Final Report for
DOE-BES Award DE-FG02-11ER46817
Awarded to: Montana State University-Bozeman
Period Covered: October 2011-July 2016

Project Title:

Making the Grid "Smart" Through "Smart" Microgrids: Real-Time Power Management of Microgrids with Multiple Distributed Generation Sources Using Intelligent Control

Principal Investigator:

Hashem Nehrir, Professor, IEEE Life Fellow
Electrical & Computer Engineering Department, MSU-Bozeman
hnehrir@ece.montana.edu, phone: 406-994-4980

Submitted: October, 20, 2016

Submitted to:

Dr. Tim Fitzsimmons, DOE Office of Basic Energy Science,
Tim.Fitzsimmons@science.doe.gov

Copied to:

Ms. Cheryl Howard, DOE Office of Basic Energy Science
Cheryl.Howard@science.doe.gov

Ms. Merrill Smith, Microgrid Program Manager, DOE Office of Electricity Delivery & Energy Reliability, Merrill.Smith@hq.doe.gov

Dr. Donald Hammerstrom, contact at Pacific Northwest National Laboratory,
Donald.hammerstrom@pnl.gov

Dr. Chris Marnay, contact at Lawrence Berkeley National Laboratory,
chrismarnay@lbl.gov

Making the Grid "Smart" Through "Smart" Microgrids: Real-Time Power Management of Microgrids with Multiple Distributed Generation Sources Using Intelligent Control

Project Summary:

In this Project we collaborated with two DOE National Laboratories, Pacific Northwest National Lab (PNNL) and Lawrence Berkeley National Lab (LBL). **Dr. Hammerstrom of PNNL** initially supported our project and was on the graduate committee of one of the Ph.D. students (graduated in 2014) who was supported by this project. He is also a committee member of a current graduate student of the PI who was supported by this project in the last two years (August 2014-July 2016). The graduate student is now supported be the Electrical and Computer Engineering (ECE) Department at Montana State University (MSU). **Dr. Chris Marney of LBL** provided actual load data, and the software WEBOPT developed at LBL for microgrid (MG) design for our project. **NEC-Labs America, a** private industry, also supported our project, providing expert support and modest financial support. We also used the software "HOMER," originally developed at the National Renewable Energy Laboratory (NREL) and the most recent version made available to us by HOMER Energy, Inc., for MG (hybrid energy system) unit sizing. We compared the findings from WebOpt and HOMER and designed appropriately sized hybrid systems for our case studies.

The objective of the project was to investigate real-time power management strategies for MGs using intelligent control, considering maximum feasible energy sustainability, reliability and efficiency while, minimizing cost and undesired environmental impact (emissions). Through analytic and simulation studies, we evaluated the suitability of several heuristic and artificial-intelligence (AI)-based optimization techniques that had potential for real-time MG power management, including genetic algorithms (GA), ant colony optimization (ACO), particle swarm optimization (PSO), and multi-agent systems (MAS), which is based on the negotiation of smart software-based agents. We found that PSO and MAS, in particular, distributed MAS, were more efficient and better suited for our work. We investigated the following:

- Intelligent load control - demand response (DR) - for frequency stabilization in islanded MGs (partially supported by PNNL).
- The impact of high penetration of solar photovoltaic (PV)-generated power at the distribution level (partially supported by PNNL).
- The application of AI approaches to renewable (wind, PV) power forecasting (proposed by the reviewers of our proposal).
- Application of AI approaches and DR for real-time MG power management (partially supported by NEC Labs-America)
- Application of DR in dealing with the variability of wind power
- Real-time MG power management using DR and storage (partially supported by NEC Labs-America)
- Application of DR in enhancing the performance of load-frequency controller
- MAS-based whole-sale and retail power market design for smart grid

A brief description of the above investigations is given in the next section.

Description of the Investigations Undertaken:

DR for frequency stabilization in islanded MGs: We developed a comprehensive DR strategy and showed that DR can be used for ancillary services to stabilize frequency in an islanded MG. The strategy continuously balances generation and demand, using an adaptive hill climbing (AHC) controller, which manipulates load to bring frequency within the desired range fast. The AHC controller is then replaced with a step-by-step controller when frequency is within the desired range to reduce the amount of manipulated load to a minimum. [1, 2, 3, 4].

The impact of high penetration of solar photovoltaic (PV)-generated power at the distribution level: We also investigated the impact of high penetration of solar PV on frequency and voltage in distribution systems and how DR can be used under high penetration of solar PV power generation in to stabilize frequency when PV generation is not available, and when there is over supply of PV power [5, 6].

Application of AI approaches to renewable (wind, PV) power forecasting: Renewable energy resource and renewable power forecasting was proposed by the reviewers of our proposal. We investigated how a combination of intelligent algorithms, wavelet transform (WT) and fuzzy ARTMAP (FA) network optimized by using firefly (FF) optimization algorithm, can be used for enhanced short-term forecasting of renewable energy resources (wind, solar) and variable renewable generation (VRG) [7, 8]. Dependable short-term forecasting of renewable energy resources and VRG help power marketers in being better accountable in providing power to system operators and system operators being accountable to the retail markets (i.e., distribution utilities.)

Application of AI Approaches and DR for Real-Time Power Management of MGs: We investigated the feasibility of several nature-based algorithms GA, PSO, ACO, and AI-based distributed MAS for power/energy management of MGs. We noticed that among the different approaches evaluated, PSO and distributed MAS gave the most satisfactory results. We collaborated with LBL in a part of this work for the evaluation of GA and PSO. LBL (through Dr. Chris Marney) provided the software WebOpt (developed at LBL) and helped us using it. We used the software for technology selection and design of the MG we used in our study. We also used the commercial software HOMER for MG design and compared results with those obtained using WebOpt. We used actual load data for a university in San Francisco (provided by LBL) for this study [9, 10, 11].

We also investigated the feasibility of using distributed MAS for real-time MG power management for grid connected and off grid MGs and some initial work on the resiliency of a MG-based power system. The result of this study was very successful. We had several publications, including an invited international presentation/publication [17], a best paper Award [18], two panel presentations, and collaboration with NEC Labs-America. The publications related to this part of the project are: [12, 13, 14, 15, 16, 17, 18].

Application of DR for dealing with the variability of wind power: We investigated the feasibility of raising the thermostat setpoint of residential/commercial electric water heaters (EWHs) up to 160^{o} F (assuming customer participation) to absorb excess available wind power so that wind turbines won't have to be shut off. This technique assumes that extra hot water inside water heater tank is mixed with cold water (using a mixing valve) before water comes out of faucet; it is particularly useful during the periods of high wind and low power demand, for example in the middle of night. We also showed that our proposed method can be used to lower the temperature setpoint of water heaters for participating customers down to 116^{o} F during low-wind or no-wind periods. This method can prevent some EWHs to demand power during low-wind/no-wind periods. These methods help prevent power imbalances between generation and demand and could also be helpful in load-shifting and leveling utility power demand profiles. They are effective DR strategies which encourage customer active participation, which is a DOE smart grid feature [19, 20].

The DOE power marketer, Bonneville Power Administration (BPA), has implemented a prototype of this technique. The PI was a consultant to the consulting firm Ecofys that did the implementation for BPA during 2011-2012.

The application of a combination of DR and storage for power management of off-grid MGs: We developed and evaluated a multi-timescale approach for real-time MG power management. While the MG overall power management and operation is carried out every several minutes to hours, depending

on the availability of the required data, simulation for highly dynamic devices, such as batteries and EWHs (used for DR), are performed every minute. This structure allows accurate, scalable, and practical power management taking into consideration the intra-interval dynamics of battery and EWHs [21].

Application of DR in enhancing the performance of load-frequency controller (LFC):
Evaluation of addition of a DR signal into the control loop of load-frequency controller in power generating systems was another piece of our work, done for single and multi-area power systems [22, 23]. We showed that the addition of the DR signal enhanced the response of LFC.

Application of distributed MAS in power market design and in enhancing the resiliency and self-healing of power systems: We have also used distributed agents for optimal wholesale and retail power market design for smart grid [24, 25]. We are currently continuing this project with financial support for the Ph.D. student (Mr. Kaveh Dehghanpour) working on this project from Montana State University to investigate the application of distributed MAS and distributed optimization for MG resiliency and power management, and self-healing of power systems using a MG-based power system architecture. Dr. Hammerstrom of PNNL is on the graduate committee of the Ph.D. student.

Other professional activities of the PI during the course of this project:

- A visiting Ph.D. student from Aalborg University, Denmark joined the PI's research team during the academic year 2013-2014. The student worked with the PI on assessing the potential of plug-in electric vehicles in active distribution networks and on optimal sizing and allocation of residential PV generation in a distribution system [26, 27]. This student had his own support.

- A female student (Aili Shigwedha) from Namibia joined the PI's research team in 2013 to study for her MSEE degree. Under the supervision of the PI, she investigated the Techno-economic feasibility of hybrid renewable energy systems for an underprivileged community in Namibia. She graduated with the MSEE degree in May 2015 and returned to her home country [28].

- The PI was the speaker at an IEEE Central Montana Section meeting in 2013. The title of his presentation was: Power Generation Options for the Future-Opportunities and Challenges with Renewables

- The PI organized and chaired two panel sessions at IEEE PES conferences, and he and his former student Chris Colson had presentations (Real-Time Microgrid Power Management and Control with Distributed Agents) at the panels, listed below.

    - 2014 Innovative Smart Grid Technologies Conference, Washington, DC, Feb. 19-22.
    - 2014 IEEE PES General Meeting, National Harbor, MD, July 27-31.

- The PI and Chris Colson had an invited article, "Integrating microgrids and multi-agent management," published in the *IEEE Smart Grid Newsletter* in 2014 [29].

- The PI was invited to speak/present as a keynote speaker at the 2014 International Conference on Renewable Energy Utilization, Coimbatore, India. The title of his presentation was: "Renewable Energy Utilization and Role of Energy Storage for Improved Reliability and Resiliency of Smart Grid.

- The PI was also invited to speak at the Southern and Northern Alberta IEEE Sections in Canada in 2014. The title of his presentation was: Role of Storage in Renewable Energy Utilization

- The PI was the recipient of the 2016 IEEE Power and Energy Society "*Ramakumar Family Renewable Energy Excellence Award*" for his contribution to renewable/alternative energy power generation.

Personnel Who Worked on the Project:

The project supported a postdoc, three Ph.D. students, five M.S. students, and one undergraduate student, who worked on different aspects of the project for different time periods during the course of the project, as follows:

- Ashraf Haque, postdoc fellow, full support October 2012-July 2013
- Christopher Colson, Ph.D. 2012, full support in the academic year (AY) 2011-2012
- Ali Pourmousavi, Ph.D. 2014, full support August 2012-December 2013
- Kaveh Dehghanpour, current Ph.D. student, full support August 2014-July 2016
- Stasha Patrick (female student), MSEE 2011 (supported by the MSU ECE Department)
- Aric Litchy, MSEE 2013, full support summers 2012and 2013
- Reza Ahmadi, visiting Ph.D. student from Aalborg University, Denmark, AY 2013-2014. The student had his own support through Aalborg University.
- Kevin Marchase, MSEE 2014, partial support
- Colin Young, MSEE 2014, full support in AY 2013
- Aili Shigwedha (female student), MSEE 2015 (Fulbright Fellow – had her own support)
- Andrew Klem, MSEE 2016, full support August 2015-July 2016
- Louisa Serpe (female undergraduate student), hourly support summer 2016
- Mohammad Anani (undergraduate student), summer 2016 (no support)

References (Name of the student and the postdoc authors are in **bold**):

[1] **S.A. Pourmousavi**, M.H. Nehrir, "Real-Time Central Demand Response for Primary Frequency Regulation in Microgrids," *IEEE Transactions on Smart Grid (Special issue on Microgrid)*, Vol. 3, No. 4, December 2012. Also presented at the 2013 IEEE PES General Meeting, July 21-25, Vancouver, B.C., Canada.

[2] **S.A. Pourmousavi** and M.H. Nehrir, "Demand Response for Smart Microgrid: Initial Results, in *Proceedings*, 2011 IEEE Innovative Smart Grid Technologies Conference, Jan. 16-19, Anaheim CA.

[3] M.H. Nehrir, and C. Sastry, "Providing Ancillary Services through Demand Response with Minimum Load Manipulation," in *Proceedings*, 2011 North American Power Symposium, August 4-6, Boston, MA.

[4] **S.A. Pourmousavi**, M.H. Nehrir, "Real-Time Optimal Demand Response for Frequency Regulation in Smart µGrid," in *Proceedings*, 2012 IASTED Power and Energy Systems Conference (Euro PES 20112), June 25-27, Naples, Italy.

[5] **S.A. Pourmousavi, A.S. Cifala**, and M.H. Nehrir, "Impact of High Penetration of PV Generation on Frequency and Voltage in a Distribution Feeder," in *Proceedings*, 2012 North American Power Symposium, Urbana-Champaign, IL, September 9-11, 2012.

[6] **Kevin Marchese, S.A. Pourmousavi**, and M.H. Nehrir, "The Application of Demand Response for Frequency Regulation in an Islanded Microgrid with High Penetration of Renewable Generation," in *Proceedings*, 2013 North American Power Symposium, Kansas State University, Manhattan, KS, Sept. 22-24.

[7] **A.U. Haque**, M.H. Nehrir, and P. Mandal, "A Hybrid Intelligent Model for Deterministic and Quantile Regression Approach for Probabilistic Wind Power Forecasting," *IEEE Transactions on Power Systems*, Vol. 29, No. 4, July 2014.

[8] **A.U Haque**, M.H. Nehrir, and P. Mandal, "Solar PV Power Generation Forecast Using a Hybrid Intelligent Approach," in *Proceedings*, 2013 IEEE PES General Meeting, July 21-25, 2013, Vancouver, B.C, Canada.

[9] A.J. Litchy, REAL-TIME ENERGY MANAGEMENT OF AN ISLANDED MICROGRID USING MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION, M.S. thesis, Montana State University, 2013.
[10] **A.J. Litchy, C. Young, S.A. Pourmousavi**, and M.H. Nehrir, "Technology Selection and Unit Sizing for a Combined Heat and Power Microgrid: Comparison of DER-CAM and HOMER Application Programs," in *Proceedings*, 2012 North American Power Symposium, Urbana-Champaign, IL, September 9-11.
[11] **A.J. Litchy** and M.H. Nehrir, "Real-Time Energy Management of an Islanded Microgrid Using Multi-Objective Particle Swarm Optimization," in *Proceedings*, 2014 IEEE PES General Meeting, National Harbor, MD, July 27-31.
[12] C.M. Colson, TOWARDS REAL-TIME POWER MANAGEMENT OF MICROGRIDS FOR POWER SYSTEM INTEGRATION: A DECENTRALIZED MULTI-AGENT BASED APPROACH, Ph.D. dissertation, Montana State University, 2012.
[13] **C.M. Colson** and M.H. Nehrir, "Comprehensive Real-Time Microgrid Power Management and Control with Distributed Agents," *IEEE Transactions on Smart Grid (Special issue on Computational Intelligence)*, Vol. 4, No. 1, March 2013.
[14] **C.M. Colson**, M.H. Nehrir, *R.K. Sharma, and B. Asghari*, "Improving Sustainability of Hybrid Energy Systems - Part I: Incorporating Battery Round-trip Efficiency and Operational Cost Factors," *IEEE Transactions on Sustainable Energy*, Vol. 5, No. 1, Jan. 2014.
[15] **C.M. Colson**, M.H. Nehrir, *R.K. Sharma, and B. Asghari*, "Improving Sustainability of Hybrid Energy Systems - Part II: Managing Multiple Objectives with a Multi-agent System," *IEEE Transactions on Sustainable Energy*, Vol. 5, No. 1, Jan. 2014.
[16] C.M. Colson and M.H. Nehrir, "Algorithms for Distributed Decision-Making for Multi-agent Microgrid Power Management," in Proceedings, 2011 IEEE PES General Meeting, July 24-28, Detroit, MI.
[17] (invited paper) C.M. Colson, M.H. Nehrir, and R.W. Gunderson, "Multi-agent Microgrid Power Management," in Proceedings, 2011 IFAC World Congress, August 28-September 2, Milan, Italy.
[18] C.M. Colson, M.H. Nehrir, and R.W. Gunderson, "Distributed Multi-Agent Microgrids: A Decentralized Approach to Resilient Power System Self-healing," in Proceedings, 2011 International Symposium on Resilient Control Systems (ISRCS), August 9-11, Boise, ID. This paper won the Best Symposium Paper Award.
[19] S.N. Patrick, CONTROL OF AGGREGATE ELECTRIC WATER HEATERS FOR LOAD SHIFTING AND BALANCING INTERMITTENT RENEWABLE ENERGY GENERATION IN A SMART GRID ENVIRONMENT, M.S. thesis, Montana State University, 2011.
[20] S. Ali Pourmousavi, Stasha N. Patrick, and M. Hashem Nehrir, "Real-Time Demand Response through Aggregate Electric Water Heaters for Load Shifting and Balancing Wind Generation," IEEE TRANSACTIONS ON SMART GRID, VOL. 5, NO. 2, MARCH 2014. Also presented at the 2014IEEE PES General Meeting, National Harbor, MD.
[21] S.A. Pourmousavi, M.H. Nehrir, and R. Sharma, "Multi-Timescale Power Management for Islanded Microgrids Including Storage and Demand Response," *IEEE Transactions on Smart Grid*, Vol. 6, No. 3, May 2015.
[22] **S. A. Pourmousavi,** M. H. Nehrir, and R.K. Sharma, "**S. A. Pourmousavi** and M. H. Nehrir, "Introducing Dynamic Demand Response in the LFC Model," *IEEE Transactions on Power Systems*, Vol. 29, No. 4, July 2014.
[23] **S. Ali Pourmousavi**, Mahdi Behrangrad, M. Hashem Nehrir, Ali Jahanbani Ardakani, "LFC Model for Multi-Area Power Systems Considering Dynamic Demand Response," accepted for publication and presentation, 2016 IEEE Transmission & Distribution Conference and Exposition, Dallas, TX, May 2-5.
[24] **Kaveh Dehghanpour**, M. Hashem Nehrir, John W. Sheppard, and **Nathan Kelly**, "Agent-Based Decision Making in Electrical Energy Markets Using Dynamic Bayesian Networks," accepted for publication in *IEEE Transactions on Power Systems*, early access available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7420752.

[25] **Kaveh Dehghanpour**, M. Hashem Nehrir, John W. Sheppard, and **Nathan Kelly**, "Agent-Based Modeling of Retail Electrical Energy Markets with Demand Response," revised and resubmitted for review to *IEEE Transactions on Smart Grid*, 2016.
[26] Assessing the Potential of Plug-in Electric Vehicles in Active Distribution Networks," *Energies*, 2016, 9(1), 34, (2015).
[27] R. Ahmadi, **S. A. Pourmousavi**, J. R. Pillai, H. M. Hasanien, B. Bak-Jensen, and M. Hashem Nehrir, "Optimal Sizing and Allocation of Residential Photovoltaic Panels in a Distribution Network for Ancillary Services Application," in *Proceedings*, International Conference on Optimization of Electrical and Electronic Equipment (OPTIM 2014), Brasov, Romania, May 22-24.
[28] Aili Shigwedha, "Techno-economic feasibility of hybrid renewable energy systems for an underprivileged community in Namibia," technical report, Electrical and Computer Engineering Department, Montana state University, 2015.
[29] **C.M. Colson** and M.H. Nehrir, "Integrating-microgrids-and-multi-agent-management," *Smart Grid Newsletter*, September 2014, available at: http://smartgrid.ieee.org/newsletters/september-20142/integrating-microgrids-and-multi-agent-management.