro	Existing pumped storage may be used without substantial capital investments	Seasonally limited hydro power flexibility may reduce function	- Regulation energy is virtually unlimited - Ramping capacity can be as high as full capacity in 1 minute	- Wearing and tearing problem caused by frequent changes of the regulation signal	Relatively high if an existing unit is selected to provide this service	A major capital cost is involved unless an existing unit is selected	System topography and environmental restrictions may not allow siting at location of maximum benefit
	2.2 Two ESDs in BPA and California ISO Areas	2.2.1 Two of the same type, e.g., two flywheels or two pumped or conventional hydro units	Much more flexibility for the interarea regulation purposes	Effective regulation capacity can be limited by the limited energy storage capacity of flywheels and battery ESDs	- Some potential cost savings from similar control and telecommunication arrangement. - This solution could provide sustainable regulation service when COI is fully loaded - Potential to operate in the "control area only" or "wide area" mode depending on the system situation - Possible for future multi-purpose applications other than regulation, such as short duration power quality improvement, grid angular stability, etc.	- Additional capital expenses will be needed	Relatively high efficiency solution	The cost, depending on the ESD size can be $30 million per ESD or more. Could be paid by a utility, IPP or external investor.	---

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
		2.2.2 Two of different type (e.g., pumped storage of conventional hydro +flywheels or batteries)	Much more flexibility for the interarea regulation + additional capability of providing regulation service	Potential difficulties of providing a coordinated regulation service if the participating ESDs belong to different owners	- Pumped storage or conventional hydro can provide sustainable service when the energy storage capacity of the flywheel or battery ESD is exhausted - This solution could provide sustainable regulation service when COI is fully loaded - Stress posed on the hydro unit can be minimized - The effective regulation range of the flywheel or battery ESD can be doubled by offsetting its state of charge point	- Project participants need to be found - "Engagement rules" need to be developed - Complicated project architecture and control algorithms	A very high efficiency solution	A major capital cost is involved unless an existing unit is selected	An existing hydro or pumped storage power plant willing to participate in this project needs to be found.
	2.3 Distributed Multiple ESD	---	Much more flexibility for the interarea regulation and load following	Complicated telecommunication and control system will be needed	- Possible future multi-purpose applications other than regulation, such as short duration power quality improvement, grid angular stability etc. - Possible combination of local and wide area ancillary services	- Problems with coordination of multiple ESDs - Business model does not exist	Apparently low because of disadvantages	Cost may be significant; Sources of financing are not very clear.	Additional research will be needed

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
	2.4 ESD Integration with Grid Wise Load Control	Beginning with ESDs complemented by opportunistic GridWise ™ control, configuration evolves to GridWise ™ control being predominant and supplemented by ESDs	Controllable load can provide regulation over a wide area and thereby leverage the regulation range of ESDs with limited stored energy	Delivery of the centralized regulation signals to individual load may constitute a significant expense	GridWise™ portion of control response can be highly distributed throughout the control area to lessen the siting criticality of individual ESDs	- Relies on incentives provided to induce customer cooperation resulting in reliance on a not completely predictable control response - Complicated telecommunication and control system will be needed	Full penetration and distribution of GridWise™ technologies would eventually reduce the number of individual ESDs needed	Cost may be significant; Sources of financing are not very clear.	Additional research will be needed
3. Type of control signal	3.1 Regulation signal similar to the one sent to a hydro unit	---	No modifications are required for the BPA and California ISO AGC systems because the ESD will be treated in the same way as one of the existing units on regulation	Potential problems with flywheel and battery ETDs because their stored energy is limited – see other considerations.	- Standard AGC interconnection requirements, performance test and performance criteria remain applicable the ESD facility	- Effective regulation capacity can be limited by the limited energy storage capacity of flywheels and battery ESDs - Potential inability to follow the regulation signals because of the limited energy storage capability	Not the most effective use of the potential opportunities that the fast responsive energy storage are potentially providing (e.g., more efficient regulation, lesser required regulation capacity, lesser stress on the conventional regulating units, etc.)	Least cost solution in terms of required AGC modifications.	The California ISO AGC system is designed to minimize the number of unit reversals on conventional units: they are kept moving up or down until it is necessary to reverse them.
	3.2 Area Control Error (ACE)	3.2.1 Two ACE signals: one from BPA, one from California ISO	No modifications are required for the AGC system because ACE is calculated in any AGC system	The ESD will be treated differently comparing with the rest of the regulating units	- No modifications are required for the AGC system because ACE is calculated in any AGC system	- Effective regulation capacity can be limited by the limited energy storage capacity of flywheel and battery ESDs - Potential inability to follow the regulation signals because of the limited energy storage capability - Special control algorithms need to be developed for flywheel and battery ESDs	- Not the most effective use of the potential opportunities that the fast responsive energy storage are potentially providing (e.g., more efficient regulation, lesser required regulation capacity, lesser stress on the conventional regulating units, etc.)	Least cost solution in terms of required AGC modifications.	---

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
		3.2.2 A sum of ACE signals from BPA and California ISO	The power mismatches will be addressed concurrently over a large geographical area	Objections may arise because this signal implicitly means a virtual "merger" of the control area balancing objectives	- No modifications are required for the AGC system since ACE is calculated in any AGC system	- The ESD will be treated differently compared to the rest of the regulating units - Effective regulation capacity can be limited due to the limited energy storage capacity of flywheel and battery ESDs - Potential inability to follow the regulation signals because of the limited energy storage capability - Special control algorithms need to be developed for flywheel and battery ESDs	Potentially a very effective solution allowing an easy inclusion of additional areas into the wide area EMS	Low	
	3.3 Interconnection frequency	---	Local signal that does not require wide-area telemetry system	There is no market for direct frequency support	- The best possible signal on the interconnection scale of the power balancing problem - The signal is the best match for the underlying ides of the CPS1 and CPS2 performance standards - This signal can also provide automatic frequency response	- This signal can potentially compromise control area CPS2 compliance (if the ESD is large enough)	Not an efficient solution for the current control objectives at BPA and California ISO	Very low cost solution	Some experience with flywheel ESD has been already gained

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
	3.4 Specially generated AGC signal	---	The newly designed signal can potentially help to additionally reduce the regulation requirement and reduce stress on conventional units	Requires a modification of the existing AGC systems	- Potential to explore "new generation" AGC algorithms	- Will require more complicated ESD algorithms - BPA and California ISO would need a very convincing evidence to undertake modifications in their AGC systems	- May be high depending on the success with additional research and developing new algorithms	- Additional costs associated with modifications of existing AGC systems	- Some ideas have been already developed in the course of a CEC-sponsored project - Additional research is needed to explore this potentially efficient option
	3.5 One of the above plus the COI flow information	---	Will help to avoid OTC limit violations resulting from regulation	Regulation service may be interrupted when it violates COI OTC limit	- ESD could help to mitigate oscillations on COI as an additional ancillary service	- Will require more complicated ESD algorithms	The efficiency of the regulation service may be reduced because of its unavailability caused by a congestion on COI	Will require some additional expenses	The project architecture with two ESDs installed in the BPA and California ISO control areas could provide sustainable regulation service when COI is fully loaded

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
4. Means of providing regulation service to a neighboring control area	4.1 ACE Sharing	4.1.1 Full actual ACE sharing [43]	A move toward larger control areas	Will require major changes in the NERC standards and control area operational practices	- This approach could be relatively easily expanded to multiple participating areas - This approach could be a global solution for the interconnection wide balancing function - Could minimize regulation requirement without adding more regulation resources	- This model would be a major change of the organizational and control structures of the U.S. electrical power system. - Require changes of the existing business practices, operating procedures, AGC systems, etc., on the control area level - It is not quite clear how to actually "share the ACE", that is it is difficult to distribute the aggregated ACE among the Control Areas	Could be a very efficient solution for a wide area integration of balancing functions; practical implications of such approach make it ineffective	Apparently, could be a high cost solution	In this report: the full actual ACE sharing is understood as pooling the area control errors together with subsequent distribution of the shares between the participating Control Areas

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
		4.1.2 Partial or full ACE sharing via dynamic schedules = Supplemental regulation service[5]	The approach is described in the NAESB Standards [41].	This is a one-directional "ACE sharing" approach because Area 1 shares the ACE with Area 2, but Area 2 does not share ACE with Area 1.	- Control area where the penetration of intermittent resources is very significant can get external help with their balancing needs. - Smaller control areas can get help from the larger areas with balancing their intermittent resources that they could not balance otherwise. - This is a relatively easy-to-implement option	- Hard to justify why a control area, where the external ACE is dynamically scheduled, could be made responsible or requested to provide balancing service for these resources. - Can increase the balancing requirements in the control area where the external ACE is dynamically scheduled - Not completely clear whether this approach is acceptable for the NERC Standards - Formulas for ACE sharing have not been derived yet, and they would be tough-to-negotiate issues	A high efficiency solution for the areas sharing their ACE with the neighbors. A low efficiency solution for addressing wide-area intermittency caused by one-directional ACE sharing.	Low cost solution	Financial mechanisms should be developed for providing this service.

[5] Supplemental Regulation Service - A method of providing regulation service in which the balancing authority providing the regulation service receives a signal representing all or a portion of the other balancing authority's ACE.

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
4.2 Pooling intermittent resource deviations over a wide area	4.2.1 The use of dynamic schedules or pseudo ties[6]	External intermittent resources can potentially get access to a intermittent resources market or incentives that may exist in neighboring control areas	Hard to justify why a control area where the external intermittent resources are dynamically scheduled could be made responsible or requested to provide balancing service for these resources.	- Utilities and control area where the external intermittent resources are dynamically scheduled can get external help with meeting the objectives of the State RPS's requirements - Smaller control areas can get help from the larger areas with their intermittent resources that they could not balance otherwise. - Integration of external resources using dynamic schedules and pseudo ties are parts of the normal business practice reflected in NAESB Standards as well as in the NERC Standards.	- Can increase the balancing requirements in the control area where the external ACE is dynamically scheduled - It is not clear why the other sources of intermittency, e.g., loads are not included into the pool	A high efficiency solution for the areas whose intermittent resources are dynamically scheduled into the neighboring systems. A low efficiency solution for addressing wide-area intermittency caused by one-directional ACE sharing.	This is a relatively low cost solution		

[6] The use of dynamic schedules or pseudo ties to virtually incorporate some intermittent resources from one area into the other area, so that the latest provide balancing services for these resources.

Classification Level 1	Classification Level 2	Classification Level 3	Main Advantage	Main Disadvantage	Other Advantages	Other Disadvantages	Efficiency	Cost	Other Considerations and Comments
	4.2.2 Real time netting the uninstructed deviations of intermittent resources between control areas[7]	Helps to effectively enlarge the geographical footprint of wind generation and by doing so decrease the relative system impact of intermittency.	If the unscheduled load variations and uninstructed deviations of the other generation resources are not involve in the scheme, this approach becomes much less effective.	- This approach can help to create regional markets to provide balancing services for intermittent resources	- Not completely clear whether this approach is acceptable for the NERC Standards - Formulas for ACE sharing have not been derived yet, and they would be tough-to- negotiate issues	Can be a high efficiency solution	This is a relatively high cost solution		

[7] Implemented between some TSO's in Germany

4.3.1 Selected Configuration

- Configuration with two ESDs: flywheel plus pumped storage (or conventional hydro) – see Figure 4-1.
- One ESD configuration can be also used (as the first step toward the two-ESD configuration or as an alternative configuration).
- Vertical configuration that would integrate the wide area EMS with the BPA and California ISO systems.
- BPA's and California ISO ACE and "conventional regulation unit" signals will be used to control the wide area EMS.
- Dynamic schedules will be used to incorporate the ESD regulation into the corresponding neighboring control area AGC system.
- Control algorithms will be designed to mimic behavior of a conventional unit of regulation and to coordinate the control functions of participating ESDs.

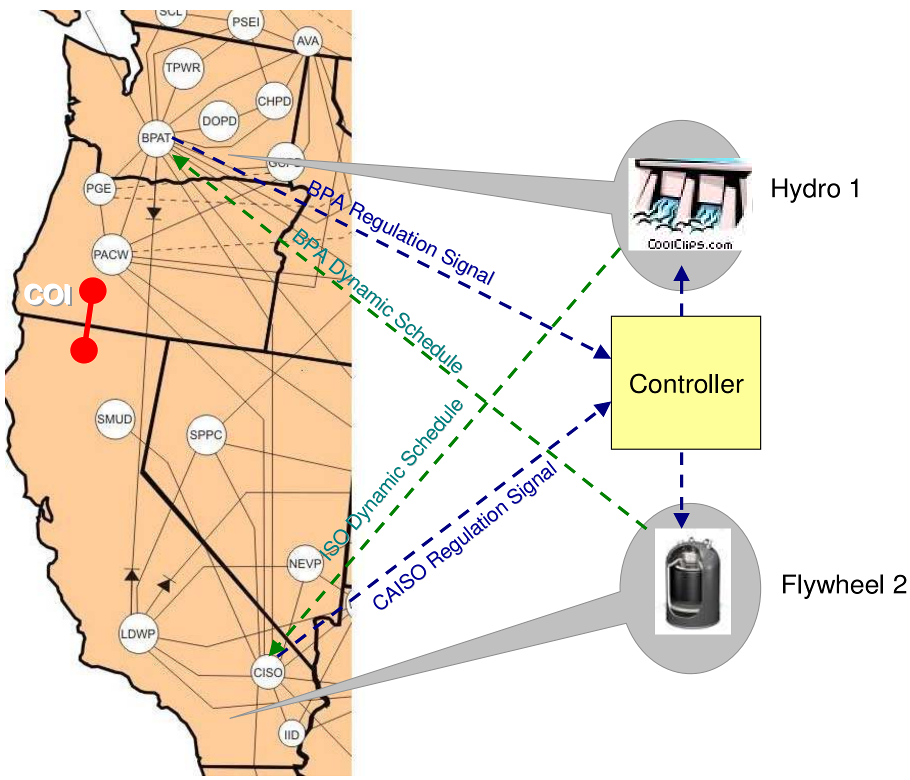

Figure 4-1 Proposed Two-ESD architecture

5. Stage Gate 3: Analyze Technical and Market Compatibility of the Proposed Integration Schemes with BPA and California ISO Systems

This section summarizes the operation processes and general requirements for the resources (including generators, energy storage devices, demand response, etc.) participating system ancillary services in the BPA and California ISO control areas. Ancillary services have multiple components in both systems. This section also focuses on the regulating reserves and operating reserves (including spinning and non-spinning reserves).

The following list outlines the aspects of operation practices summarized in this Section, for the BPA and the California ISO systems, respectively:

- Scheduling and ancillary service processes.
- How ancillary services get paid.
- Technical requirements for resources participating ancillary services.

5.1 Stage Gate 3 Objectives

Analyze technical and market compatibility of the proposed integration schemes with the existing regulation and load following systems at BPA and California ISO and identify potential minimum changes if they are required. Identify the requirements for energy storage devices to participate ancillary services in the two control areas, from both technical and business point of view. Analyze the compatibility of the WAEMS configuration selected in State Gate 2 with the existing practices, and identify potential minimum changes, if needed. Provide reference information on system operation procedures for the simulation and control algorithm design in Stage Gate 4.

5.2 Why Learning the Existing Operation Practices is Important

The practices on scheduling and ancillary services are different in different control areas. The amount of capacity requirement for individual types of operation process, e.g., load following and regulation, can change significantly in the same system with different operation procedures. The ways resources participating ancillary services are compensated, are also different between BPA and California ISO systems. Both aspects, as well as the technical requirements for participating units, will have an impact on the control methodology and economics of the WAEMS aimed at providing ancillary service.

5.3 Principal Results

The following is a brief summary of the study results.

5.3.1 Operation Practices

In the BPA system, hourly block energy is scheduled day-ahead and adjusted until 20 minutes before the operation hour. Within-hour load balancing is achieved mainly through the adjustment of several federal owned hydro plants responding to the AGC signal. There is not yet an automated load following process to dispatch generations following intra hour load variations, which leads to a comparatively larger regulation versus load capacity ratio than the California ISO system.

The cost of ancillary services is recovered by allocating charges (in $/MWh) to transmission customers based on the energy received (for regulation charge) or a percentage of the energy delivered (for operating reserve charge) [44]. The rate for ancillary services is forecasted and prescheduled before the operation year begins.

In the California ISO system, the processes of meeting generation and load consist of day-ahead schedule, hour-ahead schedule, real time dispatch (or load following, in every 5 minutes) and AGC regulation. The regulation versus load capacity ratio is usually between 1.0 and 1.6 percent depending on the operation hour [45]. The scheduled energy and ancillary service capacity are procured using a market mechanism composed of day-ahead market (DAM) and real time market (RTM). A new and improved market design called market redesign and technology upgrade (MRTU) will go live on April 1, 2008 [46]. Any generators with AGC capability can bid to the ancillary services market. Under this mechanism, the compensation (in $/MW) for resources providing ancillary services is determined by the market price and the capacity awarded by the California ISO to the participating resource.

5.3.2 Compatibility with Ancillary Service Operating Procedures

It has been determined in Stage Gate 2 that the most preferable configuration of WAEMS is flywheel pluses pumped storage (or conventional hydro), vertically integrated into the BPA and California ISO systems. BPA and California ISO ACE and “conventional regulation unit” signals will be used to control the WAEMS.

The selected configuration is compatible with both systems in terms of the qualification standard for regulating units, which requires the units to be immediately responsive to AGC to provide sufficient regulating margin.

Day-ahead and hour-ahead market processes in California ISO system are both designed for hourly ancillary service bids. Real time pre-dispatch process is for selling ancillary services at a 15 minutes interval. For regulating units in the markets, maintaining output at P_{max} and P_{min} for 15 minutes is requested [47] in the certification test for capacity. Control algorithm of WAEMS should be designed to meet this requirement.

It has been realized that to better justify the cost of WAEMS, it could be used for other types of ancillary services including spinning and non-spinning reserves as well (voltage support is another possible application, but outside the range of this report). However, for the WAEMS to qualify for operating reserves, the control algorithm must be designed to enable the energy storage device to have a sustainable output for up to one hour, as required by both system tariffs. With the combination of flywheel and hydro plant, the requirement should not be difficult to meet.

Regulating reserve is further separated into regulation up and regulation down in the California ISO system. California ISO procures these two services independently so that their amounts are not necessarily the same. This allows more flexibility for energy storage devices in the way that unsymmetrical bids can be made in the real time market and they don't always need to return to the neutral position at the end of every bidding interval (15 minutes).

5.3.3 Compatibility with AGC Systems

The BPA system AGC signals include base point adjustment and an adjustment based on ACE. The base point adjustment is allocated to regulating units based on percentage response. The ACE component is generated from system raw ACE using a static dead band and dynamic dead band mechanism. The selected WAEMS should be able to accept and respond to such AGC signal without any modification to the AGC system (e.g., use hydro plants to help the energy storage device return back to neutral position if this is not achieved through AGC signals). The BPA system may change to a feed forward AGC system, but as long as the AGC output remains the same, no change is anticipated on the WAEMS control approach.

In the California ISO system, the AGC system will also send setpoint or increase/decrease signals to the AGC units. The preferred operating point (POP) is the basis for settlement regulation capacity. The POP is the generation loading at which an AGC unit has pre-scheduled its energy from the energy markets. The amount of regulation up and/or regulation down capacity that an AGC unit can provide is dependent upon that unit's POP, maximum capacity and ramp rate. Energy management system (EMS) dispatches AGC regulation as required, but endeavors to return each unit to its POP as soon as possible [48].

How to respond to the AGC signals in BPA and California ISO systems at the same time, and thus provide regulation service to both systems, needs to be resolved in the control methodology design pursued in Stage Gate 4.

5.3.4 Technical Requirements for Providing Ancillary Services [49]

In the California ISO system, all resources including generating units, system units, participating loads and system resources providing ancillary services must comply with the technical requirements set out in the tariff relating to their operating capabilities, communication capabilities and metering infrastructure.

The operating characteristics include:

- Ramp rate increase/decrease (MW/min).
- Maximum and minimum output.
- AGC capability.

- Minimum available period, etc.

The California ISO will conduct tests to certify the capacity of the resources and monitor their compliance. For regulating units, maintaining output at P_{max} and P_{min} for 15 minutes is requested in the certification test [50].

As to the communication capabilities of regulating units, the plant operator is required to install an California ISO "validated" remote intelligent gateway (RIG), or comparable California ISO validated system, to establish voice and data interfaces between the unit's local systems and personnel and the California ISO data interfaces between the unit's local systems and personnel and the California ISO Energy Communications Network (ECN), AGC technical operation systems, and California ISO operations dispatch personnel. Digital communication circuit with adequate bandwidth and backup systems for data and voice communications are required [51]. A maximum delay of 4 seconds is defined for sending and receiving signals between AGC and the controller of the regulating unit.

For the BPA system, no technical requirements documents were found for the regulating units. For operating reserves including spinning and non-spinning reserves, it is required that the units must be available at all times; fully delivered within 10-minutes after BPA transmission business line (TBL) sends a signal for operating reserves; and sustained for the remainder of the scheduling hour unless otherwise requested by TBL [52]. The operating reserves have similar requirements in the California ISO system.

5.4 Scheduling and Load Balancing Processes in BPA and California ISO Systems

5.4.1 BPA

Generation Schedule [53]. The BPA generation scheduling process is composed of pre-schedule and real time schedule. Both are based on bulk hourly energy schedules and includes 20 minute ramps between the hours (beginning 10 minutes before the end of an hour and ending 10 minutes after the beginning of an hour). Figure 5-1 shows the timeline for the pre-schedule and real time schedule procedures.

Regulation and Load Following [54]. Regulation and frequency response service is accomplished by committing on-line generation responding to AGC signal as necessary to follow the moment-to-moment changes in load. The transmission customer must either purchase this service from the BPA-TBL or make alternative comparable arrangements to satisfy its regulation and frequency response obligation.

Load following is an instructed deviation from hourly energy schedule caused by real time energy dispatch to follow within hour load movements. There is not an automated load following process in the current BPA system. Load following in the BPA system may be interpreted as the process of manual adjustment of the generation setpoints when the deviation of the regulating units from this point exceeds certain threshold. This adjustment can be repeated any 30 minutes by BPA real time dispatches if needed.

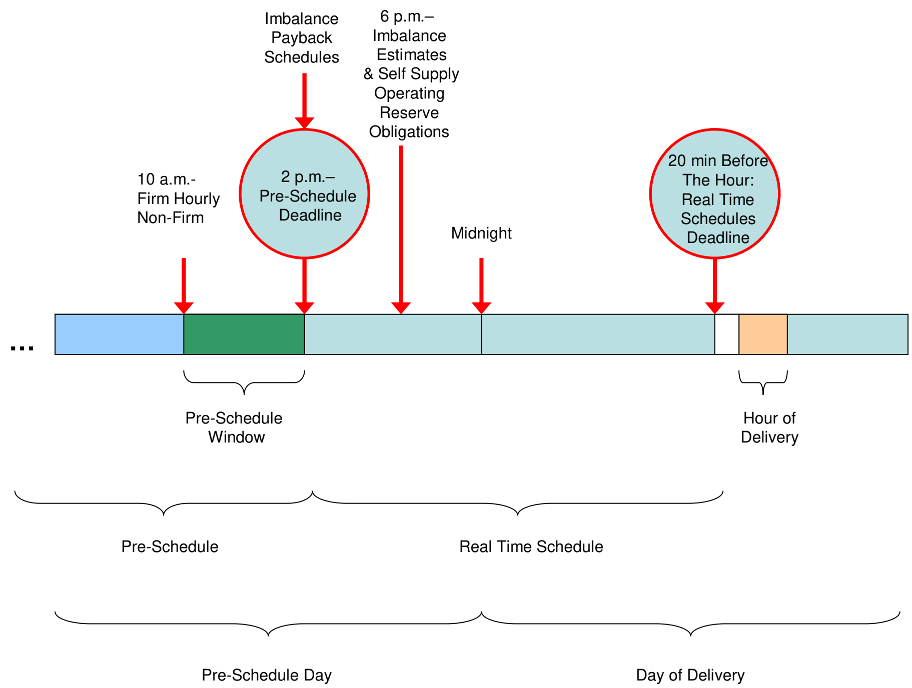

Figure 5-1 BPA scheduling procedure

5.4.2 California ISO

Generation Schedule. Generation schedule processes in the California ISO system include day-ahead schedule and hour-ahead schedule, which are also based on block hourly energy schedules including the 20-minute ramps between the hours. Energy for these schedules is procured from day-ahead market (DAM) and hour-ahead scheduling process (HASP, one of the processes in real time market, or RTM), respectively.

DAM collects energy bids from 7 days prior to the market day till 10:00 am of the day prior to the day of delivery. An hourly demand forecast is created by 10:00 am and used for selecting bids. After DAM is closed, integrated forward market (IFM) process is run to match energy bids with the scheduled load for that market day (and to arrange appropriate ancillary services (AS) for that period as well) [54]. The timeline for DAM is shown in Figure 5-2.

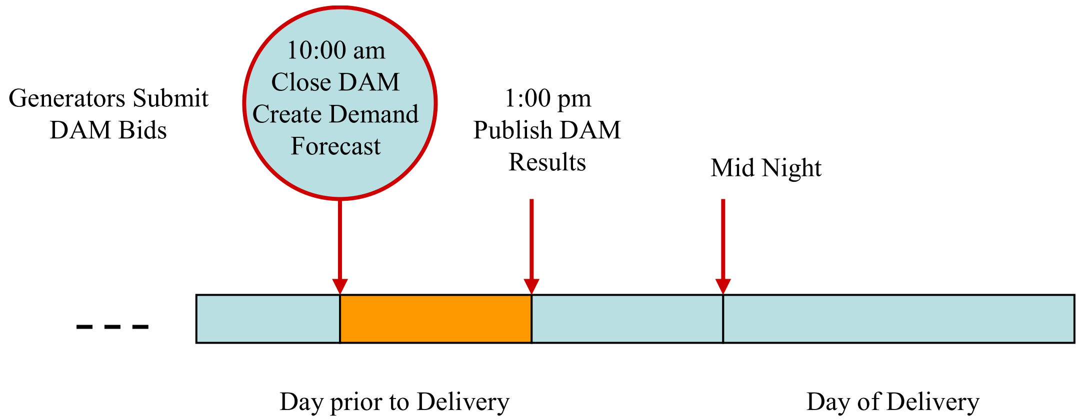

Figure 5-2 California ISO DAM timeline

For the HASP, the load forecast is provided 2 hours before the beginning of an operation hour [56]. Energy bids are submitted for HASP starting from the time day-ahead schedules are posted until 75 minutes prior to each applicable hour in the trading day. The difference between the day-ahead and hour-ahead schedules constitutes the required generation adjustment. Figure 5-3 illustrates how the timeline for HASP.

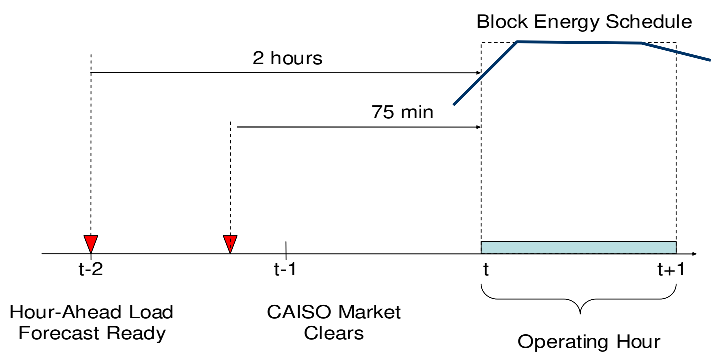

Figure 5-3 California ISO HASP timeline

Load Following and Regulation. The load following process is implemented as real time dispatch (RTD) process in the California ISO system. RTD is automatically conducted by the California ISO market applications using 15-minute intervals for unit commitment and 5-minute interval for economic dispatch. The desired changes of generation are determined in real time for each 5-minute dispatch interval 7.5 minutes before the actual beginning of the interval. Units start to move toward the new dispatch operating target (DOT) 2.5 minutes before the interval begins. They are required to reach the new DOT in the middle of the interval (2.5 minutes after its beginning). The units may ramp by sequential segments, that is, the ramp is not necessarily constant. Figure 5-4 illustrates the timeline for this process.

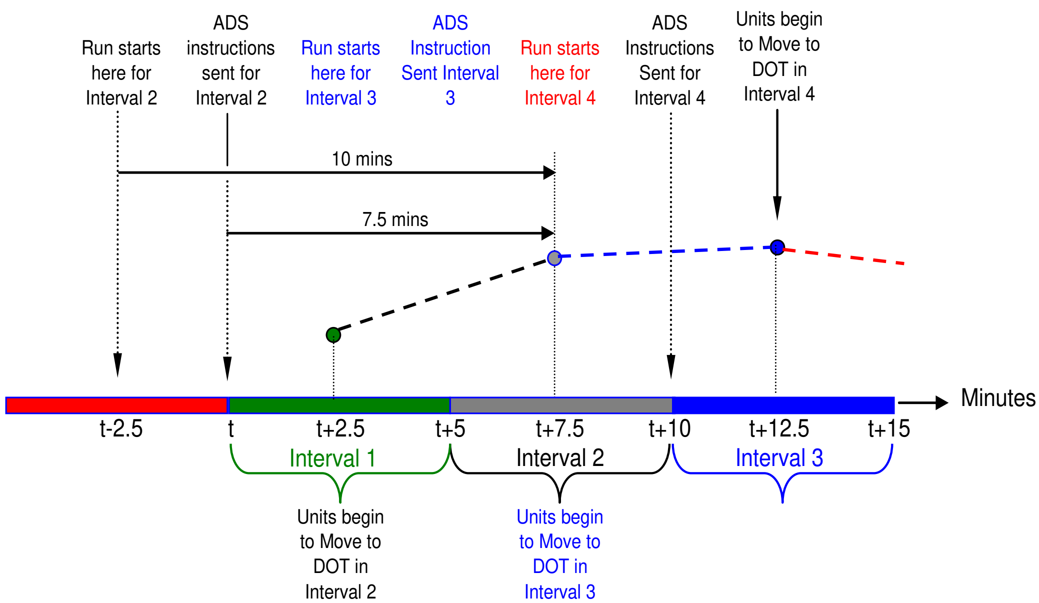

Figure 5-4 California ISO RTD timeline

Regulation quantity is set by California ISO according to historical data and real time situation. The capacity is procured from DAM and RTM. Figure 5-5 illustrates the relationship between the scheduling and balancing processes in the California ISO system.

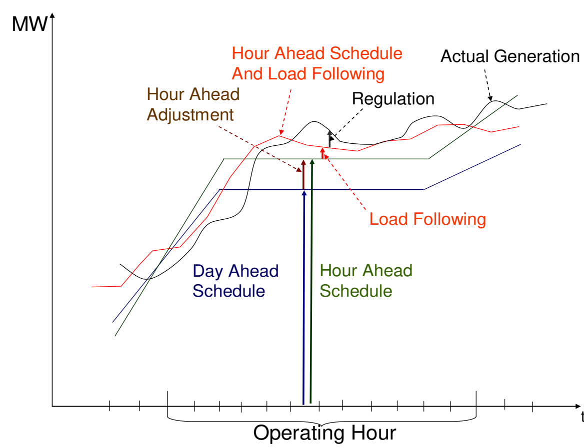

Figure 5-5 California ISO system scheduling and load balancing processes

5.5 California ISO MRTU Market Processes and Timelines [57]

5.5.1 Day-Ahead Market

The day-ahead market (DAM) is a market for trading energy, ancillary services (AS), and residual unit commitment (RUC) capacity for the next trading day that starts at midnight, and ends at the following midnight. The bid submission for the DAM is allowed as early as 1 week ahead and up to 10:00 am 1 day ahead of the trading day. The results of the DAM are published by 1:00 pm 1 day ahead of the trading day. The day-ahead market includes several functions that are performed in sequence:

- Market power mitigation (MPM) and reliability requirement determination (RRD).
- Integrated forward market (IFM).
- Residual unit commitment (RUC).

The integrated forward market (IFM) is a market for trading energy and ancillary services for each hour of the next trading day. The IFM uses the mitigated bids after MPM and RRD to clear supply and demand bids, and procure ancillary services to meet the California ISO ancillary services requirements at least bid cost over the next trading day.

The real time market (RTM) is a market for trading energy and ancillary services in real time. The bid submission for a given trading hour in the RTM is allowed after the DAM result publication for the corresponding trading day and up to 75 minutes before the start of that trading hour.

The RTM includes several functions that are performed in parallel, but with different periodicity:

- Market power mitigation (MPM) and reliability requirement determination (RRD).
- Hour ahead scheduling process (HASP).
- Short-term unit commitment (STUC).
- Real time pre-dispatch (RTPD).
- Real time economic dispatch (RTED).

The HASP is a process for trading hourly energy and ancillary services based on bids submitted up to 75 minutes ahead of a trading hour. The HASP is performed hourly and immediately after MPM and RRD. Hourly energy schedules and hourly ancillary services awards for hourly pre-dispatched resources in that trading hour are published no later than 45 minutes before the start of that trading hour.

The RTPD is a market for committing resources and for selling ancillary services at 15-minute intervals. The RTPD runs automatically every 15 minutes, at the middle of each quarter of each hour. The RTPD is performed simultaneously with the HASP.

The RTED is a market for trading imbalance energy and dispatching ancillary services at regular intervals. There are three modes for the RTED:

1) Real time interval dispatch (RTID) is the normal mode of RTED. It runs automatically every 5 minutes, at the middle of each 5-minute interval of each hour.
2) Real time manual dispatch (RTMD) is executed manually and it has a single 5-minute interval.

3) Real time contingency dispatch (RTCD) is also executed manually, but it has a single 10-minute interval.

5.5.2 Changes Expected Under MRTU

The content in this section is based on [61] and [62]. Reference [63] contains a comparison of the current settlement system with the future system under MRTU.

With the implementation of MRTU, the current radial zonal model will be replaced with the full network model and the locational marginal price (LMP) model. California ISO will procure the ancillary services, regulation up, regulation down, spinning reserve, and non-spinning reserve in the day ahead integrated forward market (IFM) and procure incrementally as needed in the HASP and in the RTM. Ancillary services are procured simultaneously with energy bids to meet regulation and operating reserve requirements, using submitted ancillary service bids. IFM is performed for each hour of the next trading day. The HASP is performed hourly. Only the intertie AS awards in HASP are binding. The real time unit commitment performs unit commitment and AS procurement, if needed, at 15-minute intervals for the current hour and next trading hour. The AS awards published for the first 15-minute interval of the time horizon are binding, the rest are advisory. The AS pricing and settlement will be based on ancillary service marginal price (ASMP), which are calculated for each AS region for each market time interval for each market.

The AS procurement cost is the payment for AS awarded bids in the day ahead IFM, HASP, and RTM. This charge code is part of the family of charge codes for payment to scheduling coordinators (SCs) for awarded ancillary services capacity bids: (1) regulation up, (2) regulation down, (3) spinning reserve, and (4) non-spinning reserve.

The fundamental concepts of settlement methodology for allocation of AS procurement cost to scheduling coordinators are as follows:

- The AS procurement cost allocation for all AS commodity types is hourly, system-wide, and across IFM, HASP, and RTMs.
- The cost of procuring the AS by the California ISO on behalf of the demand will be allocated to the demand using a system wide user rate. The user rate is the average cost of procuring a type of AS in both the forward and RTM for the whole California ISO system.
- The rate for each AS incorporates the no pay/non compliance capacity and the no pay/non compliance charge to reflect the ultimate average AS cost.
- The rate for each AS reflects an average AS substitution to capture the cascaded AS procurement as it is performed optimally in each AS market. For example, settlements reflect that multiple service types are procured and substituted simultaneously during IFM optimization.
- A difference between AS requirements and total AS obligations results in a neutrality adjustment for each AS.

- A difference between total AS procurement and total AS requirements over all spinning, non-spinning and regulation up ancillary services results in a single upward neutrality adjustment for all these services.
- Ancillary services awards from intertie resources are charged explicitly for the marginal cost of congestion on the relevant intertie interface at the relevant price. The cost of AS congestion charges is not recovered through the AS cost allocation, but is settled in the congestion offset.
- By design, the AS settlement methodology has the following property: If the total AS procurement matches the total AS requirements, and if the AS requirement matches the total AS obligation for each AS, the AS cost allocation is neutral.

By reflecting AS substitution in the AS rates, this AS settlement methodology eliminates any neutrality loss caused by AS substitution and results in an equitable AS cost allocation to scheduling coordinators that self-provide AS because there is no AS substitution among self-provided AS.

5.6 AGC Systems

5.6 1 BPA AGC System

The BPA AGC signal consists of two components:

(1) Base point adjustment - This component follows real time load. The base point adjustment amount is equal to the difference between actual load and generation schedule. It keeps regulating units from going back to original set points.

(2) Signal generated based on raw ACE - This component regulates raw ACE using a mechanism involving a static dead band and a dynamic dead band. The present setting for static dead band is ±60 MW, and dynamic dead band is ±500 MW. When ACE is inside the static dead band, no action is taken. When ACE exceeds static dead band, the dynamic dead band starts decreasing towards 0 MW with a rate of 500 MW/32 sec. When the dynamic dead band meets with raw ACE, regulation action starts by adjusting (using full ACE) the output of the responding units. When ACE is reduced to below 10 MW, the dynamic dead band jumps back to 500 MW and regulation of ACE stops.

Figure 5-6 and Figure 5-7 illustrate the above described mechanism.

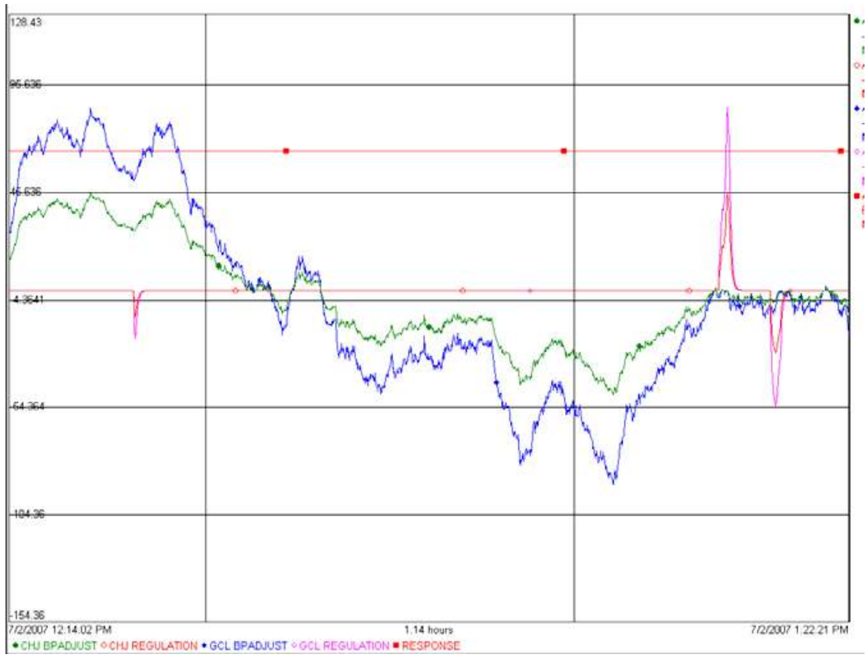

Figure 5-6 AGC components in the BPA system

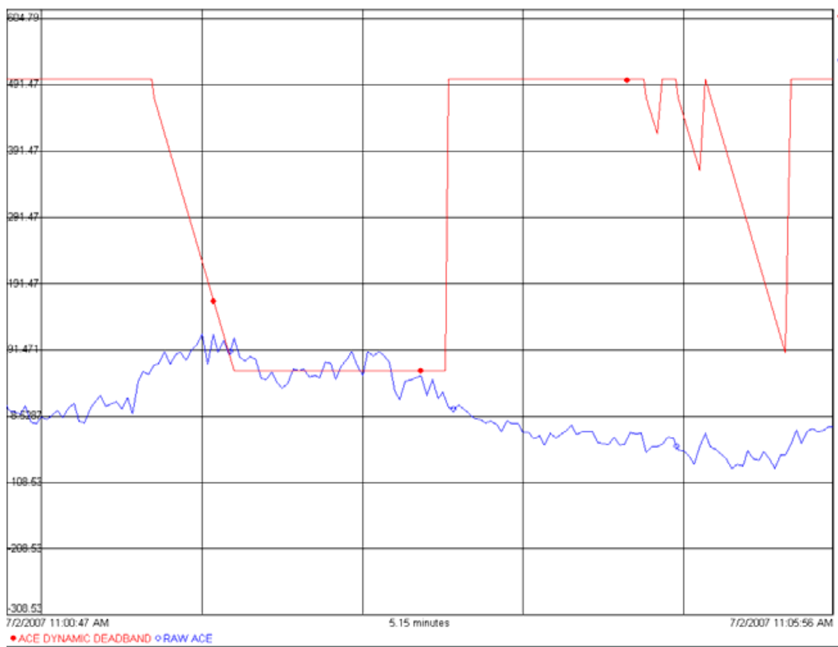

Figure 5-7 Static and dynamic dead bands mechanism based on ACE values

5.6.2 Alternative BPA AGC System[8]

BPA has an alternative AGC system that is not currently operational. The analysis provided in this sub-section is based on the study conducted by Yuri Makarov in [75].

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[8] The authors are thankful to BPA engineers Warren McReynolds (retired) and Bart McManus for their assistance and information regarding the BPA CPS1 and CPS2 control algorithms.

The BPA CPS1 and CPS2 control algorithms are original stand-alone algorithms integrated into the BPA feed-forward AGC system – see Figure 5-8 and [76].

The principles of feed-forward AGC systems are formulated in [77]. The main idea of these systems is to determine the future area requirement (AR) as a function of time based on the load forecast curve, scheduled generation for non-regulating units and interchange schedules, correct this look-ahead AR with respect to the currently observed generation scheduling and load forecasting errors and CPS1/2 requirements, and allocate the AR among the regulating units.

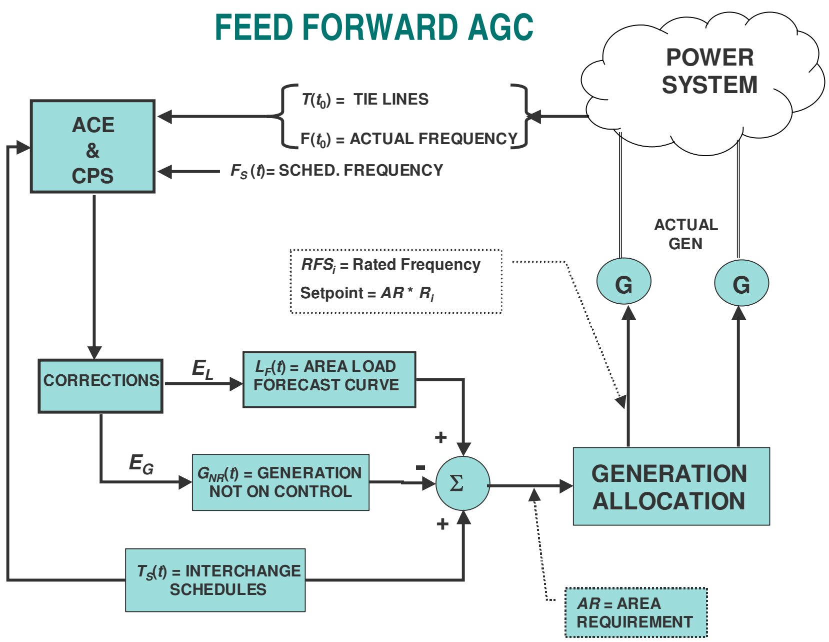


Figure 5-8 Design of the BPA Feed Forward AGC System

The total correction is determined based on the ACE at the current AGC cycle [76]. This correction creates a sort of negative feedback where the current generation and load forecast errors are used to dynamically adjust the future area requirement $AR(t)$ ($t > t_0$). In the BPA algorithm, the generation and load correction terms are processed separately, so that *the generation correction* goes through a proportional block while *load correction* goes through a pure integral block.

The CPS1 and CPS2 compliance analysis that may trigger the corrective action is monitored for k = 1, 2, 5, 7, 10, 20, 30, or 60 minutes past averaging intervals. The CPS compliance is graphically represented on a special BPA CPS compliance display [76] (see Figure 5-9).

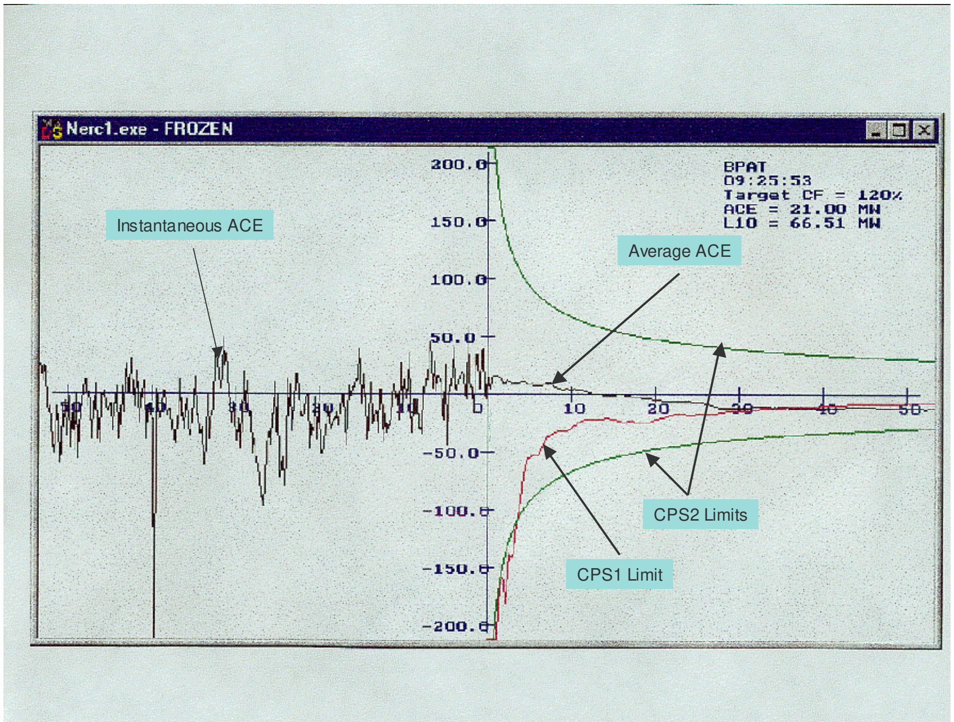


Figure 5-9 BPA CPS compliance display

The green lines denote the CPS2 limits, the red is the limit for CPS1, and the black line denotes the ACE. On the left side of the Y-axis is the actual ACE, going from the current time to 50 minutes ago. The right side of the Y-axis has the averaged quantity of ACE that is, for example, at $t = 20$ minutes the average ACE for the last 20 minutes is plotted. These are all rolling averages.

For CPS1, the average ACE has no boundary when in opposition to the CPS1 limit so is bounded by the CPS2 limit. The CPS1 limit is usually the tighter limit on the average ACE when ACE is in the same direction as the limit. During the course of a normal day, the CPS1 bound is inside the CPS2 bound from about 5 to 7 minutes and out.

In the example given in Figure 5-9, a CPS1 violation is detected for the rolling averages of 36 minutes and more.

5.6.3 California ISO AGC System [64]

ACE signals as the input of the AGC algorithm in EMS are processed with a Butterworth and PI filters (see Figure 5-10). The Butterworth filter helps to eliminate AGC reaction to rapid changes of ACE. The PI filter has a proportional and integral control gains. The integral gain steadily increases the AGC signal to eliminate persistent ACE deviations. The filtered ACE is used as the total regulation needed in the system. This total regulation requirement is distributed to the units based on generators' participation factors with consideration of their ramp rates, regulation range and the current status. Faster units are moved faster. But nevertheless the control signal is send to all units being currently on regulation. The look-ahead capability (feed forward AGC principle) is available in the existing AGC system, but it is not currently used.

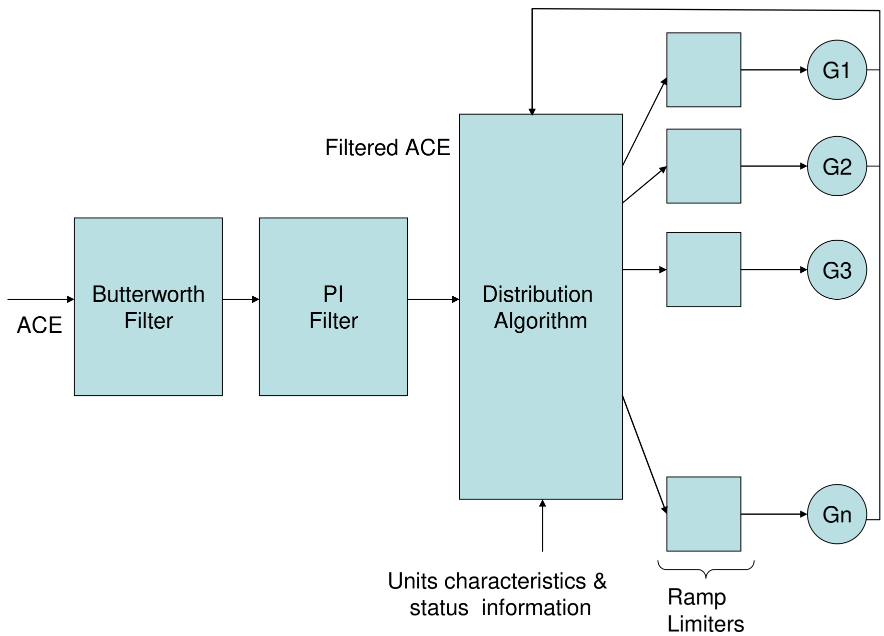


Figure 5-10 Illustrative block diagram of California ISO AGC system

Energy management system (EMS) dispatches AGC regulation as required, but endeavors to return each unit to its POP as soon as possible. Figure 5-11 shows a 22-minute interval where ACE changes from positive values to large negative values. The AGC system responds by moving regulating units in the positive direction. Since some of the units deviate in the negative direction initially, there is a period where positive and negative deviations from POP coexist.

Depending on the magnitude of ACE, AGC has these three different operating zones.

- Dead Zone. When ACE is within the dead zone, AGC moves some of the regulating units up and others down to get them return to their POP.
- Economic Control Zone. When ACE is outside the dead zone but not very large, AGC distributes the required regulation amount among all the regulating units procured in the day-ahead and hour-ahead regulation market, based on their bids, ramp rates and regulation capacity.
- Emergency Control Zone. When ACE is extremely big, the AGC dispatches any resources under its control to reduce ACE. This can be called the emergency control zone.

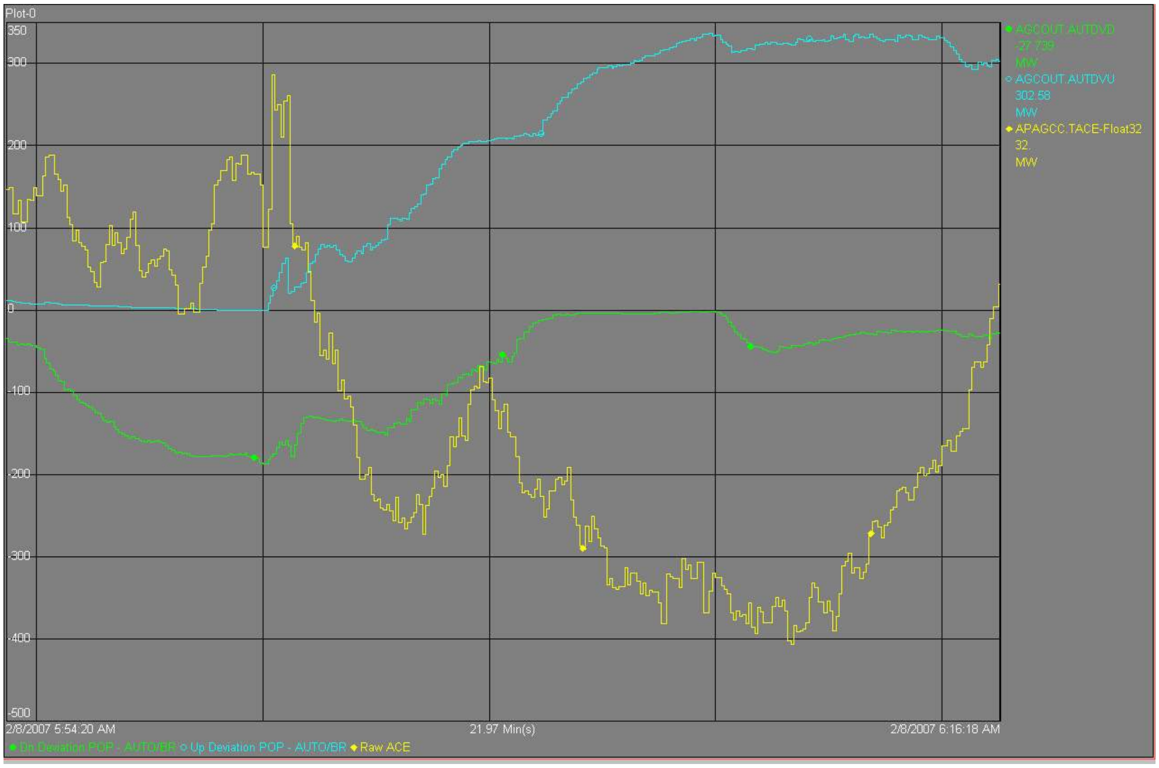


Figure 5-11 ACE (yellow) vs. regulation up (blue) and regulation down (green)

The AGC system sends either set point signals or increase/decrease pulses to the AGC units. (There are some units still requiring increase or decrease pulses, but very rare now.) A regulating unit is expected to be capable of developing ramp rate provided by this unit for the ISO. But the ISO can move the unit with a lower than maximum rate. The ramp limiters prevent the ISO from sending set point signals exceeding the maximum ramping capability of a unit.

5.7 Ancillary Service Standards

5.7.1 BPA Operating Reserve Error! Reference source not found.

A transmission customer's operating reserve requirement for spinning and supplemental services for all of its agreements with TBL must be supplied by one of the following alternatives: purchase from TBL, self-supply or third party supply.

Present TBL operating reserve requirements are 7% of non-hydro generation output on-line plus 5% of hydro and wind generation output on-line (deliveries from PBL resources require a 5.2% operating reserve requirement based upon an average of PBL's resource mix.)

The operating reserve requirements must be available at all times, fully delivered within 10 minutes after TBL sends a signal for operating reserves, and sustained for the remainder of the scheduling hour unless otherwise requested by TBL.

TBL will perform unannounced capability tests to assure that capacity is fully available within 10 minutes.

5.7.2 California ISO Operating Reserves [58]

The California ISO procures operating reserves in the day-ahead market and in the real time market that are necessary to meet California ISO requirements not met by self-provided reserves. The percentage requirement of spinning and non-spinning reserves is the same as BPA system. The standards for various types of services are described as follows:

- Spinning Reserves: The portion of unloaded synchronized generating capacity, controlled by California ISO, which is capable of being loaded in 10 minutes, and which is capable of running for at least 2 hours.
- Non-Spinning Reserve: The portion of off-line generating capacity, controlled by California ISO, which is capable of being started, synchronized to the California ISO power grid and loaded to a specific point in 10 minutes or load which is capable of being interrupted in 10 minutes and which is capable of running (or being interrupted) for at least two hours.
- Regulating Reserve: Sufficient spinning reserve that is immediately responsive to AGC to provide sufficient regulating margin to allow the balancing area to meet NERC control performance criteria.
- Replacement Reserves is generating capacity capable of starting up, if not already operating, synchronized to the California ISO power grid and ramping to a specified load point within a 60-minute period, with the output continuously maintained for a 2-hour period.

California ISO procures sufficient reserves to maintain the greater of the:

- Most severe single contingency.
- Suof 5% of the load responsibility served by generation from hydroelectric resources plus 7% of the load responsibility served by generation from other resources.

California ISO procures sufficient reserves:

- T cover interruptible imports and on-demand obligations minus the non-firm exports on a MW for MW basis.
- For a minimum of 50% of the reserves using spinning reserves.
- To satisfy the needs of local area requirements, additional operating reserves may need to be procured.

5.7.3 California ISO Regulation Procurement [58]

Regulation procurement is dynamic and may be adjusted daily or hourly by the shift manager or the generation dispatcher. Because of operating variances or system conditions, it may be necessary to adjust the procurement amount higher or lower.

- Min/Max: A base of 350-MW for regulation procurement, for regulation up and regulation down each ensures adequate response to frequency deviations; however, this base can be lowered if system conditions do not warrant a 350-MW procurement minimum. A 600-MW procurement ceiling should be utilized for regulation up and for regulation down each.
- Actual Regulation Used: The actual amount of regulation used is considered to find the maximum amount of regulation used for each of the 24 hours over the previous 7 days. This is determined by the regulating units' deviations from DOT (dispatch operating target). The average of this amount for each hour is used as a benchmark.
- ACE greater than the California ISO's L_{10}: It is determined by the CPS2 violations over the same 7-day period as described above. This portion of the methodology also considers the average California ISO raw ACE and the number of intervals that ACE exceeds L_{10} in either the positive or the negative direction.

The regulating reserve to procure is determined using the following calculation:

- Start with a minimum of 350-MW floor used for both upward and downward regulation to ensure adequate response to frequency deviations.
- Add 25% to the actual regulation usage.
- Add additional amounts for predetermined non-responsive unit schedules.
- Limit procurement to 600 MW for both upward and downward regulation based on actual regulation used. The actual requirement may be greater than 600 MW if CPS2 violations occur.
- Add 2% for each CPS2 violation.

5.7.4 Effects of Ramp Rates on Ancillary Service Procurement [59]

AS awards are limited by applicable ramp rates as follows:

- Regulation down service must be delivered in 10 minutes according to its bid-in regulation ramp rate. In other words, the maximum amount of regulation down service that a unit can provide is limited to the regulation ramp rate times 10 minutes.
- Regulation up, spinning reserve and non-spinning reserve must be delivered in 10 minutes according to regulation ramp rate and operating reserve ramp rate as follows:

$$\frac{\text{Reg Up}}{\text{Reg Ramp Rate}} + \frac{\text{Spin Res+NonSpin Res}}{\text{Operating Reserve Ramp Rate}} \leq 10 \text{ minutes} \tag{5.1}$$

- Resources, taking longer than 20 minutes to ramp down from 1 hour energy schedule to the next hour's energy schedule, shall not be eligible to provide regulation down in both hours. Conversely, resources that self-provide regulation down in a given hour will have their energy schedules constrained, and if applicable their energy self-schedules (except the reliability must run (RMR) units) adjusted, so that this rule is not violated.
- Resources, taking longer than 20 minutes to ramp up from 1 hour energy schedule to the next hour's energy schedule, shall not be eligible to provide regulation up, spinning reserve, or non-spinning reserve in both hours. Conversely, resources that self-provide regulation up, spinning reserve, or non-spinning reserve in a given hour will have their energy schedules constrained, and if applicable their energy self-schedules (except RMR) adjusted, so that this rule is not violated.

5.8 Rates of Ancillary Services

5.8.1 BPA Rates [65]

In the BPA control area, energy storage values were taken as the values placed on ancillary services published in BPA's 2008 Transmission and Ancillary Service Rates Summary [71]. Specifically, the estimated benefit of energy storage in the BPA service area is the sum of:

Service 10 - hourly scheduling, system control and dispatch (0.59 mills/kWh),
Service 12 - regulation and frequency response (0.33 mills/kWh), and
Service 14/15 - operating reserves - spinning and supplemental (7.93 mills/kWh).

Regulation and frequency response billing factor is the transmission customer's total load in the BPA control area in kWh.

Spinning and non-spinning reserves billing factor for the rate is the transmission customer's spinning reserve requirement determined in accordance with applicable WECC and NWPP standards.

Application of current standards establishes a minimum spinning reserve requirement equal to the sum of:

- 2.5% of the hydroelectric and wind generation dedicated to the transmission customer's firm load responsibility.
- 3.5% of other generation dedicated to the transmission customer's firm load responsibility.

5.8.2 California ISO Settlement Process for Regulation [60]

The California ISO regulation market is capacity based. This means that the regulating units bid a part of their capacity into the market, ant if they are accepted, they are paid the market clearing price (MCP).

Radial zonal structure for the MCP is used by California ISO currently.

Regulation capacity is procured in the day-ahead and hour-ahead markets. Regulation is procured for each operating hour.

The regulation payment due scheduling coordinators (SCs) is calculated using the following basic formula:

$$CT^{**} = RC \cdot MCP \tag{5.2}$$

where:

*CT*** is the charge type due SC (billable quantity for regulation capacity provided).
CT005 is day-ahead AGC/regulation up due SC.
CT006 is day-ahead AGC/ regulation down due SC.
CT055 is hour-ahead AGC/regulation up due SC.
CT056 is dour-ahead AGC/regulation down due SC.
RC is final quantity of regulation capacity accepted [MW].
MCP is the market clearing price derived from rational buyer process (zonal MCP for AGC/regulation capacity) [$/MW], and MCP is posted on OASIS ancillary tab under final MCP.

<u>Regulation Charges Due ISO</u> is calculated using the following basic formula:

$$CT^{***} = RO \cdot RR \tag{5.3}$$

where:

*CT**** is the charge type due SC (billable quantity for regulation capacity provided).
CT115 is regulation up due ISO.
CT116 is regulation down due ISO.
RO is net regulation obligation [MW].
RR is regulation rate [$/MW].

5.8.3 California ISO Regulation Prices [66]

Figure 5-12 shows the ancillary service day-ahead average bid volume by price bin in August and September 2007. Although some day-ahead regulation bids exceed $90/MW, the average market clearing price remained in the range $5/MW-$15/MW per hour.

Figure 5-13 shows the weekly weighted average ancillary service prices from April 2007 to September 2007. The regulation up price reaches $40/MW in May and exceeds $30/MW in May and June. The regulation down price reaches $20/MW in the midle of September.

The average regulation price in 2006 was $18/MW ($17 for regulation down and $19 for regulation up) [68].

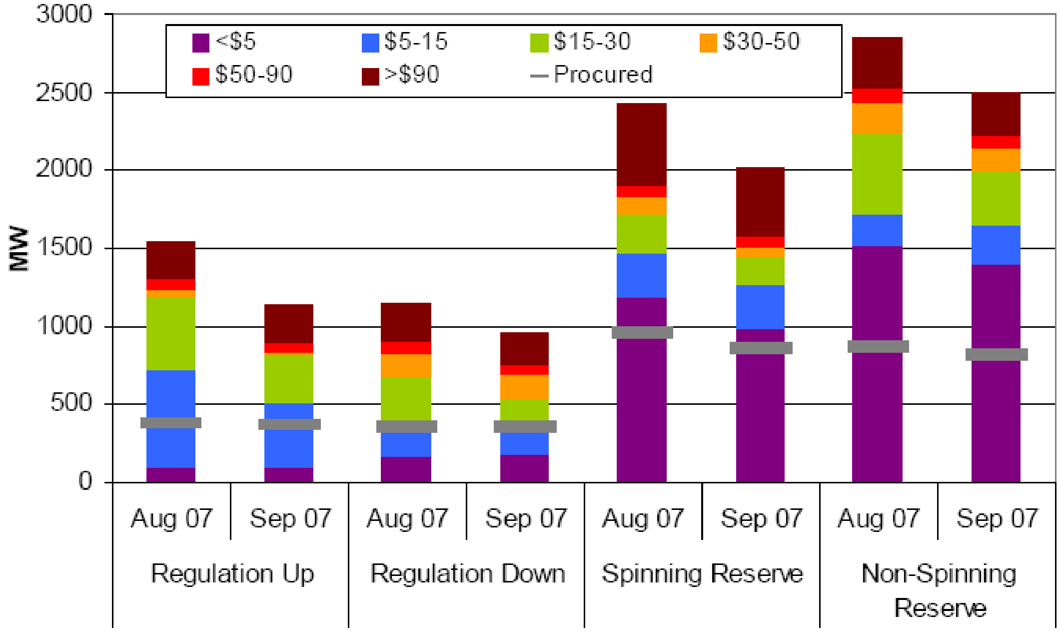


Figure 5-12 Ancillary service day-ahead average bid volume by price bin (August and September 2007)

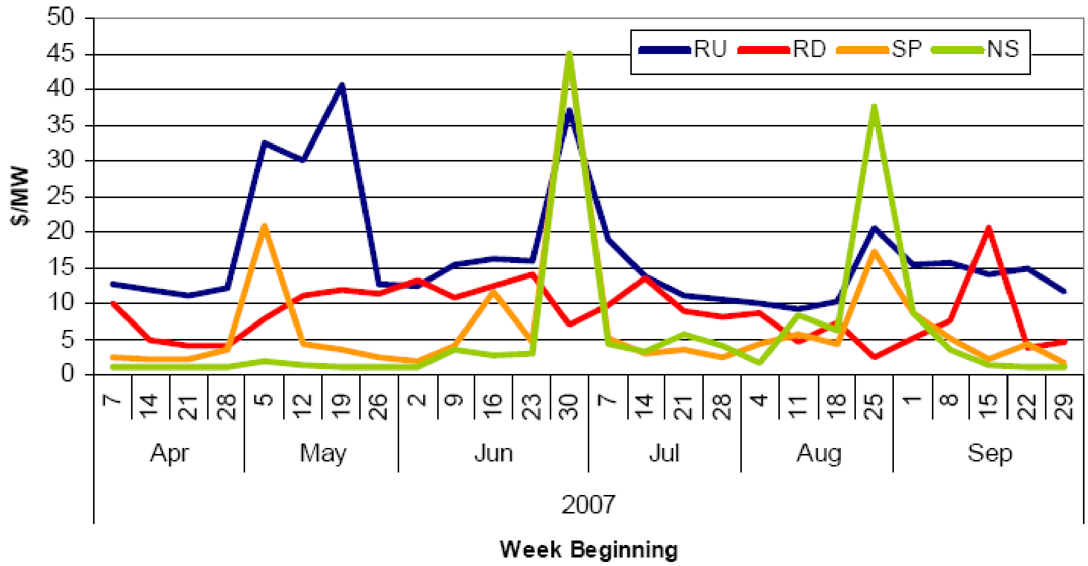


Figure 5-13 Weekly weighted average ancillary service prices (April to September 2007)

6 Stage Gate 4: Develop Algorithms and Conduct Experiments Using MATLAB Models. Carry Out Cost Benefit Analysis.

6.1 Stage Gate 4 Objectives

- Develop initial algorithms for the energy storage control. Implement them as MATLAB codes.
- Collect and preprocess data needed for experiments from BPA and California ISO.
- Conduct experiments using MATLAB models and collected data.
- Carry out the cost benefit analysis based on simulation results.
- Evaluate changes that are needed for the San Ramon prototype flywheel ESD (if any).
- Provide a summary of results and recommendations for BPA on continuation of the project. Write up and submit Phase 1 report.

6.2 Data Sets

Because of the limited availability of BPA data, a decision has been made to use the BPA and California ISO ACE signals as a substitute for the real regulation signals. A total of 36 days of 4-second data have been pulled out from the California ISO PI Historian. The analyzed period is 2006 including the 1st, the 15th, and the 30th days of each month except February. In February, the 28th day of the month has been used instead of the 30-th day used for the other months. The ACE data from each control area was scaled down to fit into the ±20 MW range of change.

6.3 Hydro Power Plant Model

A hydro power plant model has been developed to simulate the hydro power plant response to regulation signals. The block diagram of this model is given in Figure 6-1.

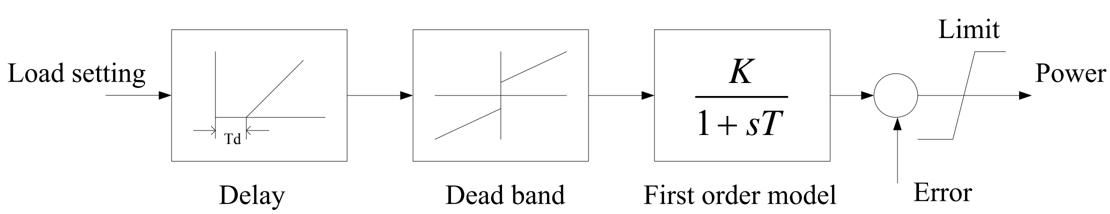


Figure 6-1 Block diagram of the hydro power plant model

The hydro power plant model includes:

- A delay block simulating the delay in the plant's response (Td) to the changing regulation signal (load setting).
- Dead band element.
- First order plant response model.
- Error range simulating deviations of the actual plant response from the load setting.
- Limiting element restricting the maximum and minimum regulation output provided by the plant.

Figure 6-2 represents a model response to step changes of the plant's load setting.

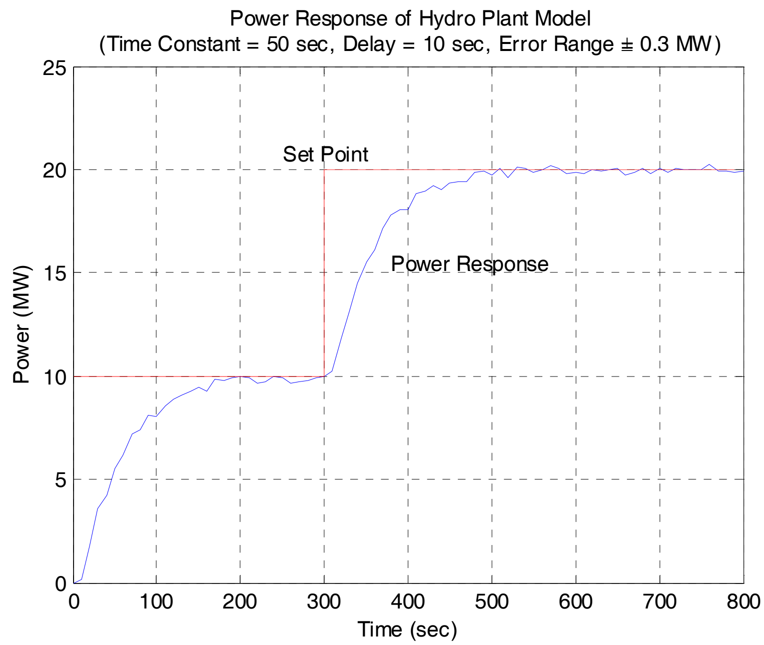


Figure 6-2 Hydro power plant model response to step signals

The hydro power plant model has been validated with the experimental results provided in Ref. [69]. The model has been implemented as MATLAB codes.

6.4 Flywheel Energy Storage Model

A block diagram of the flywheel energy storage model is shown in Figure 6-3.

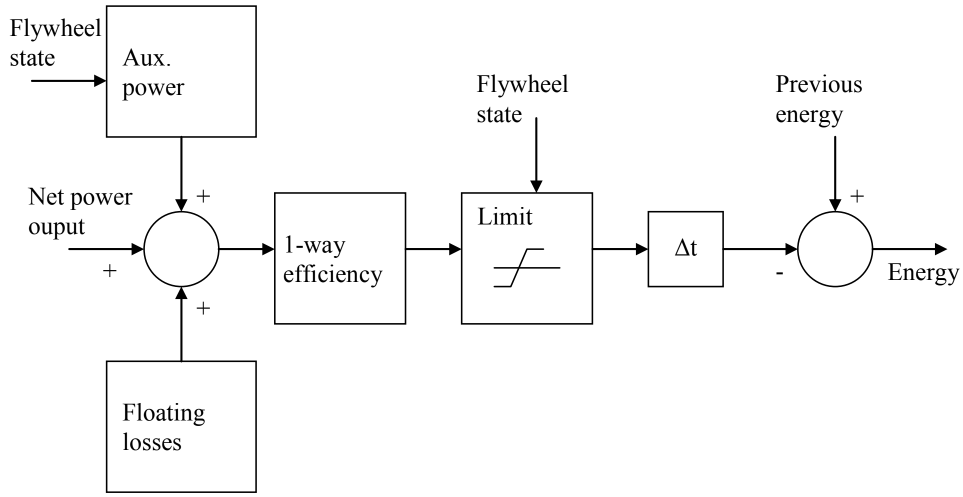


Figure 6-3 Flywheel energy storage model

The flywheel model was initially developed and supplied by Beacon Power Corporation [81], and it has been converted to a MATLAB model by PNNL. The model incorporates charging and discharging losses, floating losses and auxiliary power.

6.5 Integrated System Model

6.5.1 Integrated Model

The integrated model is implemented as MATLAB codes, consisting of three major parts:

- Control algorithm.
- Hydro plant model.
- Flywheel model.

The relation between these parts is illustrated in Figure 6-4. The regulation signal is a sum of regulation signals received from the BPA and California ISO AGC systems. The control algorithm distributes the regulation signal between the flywheel energy storage and the hydro power plant based on their current states and system constraints. The varying flywheel and hydro power plant outputs are required to match the regulation signal. Dynamic scheduling is used to distribute a part of the outputs into the neighboring control area.

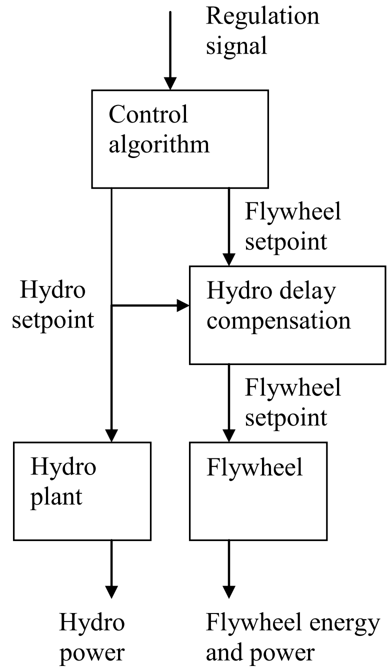


Figure 6-4 Integrated system model

The hydro delay compensation recalculates the steady-state setpoints from the control algorithm to a new setpoint for the flywheel, which compensates for the response time in the hydro plant, such that the aggregated response to the input signal is much faster than that of the hydro plant alone.

6.5.2 Control Algorithm

The control algorithm seeks an optimal trade-off between the state of charge of the flywheel and the hydro power output related to the efficiency of the hydro power plant. The relative weight of these two objectives has a significant influence on system behavior and must be chosen carefully. By changing this relative weight, the system can be designed to let either the flywheel or the hydro take a relatively larger share of the regulation task.

The optimization variables are X_{fw} and X_{hyd}, which denote the regulation power output from the flywheel and the hydro plant, respectively.

6.5.3 Non-interdependent Constraints

Power output or input from flywheel is limited by the power converter:

$$P_{fw\min} \leq X_{fw} \leq P_{fw\max} . \tag{6.1}$$

Furthermore the energy stored in the flywheel cannot go below a certain minimum value or exceed a certain maximum value during the following period of operation:

$$E_{fw,\min} \le E_{fw,next} \le E_{fw,\max}\ . \tag{6.2}$$

The relation between energy and power is given by

$$E_{fw,next} = E_{fw} - X_{fw} \cdot \Delta t\ , \tag{6.3}$$

which inserted into (6.2) gives:

$$\frac{E_{fw} - E_{fw,\max}}{\Delta t} \le X_{fw} \le \frac{E_{fw} - E_{fw,\min}}{\Delta t}\ . \tag{6.4}$$

The hydro plant is similarly constrained by its physical upper and lower limits of power output:

$$P_{hyd,\min} \le P_{hyd} \le P_{hyd,\max}\ . \tag{6.5}$$

The total power output from the hydro plant P_{hyd} is a sum of the scheduled output and the regulation output:

$$P_{hyd} = P_{hyd,sch} + X_{hyd}\ , \tag{6.6}$$

which inserted into (6.5) gives the limit for the regulation output:

$$P_{hyd,\min} - P_{hyd,sch} \le X_{hyd} \le P_{hyd,\max} - P_{hyd,sch}\ . \tag{6.7}$$

In addition, the capacity reserved for regulation may have an upper and lower limit:

$$P_{hyd,cap,\min} \le X_{hyd} \le P_{hyd,cap,\max}\ . \tag{6.8}$$

To summarize, the optimization variables X_{fw} and X_{hyd} are bound by the non-interdependent limits given by:

$$\begin{aligned}
&X_{fw,\min} \le X_{fw} \le X_{fw,\max} \\
&X_{hyd,\min} \le X_{hyd} \le X_{hyd,\max} \\
&X_{fw,\min} = \max\left(P_{fw\min}, \frac{E_{fw} - E_{fw,\max}}{\Delta t} \right) \\
&X_{fw,\max} = \min\left(P_{fw\max}, \frac{E_{fw} - E_{fw,\min}}{\Delta t} \right) \\
&X_{hyd,\min} = \max\left(P_{hyd,cap,\min}, P_{hyd,\min} - P_{hyd,sch} \right) \\
&X_{hyd,\max} = \min\left(P_{hyd,cap,\max}, P_{hyd,\max} - P_{hyd,sch} \right)
\end{aligned} \tag{6.9}$$

6.5.4 Interdependent Constraints

The total regulation performed by both units must match the regulation signal *RS*, which is the input to the control algorithm:

$$X_{fw} + X_{hyd} = RS\ . \tag{6.10}$$

Due to the physical location of the units on each side of the COI, additional constraint may be necessary when the intertie is congested to prevent overloading.

6.5.5 Objective Function

The objective function is a sum of two cost functions: one for the flywheel and the other for the hydro plant:

$$Cost = Cost_{fw} + Cost_{hyd}\ . \tag{6.11}$$

The design of the flywheel cost function aims at maintaining the energy stored in the flywheel at a certain level, i.e., $E_{fw,offset}$. The deviation from this level in the next period of operation adds quadratically to the cost:

$$Cost_{fw} = a_{fw}\left(E_{fw,next} - E_{fw,offset}\right)^2\ . \tag{6.12}$$

Figure 6-5 shows a plot of the flywheel energy deviation cost function.

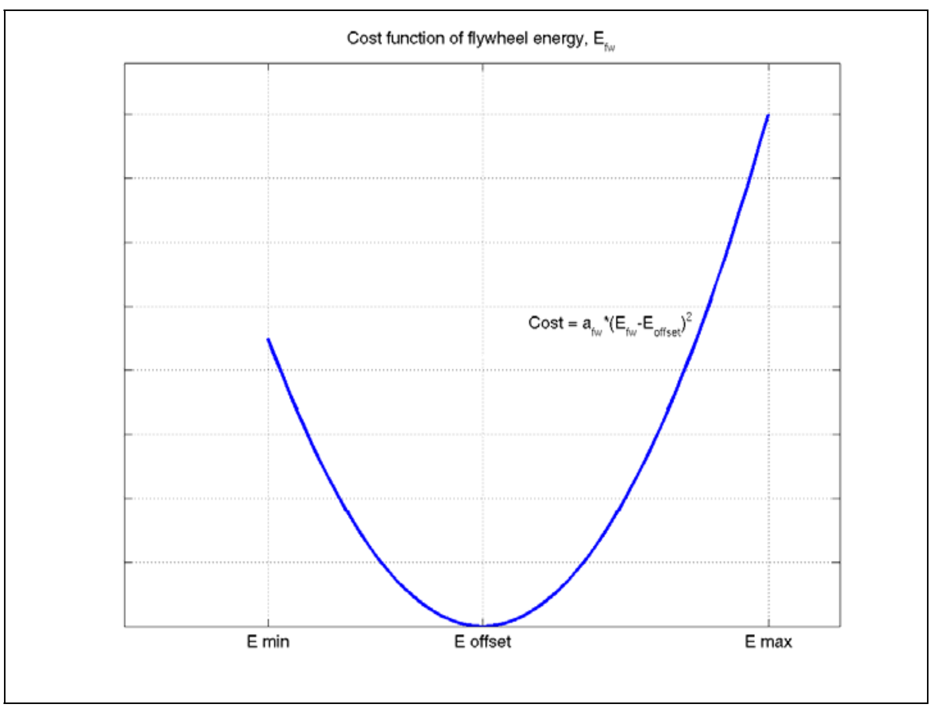


Figure 6-5 Plot of the flywheel energy deviation cost function

Because the optimization variable is power, not the energy, the cost function is written as a function of X_{fw} by inserting (6.3) into (6.12):

$$\begin{aligned} Cost_{fw} &= a_{fw} \cdot \left(E_{fw} - X_{fw} \cdot \Delta t - E_{fw,offset}\right)^2 \\ &= a_{fw} \cdot \left(\left(E_{fw} - E_{fw,offset}\right)^2 + \left(X_{fw} \cdot \Delta t\right)^2 - 2 \cdot \left(E_{fw} - E_{fw,offset}\right) \cdot X_{fw} \cdot \Delta t\right) \end{aligned} \tag{6.13}$$

The cost function of the other optimization variable X_{hyd} is designed to reflect the preferred operation at the most efficient power output setpoint. Deviation from the optimum adds quadratically to the cost:

$$Cost_{hyd} = a_{hyd} \cdot \left(P_{hyd} - P_{hyd,eff}\right)^2 . \tag{6.14}$$

Figure 6-6 shows a plot of the the hydro power plant cost function, which helps to minimize deviations of the hydro power plant output from the maximum efficiency point.

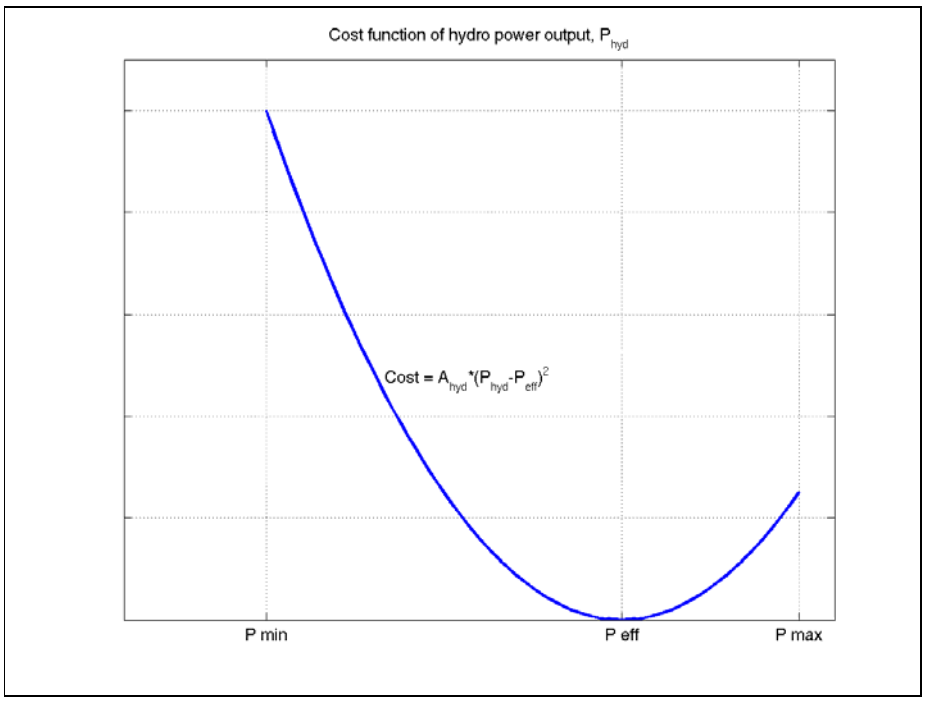


Figure 6-6 Cost function of the hydro power plant

The cost function of hydro power plant is written as a function of the optimization variable X_{hyd} by inserting (6.6) into (6.14):

$$\begin{aligned} Cost_{hyd} &= a_{hyd} \cdot \left(P_{hyd,sch} + X_{hyd} - P_{hyd,eff}\right)^2 \\ &= a_{hyd} \cdot \left(\left(P_{hyd,sch} - P_{hyd,eff}\right)^2 + X_{hyd}{}^2 + 2 \cdot X_{hyd} \cdot \left(P_{hyd,sch} - P_{hyd,eff}\right)\right) \end{aligned} \tag{6.15}$$

6.5.6 Global Minimization Problem

Then, the problem of (6.11) is formulated as a global minimization problem. The global minimization problem is solved by minimizing the total cost function given by the sum of the cost functions in (6.13) and (6.15). The total objective function may thus be written as:

$$Cost = \frac{1}{2} \cdot X \cdot H \cdot X^T + f^T \cdot X \tag{6.16}$$

where:

$$X = \begin{bmatrix} X_{fw} \\ X_{hyd} \end{bmatrix},$$

$$H = \begin{bmatrix} 2 \cdot a_{fw} \cdot \Delta t^2 & 0 \\ 0 & 2 \cdot a_{hyd} \end{bmatrix},$$

$$f = \begin{bmatrix} -2 \cdot a_{fw} \cdot \left(E_{fw} - E_{fw,offest}\right) \cdot \Delta t \\ 2 \cdot a_{hyd} \cdot \left(P_{hyd,sch} - P_{hyd,efft}\right) \end{bmatrix}.$$

6.6 Simulation Results

6.6.1 Key Parameter Description

The ACE signal is a time sequence signal with a 4-second interval between control points. The results shown below in simulation Part 1 and simulation Part 2 are provided for a 2000-second period. This number of points is sufficient to reflect the details of the algorithm's performance. The original regulation signal (a sum of regulation signals from BPA and California ISO) is scaled in the range of total regulation capacity of the fly-wheel/hydro aggregate.

Table 6-1 shows the model's parameter settings used in the simulations.

Table 6-1 Model Parameter Settings

No.	Parameters	Minimum (MW)	Maximum (MW)
1	Hydro regulation capacity	-40	0
2	Total hydro capacity	+100	+400
3	Flywheel power	-20	+20
4	Flywheel energy	0 (MWh)	+5 (MWh)
5	Total regulation capacity to system	-40	+40
6	Hydro power plant efficient point	316.8 (=400*0.8*0.99)	323.2 (=400*0.8*1.01)

- Hydro regulation capacity includes maximum and minimum hydro power plant regulation range. It limits the ability of the hydro power to follow the regulation signal.
- Total hydro capacity represents the range of hydro power plant's generation.

- Flywheel power is flywheel power output capacity. When there is a negative power capacity, the flywheel is working on discharging state, delivering power to the grid.
- Flywheel energy gives flywheel energy storage capacity. It is selected to sustain maximum power output (i.e. 20 MW) for 15 minutes.
- Total regulation capacity scales the range of the regulation signal.
- Hydro power plant efficient point describes the range of hydro power operating economically efficiently. It is determined by assuming most efficient hydro operation at 80% of maximum, and allowing 1 % deviation.

It is worth mentioning that the parameter settings shown in Table 6-1 are an example of an asymmetrical task distribution where the hydro plant delivers down regulation and the flywheel up regulation. The regulation task may be divided differently, e.g., symmetrically. To obtain 40 MW up regulation from the flywheel, the actual range of [-20, +20] MW from the flywheel has been offset 20 MW in the simulation. It may practically be obtained by simply purchasing 20 MW constant generation, scheduled to be absorbed by the flywheel (because the regulation output is a deviation from a scheduled setpoint, i.e., if the scheduled setpoint is -20 MW an output of 0 MW is actually +20 MW of regulation). For the symmetrical parameter setting scenario, the minimum and maximum hydro regulation capacities are -20 MW and +20 MW, respectively. The corresponding results (for case 2) are shown in simulation Part 5 and simulation Part 6 below for the comparison purpose.

6.6.2 Simulation Cases

Two simulation cases are involved in the simulation. In these two simulation cases, the weight of hydro power in the cost function is different. The first case uses a proportion of weight of (hydro/flywheel) = 5 : 1, and the second case use a proportion of 10 : 1. Table 6-2 shows the proportions of the hydro and flywheel powers of the cases used in the simulations.

Table 6-2 Weight of Hydro Power Plant and Flywheel Power

	Hydro	Flywheel
Case 1	5	1
Case 2	10	1

Two situations are considered in each of the cases. In the two simulations, the difference lies in the flywheel energy offset point.

In the first situation, the flywheel energy offset point is located at the middle point of flywheel energy range, i.e., E_fw_offset=(E_fw_min+E_fw_max)/2.

In the second situation, the flywheel energy offset point is located at the 90% of the flywheel energy range, close to the maximum energy point, i.e. E_fw_offset=E_fw_max-(E_fw_max-E_fw_min)*0.1.

Each of the two situations was simulated for each of the two cases. The results are arranged accordingly in the sequel.

Two different time durations of the regulation signal are used to plot the simulation results, namely 2000 seconds and 48 hours. 2000 seconds duration provides more detailed information about the simulated curves. The 48-hour duration presents the results reflecting long-term performance of the algorithm.

6.6.3 Presentation of Results

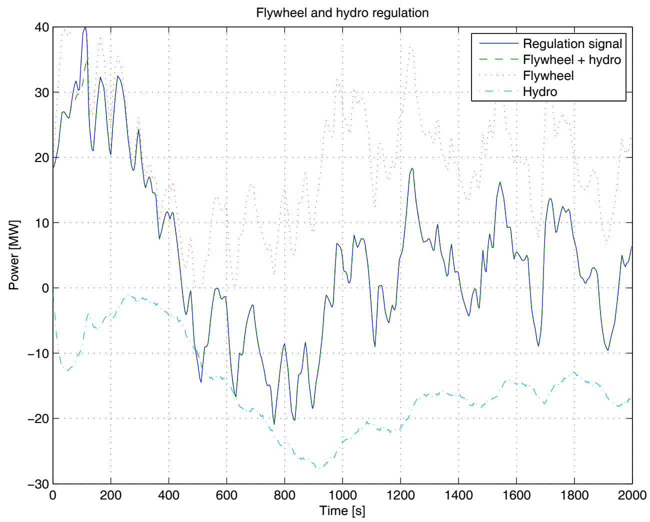
Diagrams were generated for each of the simulation cases for each of the situations, namely "Flywheel and Hydro Regulation", "Flywheel State of Charge" and "Hydro Power".

"Flywheel and Hydro Regulation" diagrams provide overall information regarding the original regulation signal, and the contributions of flywheel and hydro power. For example, from Figure 6-7 we can see that the original regulation signal is scaled in the range of -40… 40 MW. The combination of flywheel and hydro power closely match the scaled regulation signal. Furthermore, flywheel power is in the range of 0… 40 MW, which means most of the regulation up service is provided by flywheel power. Similarly, hydro power is in the range of -40… 0 MW, which means they will provide most of the regulation down service.

"Flywheel State of Charge" diagrams illustrate the energy stored in the flywheel with respect to the time. For instance, Figure 6-8 shows that the energy stored in the flywheel is around 1…3 MWh during the period of 2000 seconds. The selection of flywheel energy offset point has a significant impact on the energy level in the "Flywheel State of Charge" diagrams. For example, if the flywheel energy offset point is selected at the middle point of energy range of flywheel, the energy level stays in the range of 1…3 MWh, as shown in Figure 6-8. If the flywheel energy offset point is located at 90% of flywheel energy range, the energy level falls into the range of 3…5 MWh, as shown in Figure 6-8.

"Hydro Power" diagrams demonstrate variation of hydro power. The two red lines correspond to 1% variation around the hydro power most efficient operating point. From the "Hydro Power" diagrams for 48 hours, we can see that most of time hydro power stays within the efficiency range.

6.6.4 Simulation Part 1



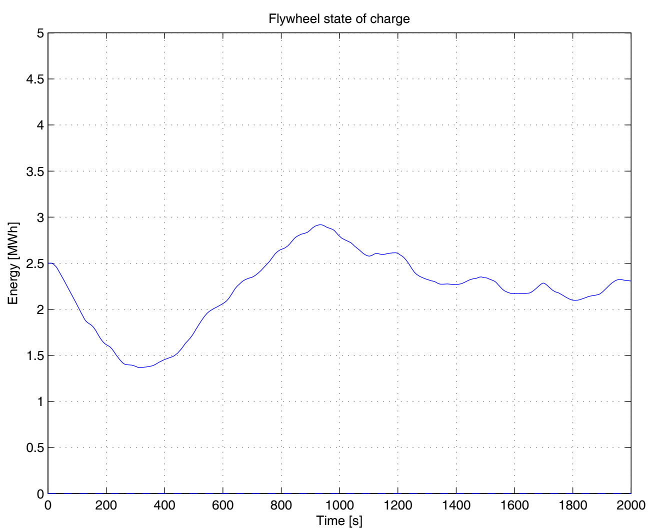
Comments

The flywheel/hydro aggregate follows the regulation signal exactly.

Flywheel provides regulation up service; Hydro power plant provides regulation down service.

Flywheel takes most of the regulation job in terms variability of regulation. Lesser stress is posed on the hydro unit.

Figure 6-7 Flywheel and hydro regulation. Flywheel energy offset point is located at the middle of energy range of flywheel (Duration = 2000 sec, Flywheel weight = 1, Hydro weight = 5)

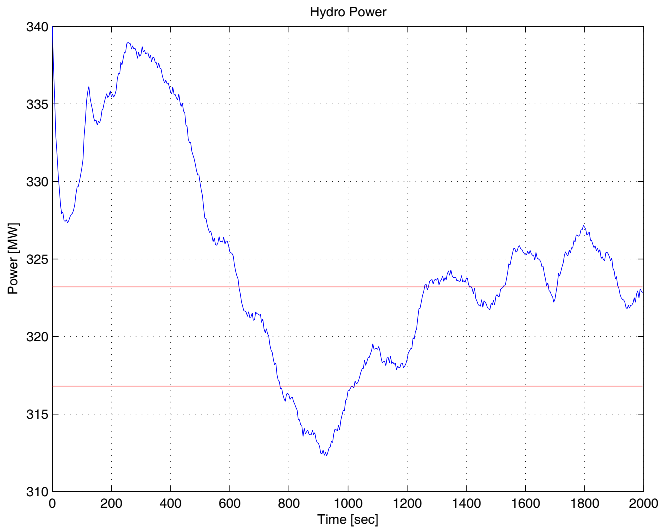


Comments

Flywheel's energy is kept close to the midpoint. Hydro power plant helps to make this happen.

There is a reserve of energy that could allow the flywheel to do more regulation job.

Figure 6-8 Flywheel state of charge. Flywheel energy offset point is located at the middle of energy range of flywheel (Duration = 2000 sec, Flywheel weight = 1, Hydro weight = 5)

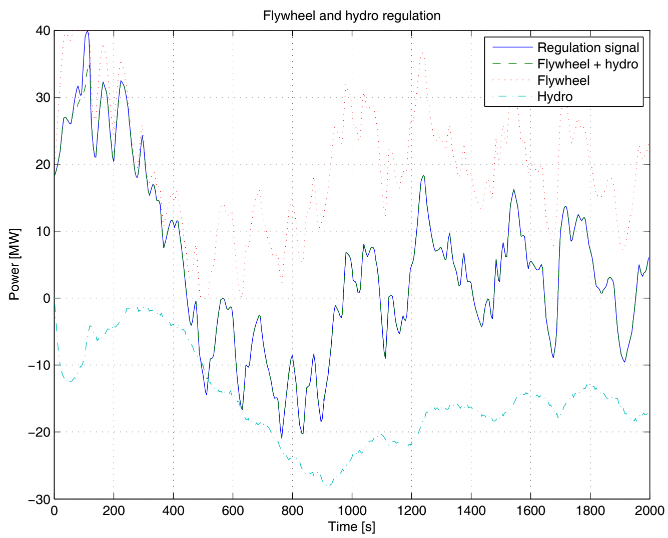


Comments

The hydro power plant output varies in the range 312…336 MW (26 MW swing) while the flywheel provides a 40 MW swing – see Figure 6-7.

It is recommended to increase the fly-wheel weight factor to force the fly-wheel to do more regulation job.

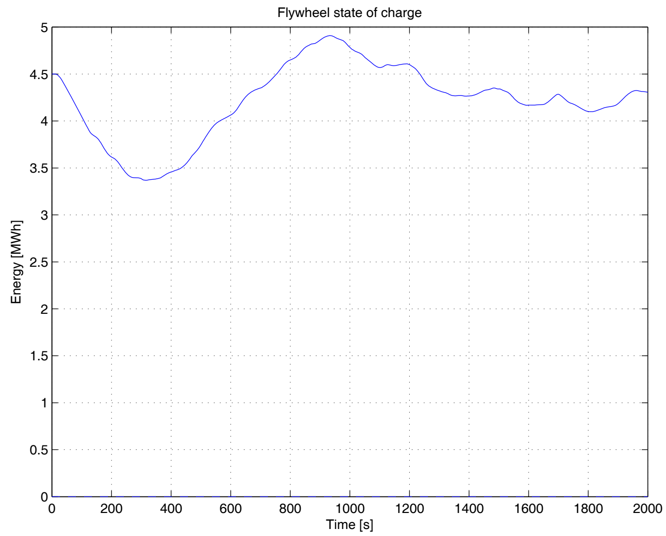
Figure 6-9 Hydro power. Flywheel energy offset point is located at the middle of energy range of flywheel (Duration = 2000 sec, Flywheel weight = 1, Hydro weight = 5)



Comments

The offset of flywheel's energy does not change does not change the job that is performed by the flywheel.

Figure 6-10 Flywheel and hydro regulation. Flywheel energy offset point is located at the 90% point of energy range of flywheel. (Duration = 2000 sec, Flywheel weight = 1, Hydro weight = 5)

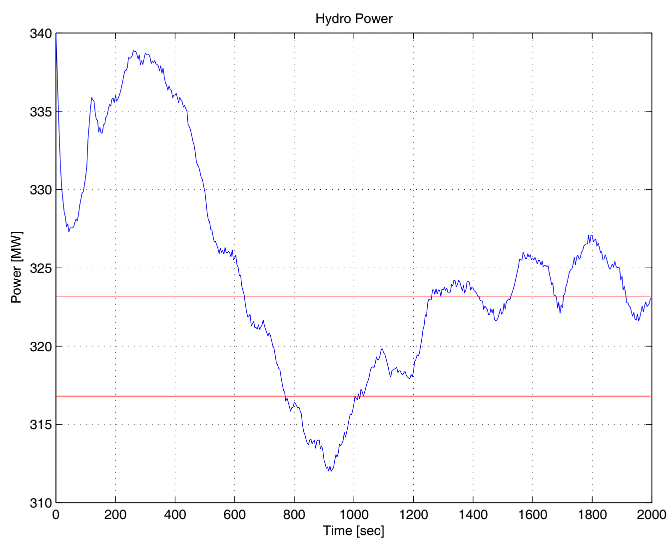


Comments

The flywheel's energy characteristic is shifted toward its maximum limit of % MWh.

This is the only observed effect of the shift – see comments made in connection with Figure 6-10.

Figure 6-11 Flywheel state of charge. Flywheel energy offset point is located at the 90% point of energy range of flywheel. (Duration = 2000 sec, Flywheel weight = 1, Hydro weight = 5)

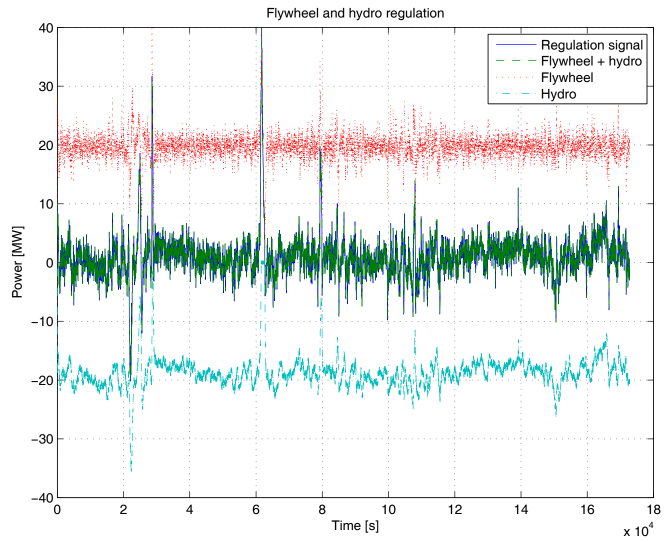


Comments

Hydro power behavior does not change comparing to the case where the flywheel energy is kept around its middle point – see Figure 6-7.

Figure 6-12 Hydro power. Flywheel energy offset point is located at the 90% point of energy range of flywheel. (Duration = 2000 sec, Flywheel weight = 1, Hydro weight = 5)

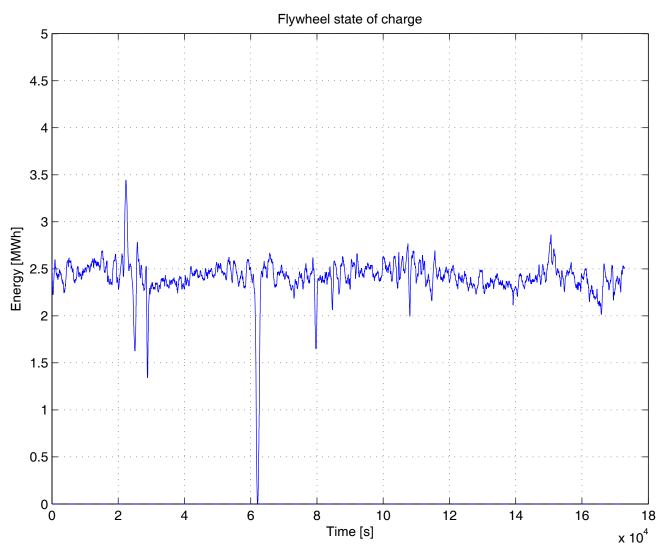
6.6.5 Simulation Part 2



Comments

See Figure 6-7.

Figure 6-13 Flywheel and hydro regulation. Flywheel energy offset point is located at the middle point of energy range of flywheel. (Duration = 48 hours, Flywheel weight = 1, Hydro weight = 5)



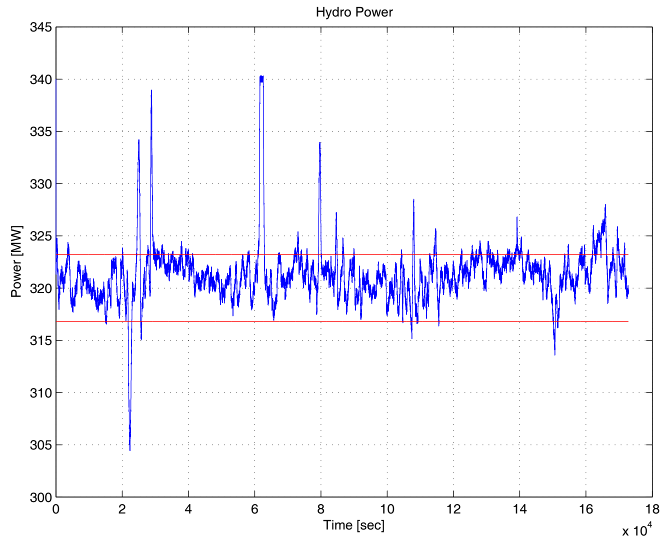
Comments

See Figure 6-8.

At some point within the 48 hour interval, the flywheel energy reaches its minimum.

The energy range above the flywheel's middle point remains underused.

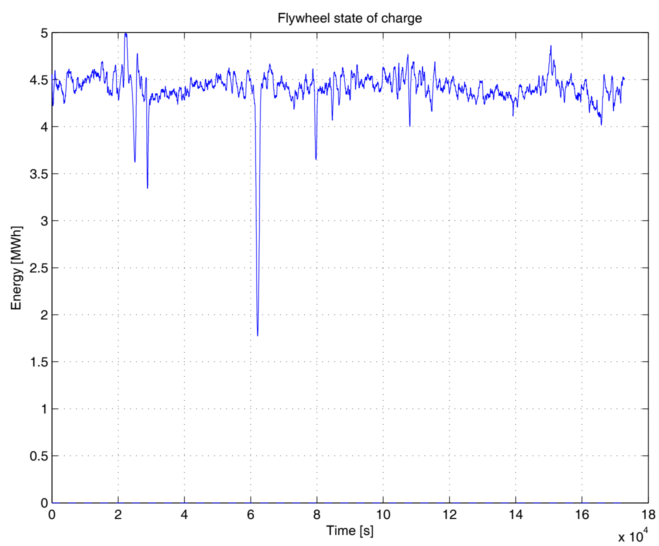
Figure 6-14 Flywheel state of charge. Flywheel energy offset point is located at the middle point of energy range of flywheel. (Duration = 48 hours, Flywheel weight = 1, Hydro weight = 5)



Comments

It is seen that the flywheel is helping to keep the hydro plant output close to the desired -1…+1% range most of the time.

Figure 6-15 Hydro power. Flywheel energy offset point is located at the middle point of energy range of flywheel. (Duration = 48 hours, Flywheel weight = 1, Hydro weight = 5)



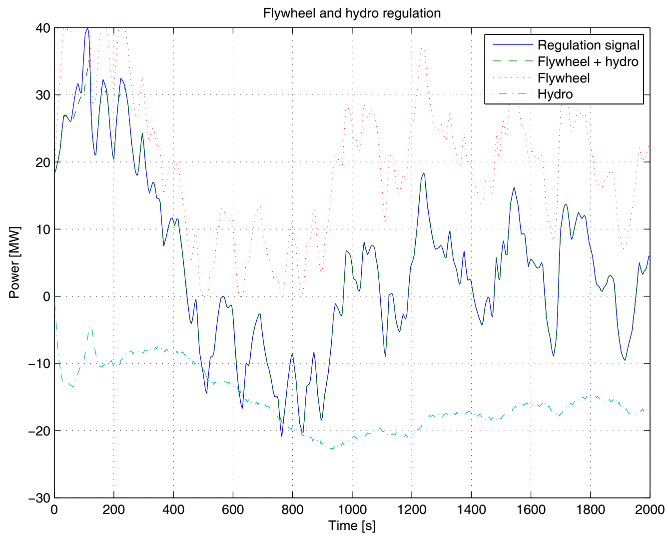
Comments

The flywheel energy curve is now shifted to the upper limit of the energy range.

Manipulation with the flywheel desired state of charge could potentially help to optimally tune this parameter and minimize the number of situations where the flywheel's energy is exhausted or reaches its maximum value.

Figure 6-16 Flywheel state of charge. Flywheel energy offset point is located at the 90% point of energy range of flywheel. (Duration = 48 hours, Flywheel weight = 1, Hydro weight = 5)

6.6.6 Simulation Part 3



Comments

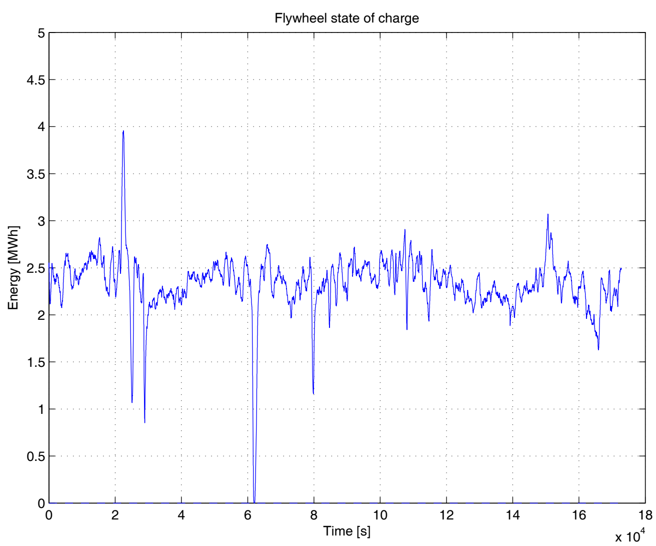
Due to increased hydro weight factor, the flywheel takes even more regulation job comparing to Figure 6-7, where the hydro weight was 5.

The flywheel operates in the entire range of its power capacity (From 0 Mw to 40 MW).

The hydro power plant regulation curve becomes more shallow and smooth.

Figure 6-17 Flywheel and hydro regulation. Flywheel energy offset is located at the middle point of energy range of flywheel. (Duration = 2000 sec, Flywheel weight = 1, Hydro weight = 10)

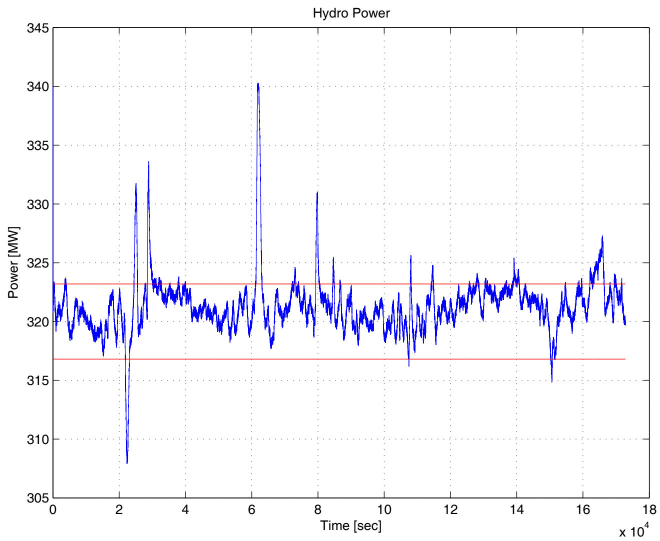
6.6.7 Simulation Part 4



Comments

Flywheel's energy range becomes more efficiently used – compare with Figure 6-14, where the hydro weight factor was 5.

Figure 6-18 Flywheel state of charge. Flywheel energy offset is located at the middle point of energy range of flywheel. (Duration = 48 hrs, Flywheel weight = 1, Hydro weight = 10)



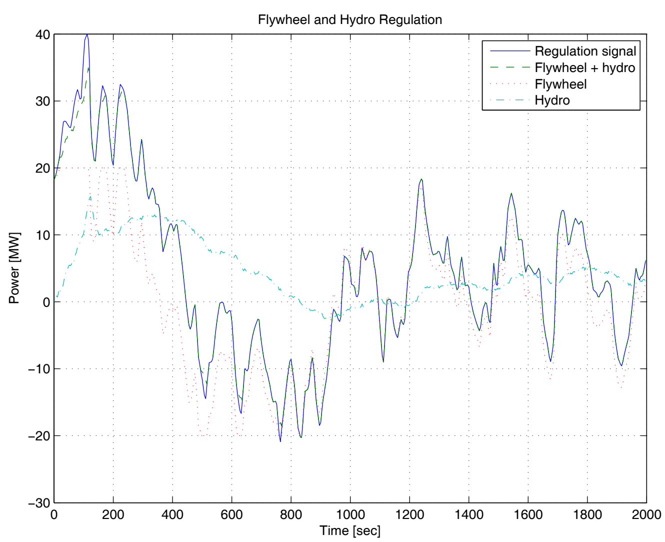
Comments

The hydro power plan's output stays within the -1…+1% range from the most efficient point most of the time.

This contributes greatly to the overall efficiency of the hydro power plant, participating in the aggregate.

Figure 6-19 Hydro power. Flywheel energy offset is located at the middle point of energy range of flywheel. (Duration = 48 hrs, Flywheel weight = 1, Hydro weight = 10)

6.6.8 Simulation Part 5 - Symmetrical parameter setting scenario



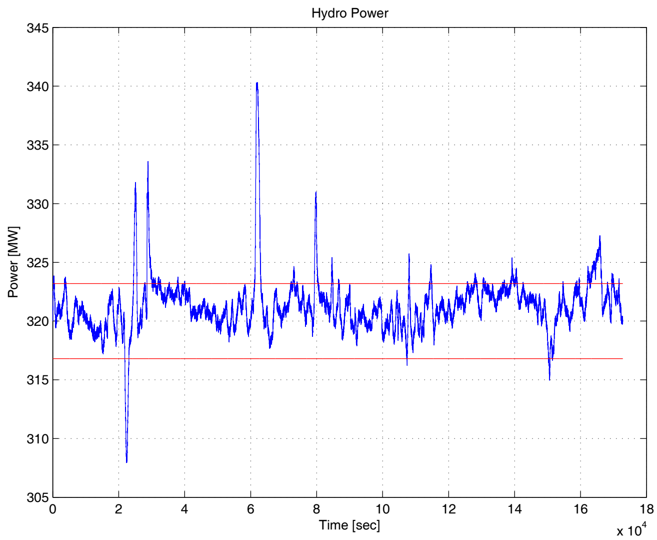
Comments

In this scenario, both the flywheel and hydro power plant perform regulation up and regulation down service.

The flywheel operates in the entire range of its power capacity (From -20 MW to 20 MW).

Figure 6-20 Flywheel and hydro regulation. Flywheel energy offset point is located at the middle of energy range of flywheel (Duration = 2000 sec, Flywheel weight = 1, Hydro weight = 5)

6.6.9 Simulation Part 6 - Symmetrical parameter setting scenario



Comments

There is no change in the hydro power plant performance comparing with the asymmetrical parameter setting scenario – see Figure 6-19.

Figure 6-21 Hydro power. Flywheel energy offset point is located at the middle of energy range of flywheel (Duration = 48 hrs, Flywheel weight = 1, Hydro weight = 10)

6.6.10 Discussion on Simulation Results

- Simulation results clearly demonstrate feasibility and efficiency of the WAEMS. The aggregated hydro power plant and energy storage provide a robust and accurate regulation service.
- The flywheel energy storage can be tuned to make the hydro power plant regulation curve shallower and smoother. This would help to minimize the wearing and tearing problem on the participating hydro power plant.
- It has been shown that the flywheel helps to keep the hydro power plant output closer to the most efficient operating point. By a proper selection of the hydro and flywheel weight factors in the cost function, the hydro power plant operating point can be kept within the 1% deviation range from the most efficient point most of the time.
- The hydro power plant is capable of holding the flywheel's state of charge closer to the selected offset point whenever it is possible and prevent failures in following the regulation requirement when the flywheel exhausts its energy regulation range.
- By selecting the weights in the cost function, the aggregate can be tuned to use the entire regulation range of the flywheel, and minimize the regulation stress posed on the participating hydro power plant.
- The flywheel energy storage can compensate for the regulation inaccuracies caused by the response delay, dead zone, and deviation characteristics of the hydro power plant.
- Both asymmetrical (where the flywheel energy storage provides regulation up, and the hydro power plant provide regulation down services) and symmetrical

(where the flywheel and the hydro power plant provide bi-directional regulation services) are feasible. There are no noticeable differences in the flywheel energy storage and hydro power plant performance in these two approaches.

- By a proper selection of the flywheel's energy offset, the flywheel energy can be adjusted to efficiently use the entire available energy range and minimize the number of violations. This energy offset adjustment does not noticeably alter the flywheel and hydro power plant performance.

6.7 Benefits of Wide Area Regulation Service

The expected benefit from the wide area regulation service is based on the fact that the BPA ACE and California ISO ACE are poorly correlated. This means that the standard deviation (*std*) of the aggregated ACE will be very accurately expressed by the following formula based on the standard deviations of parameters:

$$\begin{aligned} std\left(ACE_{BPA} + ACE_{ISO}\right) &= \sqrt{std^2\left(ACE_{BPA}\right) + std^2\left(ACE_{BPA}\right)} \\ &\le std\left(ACE_{BPA}\right) + std\left(ACE_{BPA}\right) \end{aligned} \tag{6.17}$$

For the used dataset, the correlation coefficient between these two signals was only 0.039. To evaluate the benefits numerically, the BPA and California ISO ACE signals were scaled down to a 40 MW range using the following expressions:

$$\begin{aligned} R_{BPA} &= ACE_{BPA} \frac{40}{200} \\ R_{ISO} &= ACE_{ISO} \frac{40}{600} \\ R_{Total} &= R_{BPA} + R_{ISO} \end{aligned} \tag{6.18}$$

The probability density functions were calculated for all three signals as shown in Figure 6-22. The 99.9% percentile was computed for all of them.

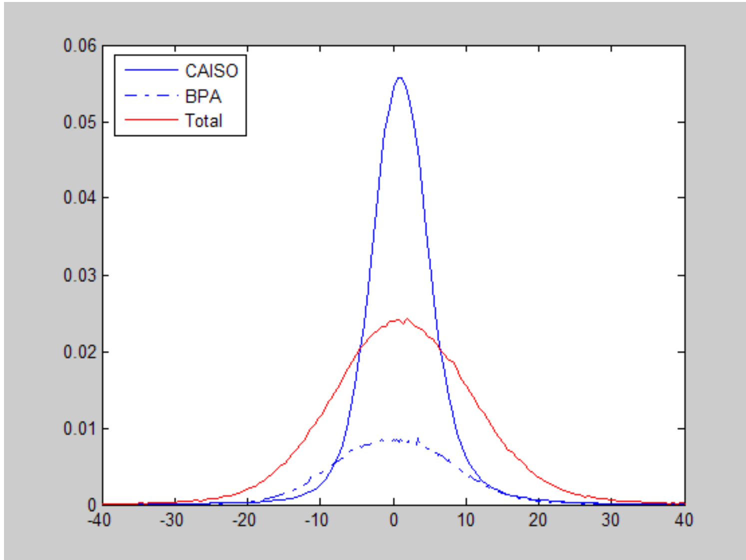


Figure 6-22 Probability density functions for BPA, California ISO and total regulation signals

The percentiles show the range where the analyzed signal remains 99.9% of the time. These percentiles were as follow:

$$
\begin{aligned}
p\left(R_{BPA}\right) &= \pm 37.38 \text{ MW} \\
p\left(R_{ISO}\right) &= \pm 45.59 \text{ MW} \\
p\left(R_{Total}\right) &= \pm 65.27 \text{ MW}
\end{aligned}
\tag{6.19}
$$

The amount of regulation that is needed for the analyze signals when the systems are balancing them separately is the sum of the first two percentiles, which is by about 30% greater than the amount of regulation needed for the total regulation, which is the third percentile.

6.8 Estimates of Benefits, Costs and Net Present Values of Energy Storage Options

A spreadsheet was developed as part of effort in Stage Gate 4 to assess the cost, benefit and net present value (NPV) of the energy storage technologies selected in Stage Gate 1.

6.8.1 Net Present Value Calculation

Net present value is the difference between the present value of cash inflows and the present value of cash outflows. NPV compares the value of a dollar today to the value of that same dollar in the future, taking inflation and returns into account [70].

The values the energy storage technologies were considered to provide are the ancillary services a utility would need to employ to accommodate relatively large fluctuations in intermittent renewable generation such as wind power. Specifically, the benefit of storage (or a hydro power) plant providing ancillary services, and up and down system regulation in particular, are the values assessed in this portion of the study.

The basis for estimating the NPV of the storage options considered in this study is the expression:

$$NPV = (AB - AC)\frac{(1+I)^n - 1}{I \cdot (1+I)^n} \tag{6.20}$$

where:

NPV is net present value ($).
AB is annual benefit ($).
AC is annual levelized cost ($).
I is discount rate.
n is plant life in years.

This formula calculates the NPV of the difference between the annual benefit and the annual levelized cost of the storage plant. The variables in this expression were derived in the following manner.

Annual Benefit. The annual benefit of all storage options was estimated as the product of the annual sum of the energy exchanges in MWh they achieve with the grid and the value in $/MWh these transactions are worth.

Service Value. In the Bonneville Power Administration (BPA) control area, energy storage values were taken as the values placed on ancillary services published in BPA's 2008 Transmission and Ancillary Service Rates Summary [71]. Specifically, the estimated benefit of energy storage in the BPA service area is the sum of:

Service 10 - hourly scheduling, system control and dispatch (0.59 mills/kWh).
Service 12 - regulation and frequency response (0.33 mills/kWh).
Service 14/15 - operating reserves - spinning and supplemental (7.93 mills/kWh).

The total value of these ancillary services ($8.85/MWh) was applied to energy storage transactions in the BPA control area. The value of ancillary service is significantly higher for the California Independent System Operator (California ISO). The average annual price for regulation per service hour in the California ISO control area has recently been $21.48/MW and $15.33/MW for up and down regulation, respectively, or $36.70 in total. Energy storage transactions in the California ISO control area were multiplied by this value to estimate storage benefits.

Two additional values increase these benefits. Because a single round trip transaction provides ancillary service during both charge and discharge cycles, the value of a single transaction based on rated storage capacity of the plant is doubled. In addition, regulation service provided in one control area can be synergistic with regulation requirements in an adjacent area. To account for this, the benefits based on the above considerations can be multiplied by an additional factor of 1.3 (as described in Section 6.7).

Energy Transaction. The gross annual energy exchanged between a storage plant and the grid was estimated from the "nameplate" capacity rating of the plant standardized as

20 MWh for all options multiplied, in turn, by a 0.95 utilization factor and 8760 hours per year. This estimate multiplied by its service value provides the annual benefit (AB) in Equation (6.21).

Annual Cost. The annual cost (AC) in the above expression is the estimated sum of the annual levelized fixed payment that recovers the capital investment in the storage plant plus annual operating costs characteristic of each technology. The derivation of the components of AC is described below.

Levelized Cost of Capital. The basis for estimating the annual fixed (mortgage-type) payment that recovers capital is:

$$AFP = CAP \frac{RF \cdot (1+RF)^n}{(1+RF)^n - 1} \tag{6.22}$$

where:
AFP is annual fixed payment ($).
CAP is plant capital cost ($).
RF is capital recovery factor also called fixed charge rate.
n is plant life in years.

The cost of capital will be different depending on the institution that makes the investment. Three cases were considered. Both the real discount rate and RF for a plant investment made by BPA is 3% [72]. This assumption is based on guidance provided in the referenced report, which provides tables of present-value factors for use in the life-cycle cost analysis of capital investment projects for federal facilities. The factors and indices presented in the reference apply to the present value of future project-related costs, especially those related to operational energy costs.

The cost of capital in the private market is higher. This study assumed a discount rate of 10% and fixed charge rates of 13% and 20% for utility-owned and private/non-utility-owned plant and equipment, respectively [73].

The capital cost of a representative 20 MWh flywheel energy storage facility was taken to be $30 million for an nth of kind plant [74]. The capital costs of hydro and the two battery technologies were estimated from the respective cost per kWh data included in Table 3-2 and Table 3-4.

Depth of Discharge Consideration for Battery Systems. The capital cost of the two battery systems studied includes a factor scaled from information in Table 3-4 that accounts for the need to oversize batteries with respect to their "nameplate" storage capacity when they are used for rapid grid regulation service. This oversizing permits their use at depths of discharge shallow enough to provide acceptable cycle life in this service mode. The resulting increase in capital cost is the principal disadvantage battery systems suffer in comparison to competing technology.

Annual Operating Cost. This cost comprises two components: (1) annual operation and maintenance (O&M) costs and (2) the energy cost of plant operation. For the flywheel and hydro systems, the annual O&M cost is estimated as a fixed 3% of the original capital cost. This factor was increased to 10% for both battery systems to account approximately for the anticipated need for battery cell replacement over the rated life of the plant.

The energy cost of plant operation was estimated to be equivalent to the round-trip inefficiency (i.e., 1 – efficiency) of each technology, as indicated in Table 3-2. The price of this energy was taken to be the $27.33/MWh PF Preference Rate and $40/MWh, respectively, for plants operating in the BPA and California ISO service areas.

6.8.2 Cost Benefit Analysis Results

A spreadsheet was constructed using the above methodology. The principal results of this analysis are shown in Table 6-3. These results correspond to the NPV of each technology and application being estimated using a 10% discount rate applied to the difference between the annual benefit and annual cost [73], as indicated in equation.

Table 6-3 Summary of Benefits, Costs, Benefit/Cost Ratios and Net Present Values

Storage System	BPA Financed	California ISO Utility Financed	California ISO Private Financed
Flywheel			
Capital Cost ($M)	30	30	30
Annual Benefit ($M)	3.83	15.88	15.88
Annual Cost ($M)	3.46	5.97	7.86
Benefit/Cost	1.11	2.66	2.02
NPV ($M)	+5.5	+84.4	+68.3
Pumped Hydro/Hydro			
Capital Cost ($M)	20	20	20
Annual Benefit ($M)	3.83	15.88	15.88
Annual Cost ($M)	2.99	4.49	5.75
Benefit/Cost	1.28	3.54	2.76
NPV ($M)	+12.5	+97	+86.2
Lead Acid Battery			
Capital Cost ($M)	226	226	226
Annual Benefit ($M)	3.83	15.88	15.88
Annual Cost ($M)	38.90	56.39	-
Benefit/Cost	0.1	0.28	-
NPV ($M)	-520	-340	-
Sodium Sulfur Battery			
Capital Cost ($M)	56	56	56
Annual Benefit ($M)	3.83	15.88	15.88
Annual Cost ($M)	9.82	14.24	17.77
Benefit/Cost	0.39	1.12	0.89
NPV ($M)	-110	+14	-16

6.8.3 Discussion of Cost Benefit Analysis Results

The approach taken represents a systematic approach to establishing the relative economic viability of four energy storage technologies reflecting benefits and costs as they are affected by plant location and financing options. The methodology is not completely rigorous. For example, it does not account in detail for financing and O&M costs, or for the cost of capital used during plant construction. Nevertheless, it provides a ready first-order means of comparing and ranking the economic value of alternative energy storage options in the two control areas of interest.

The principal reason each technology offers a higher value to the California ISO in comparison to its corresponding value in the BPA service area is the significantly higher value the California ISO places on ancillary services. The results show flywheels and pumped hydro storage would have a positive NPV in both the BPA and California ISO service areas. Sodium/sulfur battery technology is viable only as a utility-financed option where its benefits can be valued at California ISO rates. Even in the California ISO service area, the differential added cost of private financing causes this technology to exhibit a negative NPV. Lead-acid battery technology appears to be uniformly not economically viable in all storage applications in which the value of rapid regulation is its principal benefit.

7. Recommendations for Phase 2

Recommendations have been made to BPA and California ISO to continue the project into Phase 2. The main work in Phase 2 will be around physical experiments with the flywheel ESD and other technologies using real BPA and California ISO regulation signals.

The following statement of work has been suggested for Phase 2.

7.1 Specific Goal of Phase 2

Phase 2 will provide essential numerical results needed for the subsequent design of the system architecture and specification. The outcomes will include technical and performance characteristics of the flywheel energy storage, dispatchable load, and distributed generation such as response time, ramping capability, losses, energy limits, and others.

7.2 Phase 2 Tasks

Design the field experiments with the prototype flywheel energy storage at the San Ramon test facility, City of Milton-Freewater resources, transactive commercial building controllers at PNNL's buildings in Richland and Sequim, and APEL building micro turbine in Richland.

2.1 Implement changes/adjustments at the San Ramon test facility if required.

2.2 Prepare the sets of simulated control signals for these resources using the actual data provided by BPA and California ISO.

2.3 Conduct the experiments for the existing penetration levels.

2.4 Calculate an analyze performance characteristics (performance metrics) for each resource for the existing penetration levels.

2.5 In cooperation with the BPA and California ISO engineers (or with the BPA and California ISO wind generation forecasting service providers) prepare sets of look-ahead data for higher penetration levels of wind energy in these systems (future scenarios).

2.6 Conduct the experiments for the future scenarios.

2.7 Calculate an analyze performance characteristics (performance metrics) for each resource for the future scenarios.

2.8 Analyze, compare and systemize the experimental results.

2.9 Provide a summary of results and recommendations for BPA on continuation of the project. Write up and submit Phase 2 report.

7.3 Phase 2 Deliverables

- Phase 2 report including a summary of results of Tasks 2.1-2.9.
- Experimental data and results on CD.
- Recommendations for BPA on a continuation of the project.
- Provide BPA with the updated SOW and budget for Phase 3.

7.4 Expected Performance Standards (Stage Gate):

Acceptable performance regulation and load following metrics comparable to a standard generation unit on regulation (for the existing and future penetration levels).

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