Coordinated Multi-Objective Control of Regulating Resources in Multi-Area Power Systems with Large Penetration of Wind Power Generation

Preben Nyeng, Bo Yang, Jian Ma, Yuri Makarov, John H. Pease, David Hawkins, and Clyde Loutan

***Abstract*--This paper describes a control algorithm for a Wide Area Energy Storage and Management System (WAEMS). The WAEMS is designed to meet the demand for fast, accurate and reliable regulation services in multi-area power systems with a significant share of wind power and other intermittent generation. The means are utilization of flywheel energy storage units, hydro power generation, and energy exchange among the participating control areas.**

The objective of the control algorithm is to respond to the control signals from the different system operators, whilst optimizing the hydro power plant operation by reducing the tear and wear on the mechanical parts and improving the energy efficiency of the plant.

The performance of the WAEMS is simulated using a mathematical model, including hydro power plant and flywheel energy storage models. ACE measurements from the California ISO and Bonneville Power Administration control areas are used as control signals to the WAEMS.

Simulations demonstrate excellent regulation response and break-through results in terms of improved hydro power plant operation.

***Index Terms*—Control, wind power, regulation, power systems. linear programming, quadratic programming**

I. INTRODUCTION

The Bonneville Power Administration (BPA) and California ISO (CAISO) both expect a significant increase of wind power penetration in their respective service areas within near future. Studies have shown that the increased wind power penetration will require additional regulation and load-following capacity [1]-[3].

To mitigate the increased demand for regulation capacity, a Wide Area Energy Storage and Management System (WAEMS) is proposed in a research project, recently conducted by the Pacific Northwest National Laboratory for the BPA [4]. The 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.

The project develops principles, algorithms, market integration rules, functional design and technical specifications for the WAEMS system. In this paper, we propose a control algorithm to be used in the WAEMS, and present simulation results obtained using an integrated model of the control system and the participating units.

II. SYSTEM DESCRIPTION

From the point of view of each of the participating control area operators, the WAEMS must react like any other regulation resource, i.e. respond to an automatic control signal, posted every 4 seconds.

A system overview is given in Fig. 1. The principle of the WAEMS is to summarize the regulation signals from each control area operator and coordinate the operation of the individual participating storage or generation resources to meet the requested total regulation output. Dynamic schedules are used to distribute the resources between participating control areas.

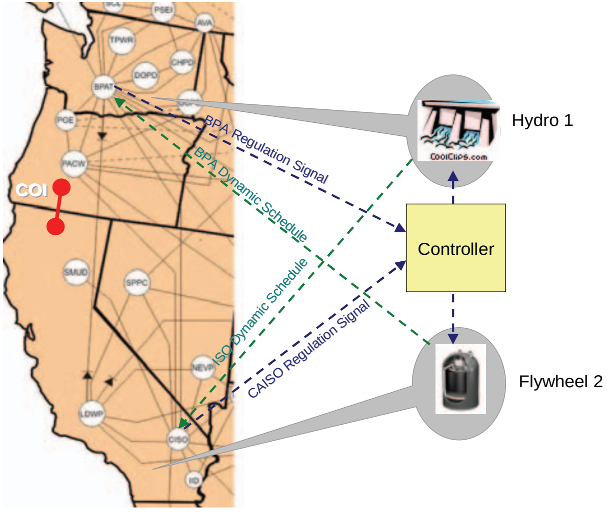

Fig. 1. Overview of the system concept.

The work has been funded under the Bonneville Power Administration Technology Innovations contract # BPA00028087/PNNL52946. California ISO, the California Energy Commission, and Beacon Power Corporation contributed in kind to this project.

The Pacific Northwest National Laboratory is operated by Battelle for the U.S. Department of Energy under Contract DE-AC05-76RL01830.

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A. Participating units

The WAEMS is conceptually designed to work with many different generation and storage resources and many participating control areas. However for the initial simulations, a setup with 1 generation resource, 1 storage resource and 2 participating control areas is evaluated. The resources are selected to provide 20 MW of regulation each, i.e. a total of 40 MW of regulation.

The generation resource is a hydro power plant commonly found in the Northwestern U.S. No specific plant is chosen for the simulation, but typical values for e.g. response time and power capacity are used:

- Power range: 100 MW … 400 MW
- Regulation service: -20 MW … + 20 MW
- Energy capacity: Unlimited
- Response time (First order step response):
  - 63% after 20 sec.
  - 86% after 40 sec.
  - 95% after 60 sec.

In the WAEMS project, numerous energy storage technologies have been evaluated. For reasons like reliability, fast response, and long cycle life, the flywheel technology has been chosen for the simulations. Further details about the evaluated storage technologies are published separately in [5].

The flywheel plant used in the simulations has the following characteristics:

- Power range: - 20 MW ... + 20 MW
- Energy capacity: 100% power for 15 min. = 5 MWh
- Response time: < 4 sec.
- Standby loss: 1.1%
- Roundtrip efficiency ~90 %

III. SIMULATION MODEL

The simulation model is outlined in Fig. 2. It consists of several parts, integrated into a unified model. Each part is described in subsequent sections. Based on the input signal, a control algorithm determines the optimal distribution of the requested regulation on the participating units. The algorithm calculates setpoints for each unit, which are then supplied to the unit models. The outcome is time series of hydro power plant output, flywheel energy state, and flywheel power output.

Compared with the flywheel, the hydro plant has a significantly longer response time. To achieve a fast aggregated response to the regulation signal, the flywheel setpoint is modified dynamically to compensate for the hydro plant delays.

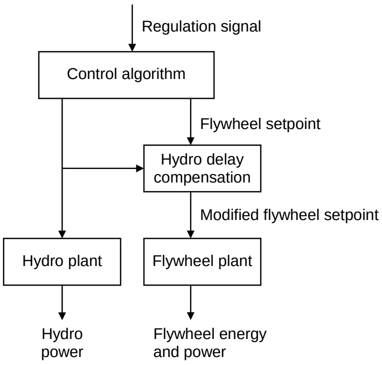

Fig. 2. Block diagram of the integrated simulation model.

A. Control algorithm

The control algorithm seeks to find the optimal distribution of resources, satisfying 3 objectives:

1. Keep the hydro plant close to its most efficient point of operation (ideally ± 1%). Deviations from this region of operation will reduce the efficiency of the hydro plant.
2. Maintain desired energy level in flywheel storage, depending on regulation service: up, down or both.
3. Supply the requested regulation service at all times.

The last objective should be met if at all possible, so mathematically it is expressed as a constraint. However if the constraint is violated (e.g. if the flywheel is depleted), an additional post-optimization step calculates a solution to ensure that the regulation service matches the input signal as close as possible.

The relative weight of objectives 1 and 2 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 plant 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.

1) Variable boundaries

Power output from, or input to, the flywheel is limited by the power converter and generator/motor:

$$P_{fw\min} \le X_{fw} \le P_{fw\max} \tag{1}$$

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:

$$E_{fw,\min} \le E_{fw,next} \le E_{fw,\max} \tag{2}$$

The relation between energy and power is given by

$$E_{fw,next} = E_{fw} - X_{fw} \cdot \Delta t \tag{3}$$

which inserted into (2) gives:

$$\frac{E_{fw} - E_{fw,\max}}{\Delta t} \le X_{fw} \le \frac{E_{fw} - E_{fw,\min}}{\Delta t} \tag{4}$$

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

$$P_{hyd,\min} \le P_{hyd} \le P_{hyd,\max} \tag{5}$$

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

$$P_{hyd} = P_{hyd,sch} + X_{hyd} \tag{6}$$

which inserted into (5) gives the limit for the regulation output:

$$P_{hyd,\min} - P_{hyd,sch} \le X_{hyd} \le P_{hyd,\max} - P_{hyd,sch} \tag{7}$$

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

$$P_{hyd,cap,\min} \le X_{hyd} \le P_{hyd,cap,\max} \tag{8}$$

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

$$\begin{aligned}
&X_{fw,\min} \le X_{fw} \le X_{fw,\max}\\
&X_{hyd,\min} \le X_{hyd} \le X_{hyd,\max}\\
&X_{fw,\min} = \max\left(P_{fw\min}, \frac{E_{fw} - E_{fw,\max}}{\Delta t} \right)\\
&X_{fw,\max} = \min\left(P_{fw\max}, \frac{E_{fw} - E_{fw,\min}}{\Delta t} \right)\\
&X_{hyd,\min} = \max\left(P_{hyd,cap,\min}, P_{hyd,\min} - P_{hyd,sch}\right)\\
&X_{hyd,\max} = \min\left(P_{hyd,cap,\max}, P_{hyd,\max} - P_{hyd,sch}\right)
\end{aligned} \tag{9}$$

2) *Variable interdependent constraints*

The total regulation performed by both units must match the regulation signal that is input to the control algorithm:

$$X_{fw} + X_{hyd} = RS \tag{10}$$

Due to the physical location of the units on each side of the California-Oregon Intertie, additional constraints are necessary when the intertie is congested to prevent overloading. However, such constraints are not considered in this model.

3) *Objective function*

To find the optimum distribution of resources, the problem is expressed as a minimization problem of an objective function, which consists of a weighted sum of objective functions for each objective:

$$\min_X F(x) = \min_X\left(F_{fw}\left(X_{fw}\right) + F_{hyd}\left(X_{hyd}\right)\right) \tag{11}$$

Selecting the objective functions influences the solution technique used to calculate the optimum. We have evaluated linear programming and quadratic programming techniques and found the latter to give the best results, with no caveats in terms of computation time. Consequently, in the following and in the presentation of results, only the quadratic programming technique is considered.

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

$$F_{fw} = a_{fw}\left(E_{fw,next} - E_{fw,offset}\right)^2 \tag{12}$$

where a_{fw} is the weight factor of the flywheel objective function in the total objective function. Fig. 3 is a plot of the flywheel objective function.

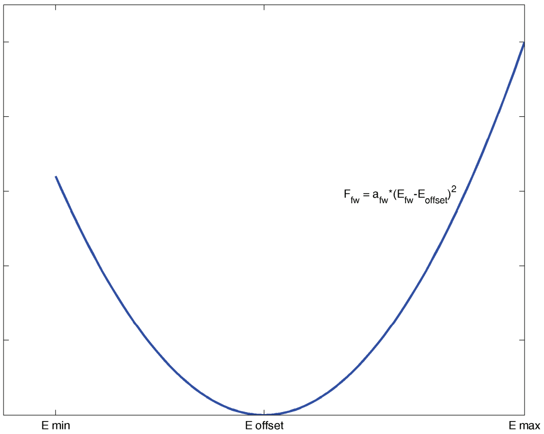

Fig. 3. Plot of flywheel objective function.

Since the optimization variable is power and not the energy, the objective function is written as a function of X_{fw} by inserting (3) into (12):

$$\begin{aligned}
F_{fw} &= a_{fw}\left(E_{fw} - X_{fw}\Delta t - E_{fw,offset}\right)^2\\
&= a_{fw}\left(\left(E_{fw} - E_{fw,offset}\right)^2\right.\\
&\quad \left. + \left(X_{fw}\Delta t\right)^2 - 2\left(E_{fw} - E_{fw,offset}\right)X_{fw}\Delta t\right)
\end{aligned} \tag{13}$$

The hydro objective function is formulated to reflect the preferred operation at the most efficient power output setpoint. Deviation from the most efficient point of operation, $P_{hyd,eff}$, adds quadratically to the objective function value:

$$F_{hyd} = a_{hyd}\left(P_{hyd} - P_{hyd,eff}\right)^2 \tag{14}$$

where a_{hyd} is the weight factor of the hydro objective function in the total objective function. Fig. 4 is a plot of the hydro objective function.

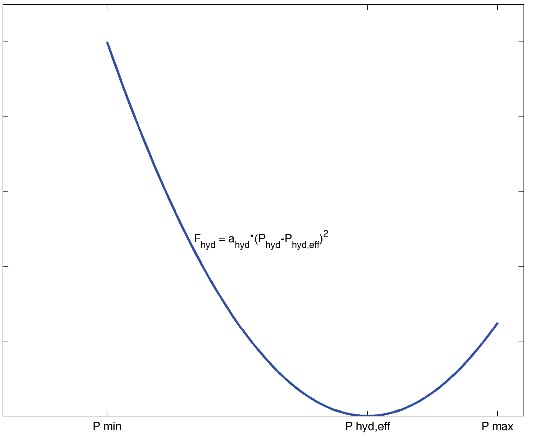

Fig. 4. Plot of hydro objective function.

The hydro objective function is rewritten as a function of the optimization variable X_{hyd} by inserting (6) into (14):

$$\begin{aligned}
F_{hyd} &= a_{hyd}\left(P_{hyd,sch} + X_{hyd} - P_{hyd,eff}\right)^2\\
&= a_{hyd}\left(\left(P_{hyd,sch} - P_{hyd,eff}\right)^2\right.\\
&\quad \left. + X_{hyd}{}^2 + 2X_{hyd}\left(P_{hyd,sch} - P_{hyd,eff}\right)\right)
\end{aligned} \tag{15}$$

4) *Global minimization*

The global minimization problem is solved by minimizing the total objective function given by the sum of the objective functions in (13) and (15). The total objective function may thus be written as:

$$F = \frac{1}{2} \cdot X \cdot H \cdot X^T + f^T \cdot X$$

with

$$X = \begin{bmatrix} X_{fw} \\ X_{hyd} \end{bmatrix} \qquad (16)$$

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

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

B. Flywheel Model

The flywheel model was initially developed and supplied by Beacon Power Corporation. For the model to be incorporated into the integrated model, outlined in Fig. 2, it has been converted to a MATLAB model by PNNL. The flywheel model includes charging and discharging losses, floating losses and auxiliary power as shown in Fig. 5.

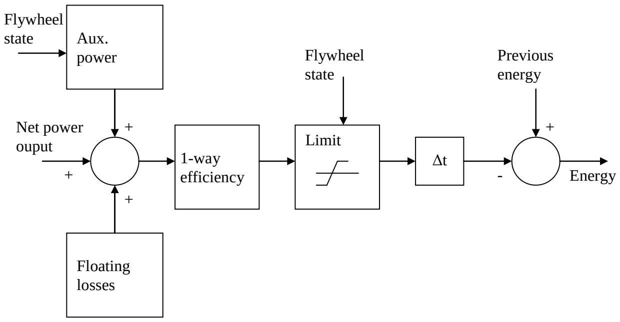

Fig. 5. Block diagram of the flywheel model.

C. Hydro Model

The developed hydro power plant model is shown in Fig. 6. 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.

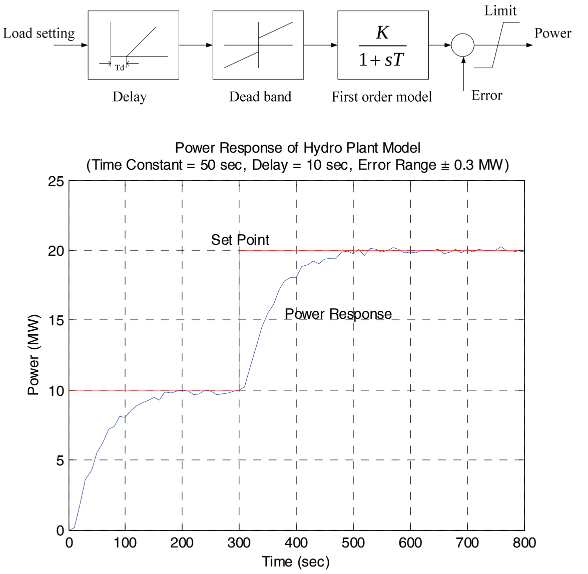

Fig. 6. Block diagram of the hydro model and a plot of a step response. In this plot a time constant of 50 seconds is assumed, but in the simulations in this paper a time constant of 20 seconds is used.

1) Input Signal

Due to the limited availability of a real regulation signal, Area Control Error (ACE) signals are used as a substitute. A total of 36 days of 4-second data throughout a year were available for the simulation. The maximum period of consecutive data is 48 hours, and the results in this paper only treat a single 48 hour period. However similar results are obtained for other 24 hour or 48 hour periods.

The ACE data from each control area are added and the result is scaled to fit into the 40 MW range of up or down regulation.

IV. RESULTS

Some results of the simulations are shown in this section. A simulation period of 48 hours is used. The three plots in Fig. 7 are a close-up on a shorter period to show the input signal and the resulting power outputs in detail. It is observed that the aggregate power output follows the input signal well, and that the hydro output curve is smoother than the flywheel output curve. In other words, the system in this simulation is tuned to let the flywheel react on the fast changes whereas the hydro plant reacts when the flywheel state of charge starts to offset from the desired energy level.

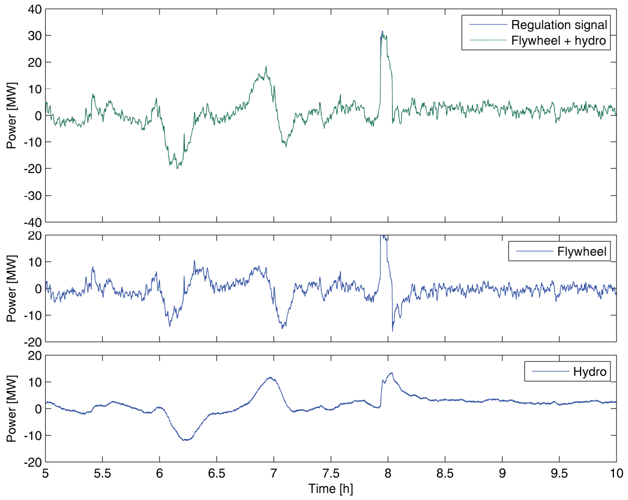

Fig. 7. Aggregate power output and input signal; flywheel power output; and hydro output.

The plots in Fig. 8 show the output from the hydro plant together with the boundaries of the region considered the most efficient operating range. Operation outside this region is reduced from 10.8 to 5.2 hours with the proposed control algorithm. Furthermore the plot shows a much smoother curve for the hydro output with much less frequent changes.

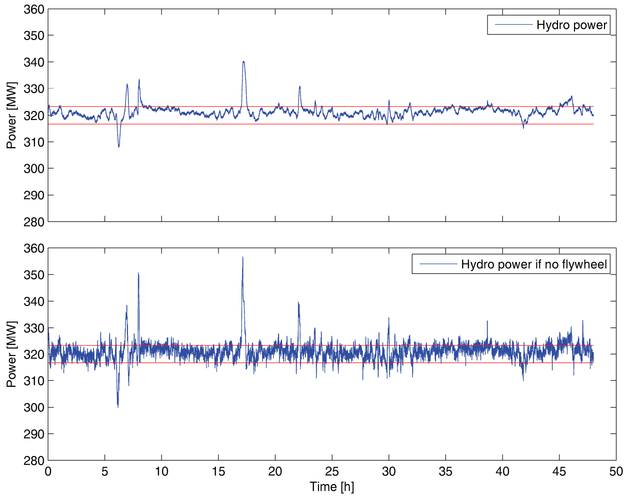

Fig. 8. Hydro power output and hydro power output if there was no flywheel. Both compared with the most efficient region of operation.

Finally, in Fig. 9, the state of charge of the flywheel is observed. The flywheel is fully depleted in a total of 7 minutes during the simulation period.

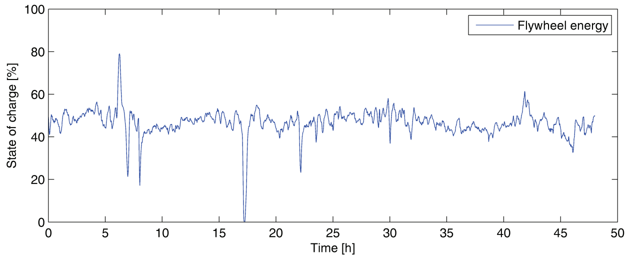

Fig. 9. Flywheel state of charge

V. CONCLUSION

Simulation results clearly demonstrate feasibility and efficiency of the proposed Wide Area Energy Management and Energy Storage system. The aggregated hydro power plant and flywheel storage plant provides a faster and more accurate regulation service, than that of the hydro plant alone. This is because the flywheel compensates for the inaccuracies caused by the response delay, dead zone, and deviation characteristics of the hydro power plant.

The use of 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. Additionally, 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 objective 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 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.

VI. ACKNOWLEDGMENT

Thanks to Carl Miller and Shuai Lu, both PNNL, for their valuable contribution on the flywheel and hydro power plant Matlab models.

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VIII. BIOGRAPHIES

Preben Nyeng received his M.Sc. in Engineering from the Technical University of Denmark in 2000. From 2000 to 2006 he was a development engineer at Logos Control Systems, Denmark. He is currently pursuing the PhD degree at the Center for Electric Technology at the Technical University of Denmark. From August to December 2007 he was a visiting researcher at the Pacific Northwest National Laboratory, Richland, Washington.

Bo Yang (S'03) received the M.S. from Shanghai Jiaotong University, Shanghai, China, in 2003 and Ph.D. from Arizona State University in 2007. She is currently a research scientist at the Pacific Northwest National Laboratory, Richland, WA. Her research interests are in the area of power system dynamics and control.

Yuri V. Makarov received his M. Sc. degree in Computers and Ph.D. in Electrical Engineering from the Leningrad Polytechnic Institute (now St. Petersburg State Technical University), Russia. From 1990 to 1997 he was an Associate Professor at the Department of Electrical Power Systems and Networks in the same University. From 1993 to 1998 he conducted research at the University of Newcastle, University of Sydney, Australia, and Howard University, USA. From 1998 to 2000 he worked at the Transmission Planning Department, Southern Company Services, Inc., Birmingham, Alabama as a Senior Engineer. From 2001 to 2005 he occupied a senior engineering position at the California Independent System Operator, Folsom, California. Now he works for the Pacific Northwest National Laboratory, Richland, WA. His activities are around various theoretical and applied aspects of power system analysis, planning and control. He participated in many projects concerning power system transmission planning (power flow, stability, reliability, optimization, etc.) and operations (control performance criteria, quality, regulation, impacts of intermittent resources, etc.). He was a member of the California Energy Commission Methods Group developing the Renewable Portfolio Standard for California; a member of the Advisory Committee for the EPRI/CEC project developing short-term and long-term wind generation forecasting algorithms, and a voting member of the NERC Resources Subcommittees and NERC Wind Generation Task Force. For his role in the NERC August 14th Blackout Investigation Team, he received a Certificate of Recognition signed by the US Secretary of Energy and the Minister of Natural Resources, Canada.

Jian Ma received the B.S. degree from Shandong University, and the M.S. degree from Dalian University of Technology, China, in 1996 and 1999 respectively. He will receive his Ph.D. degree in Electrical Engineering from The University of Queensland, Australia in June 2008. From 1999 to 2004, he worked as a Research Engineer and Senior Programmer at electrical power R&D companies in China, focusing mainly on EMS/SCADA/DTS. From 2004 to 2005, he conducted research in the School of Mechanical and Aerospace Engineering at Nanyang Technological University, Singapore. From April 2007 to present he has been a visiting research fellow at Pacific Northwest National Laboratory (PNNL), Richland, WA. His research interests include power system stability and control, power system security assessment, and artificial intelligence application in power systems.

John Pease started with Bonneville Power Administration in 1988 as a system protection engineer from 500kV to 69kV. From 1992 to 1998 he was with the BPA Laboratories, working with innovative protection and control schemes at 500kV. In 2001 he became a project manager in the Renewable Energy group for BPA Power, evaluating 26 wind projects as part of BPA's 1000 MW RFP. In 2005 he became the manager of BPA's Wind Forecasting Network, the first forecast system to predict hourly wind energy from real time to seven days in advance. In 2006, John became a project manager for Technology Confirmation and Innovation (TC/I) group at BPA, evaluating 26 wind, wave, tidal and energy storage projects as part of a 2007 RFP, managing 10 projects selected for funding. In 2008 he is managing five projects; one is the PNNL Wind Regulation & Load Following project for the integration of 3000 MW wind by 2009, and the Wide Area Energy Storage system that will assist balancing the BPA and California ISO control areas in real time. Recent achievements: Chairman, Portland Chapter of the IEEE Power Engineering Society, 1999 to 2002; IEEE-USA Professional Achievement Award in 2002. Education: BSEE University of Wyoming (1988), MBA, Portland State University (2001), Professional Engineer, State of Washington.