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NSERC Smart Microgrid Research Network

Annual Report 2014 | 2015

NSERC SMART MICROGRID NETWORK
nsmg-net

Vision

Smart Microgrids are the building blocks of a new electrical grid that, by 2020, will: provide **reliable, low cost and clean power**; **defer investments** in transmission and distribution systems; **improve power quality** and reduce system losses; **improve energy efficiency** and enable conservation; and help **reduce the carbon footprint** of the energy system.

Objectives

Capacity Building: Train personnel with the skills to transform the Canadian electricity industry, as it embraces new business models, renewable sources of energy and new digital technologies.

Research: Support and conduct multidisciplinary research in electrical engineering, planning and regulatory issues and communication technologies.

Knowledge Transfer: Adapt research activities into constructive forms of information for consumers, manufacturers and policy makers.

Business Development: Translate research into practical products and services for technology companies and electricity utilities.

Support

NSMG-Net is made possible by the NSERC Strategic Network Grants Program and several industry partners (see page 7). The host institution for NSMG-Net is British Columbia Institute of Technology, whose innovative campus microgrid provides a near-real test environment for microgrid technologies.

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Message from the Network Leader

Hassan Farhangi,
Network Leader, NSMG-Net

NSMG-Net's 5th and final year has witnessed the fruition of some of our most important initiatives and priorities. At the core of our activities in year 5 is the infusion of diverse technologies, approaches and know-how developed across the Network in the form of practical solutions for our utility and industrial partners. Such solutions are interdisciplinary in nature, and often require experts from different domains to collaborate across diverse disciplines and geographies. I am pleased to report that the last two years of the Network have seen a determined and conscious effort on the part of our researchers to collaborate across their diverse domains.

Upon its inception, as a pan-Canadian strategic research network, NSMG-Net took upon itself the critical task of bringing together some of Canada's best researchers and resources in the then relatively unknown smart grid and microgrid areas to focus on the development of technologies and know-how required to build a scaled-down version of Smart Grid, namely a Smart Microgrid. The challenge was to create an environment in which researchers with different and divergent backgrounds, and no history of collaborative work, would find a common vocabulary to communicate, exchange information and find interdisciplinary solutions for multi-faceted problems facing our utility industry.

The Network leaders knew from the start that bringing Power System Engineers, Communication System Engineers and Information Technology Experts to work together was an exceptional challenge. Nevertheless, through careful planning and execution, the right frameworks and tools were put in place to ensure cross-pollination of ideas and know-how across various domains and boundaries in the Network. I am pleased to report that the last two years of the Network, namely Years 4 and 5, have seen a steady rise in the number of fruitful collaborations across projects and themes. The results of these collaborations, in the form of technologies and solutions applicable to the design and/or operation of operational microgrids, and collected and organized in Project P2.5, will be managed by NSMG-Net's Project P2.6. This project provides NSMG-Net researchers and particularly students, with the participation of industrial partners, a unique opportunity to apply the technologies they have developed in a real-world microgrid, and test and verify the validity of their design approaches and solutions.

It should be noted that many of the projects involved the participation, in one form or another, of Network partners from government, namely Natural Resources Canada's CanmetENERGY Laboratory, utilities, including BC Hydro, Hydro-Quebec and its research arm IREQ, and Hydro One, and a number of industries. Project leaders and their students have had many interactions with these partners, who provided, among others, information about the structure and operating conditions of electric grids, including remote and isolated grids, a specific Canadian reality, and about applicable power and communication technologies.

Moreover, I am very pleased to note that, although some of the projects had a slow start, overall the projects were able to complete their scheduled milestones and deliverables. For instance, the four projects of Theme 1 have met their main objectives and planned milestones without major changes/deviations. All four projects of Theme 1 have been extended an additional six months to the end of March 2016 with no additional cost to ensure completion of the remaining objectives and milestones. The level of collaboration among Theme 1 projects, the collaboration with projects in other themes, the collaboration with universities/institutions inside and outside Canada, and the collaboration with industry partners are noteworthy. Some of these collaborative efforts, specifically with industry, will no doubt continue beyond March 2016.

The first three projects under Theme 2 have been active and have delivered research results in accordance with the original mandate and scope of work of the Network. In some cases, namely Project 2.2, the work was extended beyond the original scope to new issues arising from the deployment of microgrids, particularly multiple microgrids within larger distribution systems. In general, and particularly in the USA, microgrids are attracting increased interest on the part of regulators as a means of increasing the resiliency of distribution systems to extreme atmospheric events, and offer an alternative to reconfiguring distribution systems. The last project, P2.4, was replaced in the fall of 2014 by a new project, P2.5, Integration Design Guidelines and Performance Metrics. This project deals with the same topics as P2.4. In addition, it collates the research results developed in all projects during the mandate of the Network. It also assembles all the technologies developed during the mandate of the Network and investigates how they can be applied to and implemented on the one of the more developed Canadian microgrids, the BCIT Campus Microgrid. This project will provide the framework for a student internship program to be implemented at BCIT and described in the new Project P2.6 (p. 9), the BCIT Microgrid demonstration project. These internships will allow the participating students to apply their research results on and in the context of the BCIT microgrid.

Other than the late start of Project P3.1, due to change of the project leader, Theme 3 projects have achieved considerable progress. The level of collaboration in Theme 3 projects has been enhanced in year-5 with a Theme 2/Theme 3 Montreal workshop which took place in August of 2014 and the collaboration will continue into the extension year. All four projects of Theme 3 have been extended to the end of March 2016 at no additional cost and it is expected that more collaborative work during this period will take place in the context of P2.6, the final demonstration project in BCIT.

Year 5 also witnessed the fruition of some of our international collaborations. Project P3.4 researchers teamed up with Aachen University's Automation of Complex Power System Laboratory and E.ON Energy Research Center, RWTH, in Germany. The collaborative research between the two research groups resulted in a number of IEEE Transactions papers and international conference papers (CIGRE Canada and IEEE). One of these papers received the "Best Student Paper" award at IEEE Smart Energy Grid Engineering conference (Canada, August 2015).

In its 5 years of operation, a total of 107 students have participated in Network research (49 PhD, 47 MSc and 18 undergraduates), spread across 12 different projects and in 8 different universities across the country. In Year 5, NSMG-net's research community continued to disseminate the results of their research in the form of over 50 journal articles, conference papers and other publications.

Finally, on behalf of all NMSG-Net community, I would like to express our gratitude and thanks to our industry partners for their continued support of the network, both financial and in-kind. They have been involved at all possible levels with the Network, from guiding our research, to evaluating our results and to generously providing us with financial and technical support, without which the NSMG-Net would have not been able to secure the aforementioned achievements.

Dr. Hassan Farhangi
Network Leader, NSMG-Net

Partners

NSMG-Net's partnerships with industry, government and academia help us translate research into practical real-world applications. As well as providing funding support for Network expenses and training of Highly Qualified People, our partners offer in-kind support in the form of donated software licenses, access to professional equipment, and the time of their technical staff.

Management and Governance

The NSMG-Net Board of Directors and Scientific Committee saw a number of changes in Year 5. Board Chair John MacDonald resigned from the Board at the end of Year 4; the Network thanks him warmly for his four years of service. Chuck Filewych kindly agreed to serve as Chair for the remainder of the Network's mandate.

Mathieu Lambert has replaced Chad Abbey as Hydro Quebec representative on the Scientific Committee.

We thank all our volunteer board members, past and present, for their valuable contributions to the Network.

Board of Directors

Industry:
Mr Chuck Filewych, Smart Grid Canada
Mr Jack Li, Retired (Enmax Power Corp)
Mr Richard Wunderlich, Siemens

Academia:
Dr Liuchen Chang, University of New Brunswick
Dr Paul Fortier, University of Laval
Dr Andreas Athienitis, Concordia University
Dr Hassan Farhangi, BCIT

Government:
Mr Nat Gosman, BC Ministry of Energy
Dr Gilles Jean, NRCan
Mr Paul Ohrt, Dept of National Defense
Ms Heather Quinn, Government of New Brunswick

Ms Alison Janidlo, NSERC (non-voting)

Scientific Committee

Industry & Government:
Mr Giuseppe Stanciulescu, BC Hydro
Mr Anand Srinivasan, Eion Wireless
Dr Mathieu Lambert, Hydro Quebec
Mr Ravi Seethapathy, Retired (Hydro One)
Dr Lisa Dignard, CanmetENERGY, NRCan
Mr Tony Gray, Schneider Electric Canada

Academia:
Dr Hassan Farhangi, BCIT
Dr Reza Iravani, University of Toronto
Dr Geza Joos, McGill University
Dr Julian Meng, University of New Brunswick

Outreach Committee

Dr Geza Joos, McGill University
Dr Steven Wong, CanmetENERGY, NRCan

Project Changes

Project 2.6 (New): BCIT Microgrid Demonstration Project

In Year 5, the Board of Directors approved an additional project that will serve as a demonstration project to showcase many of the technologies developed in the Network projects in a real life installation. The BCIT Microgrid Demonstration Project will utilize the BCIT Microgrid as a full size, real life laboratory for the testing of operational procedures and technologies for Intelligent Microgrids (Theme 1 projects), including control and operation, monitoring and diagnostics, operational strategies and storage for investigating planning and regulatory issues (Theme 2 projects), including benefits, energy management, demand response, and design guidelines, and for implementing communication and information technologies (Theme 3 projects).

The demonstration project will develop out of information provided by Project 2.5. It picks up on the last milestone of Project 2.5, which deals with validating the technologies developed in the different projects with field results obtained from the BCIT microgrid. It will involve the following steps:

- Identifying the technologies from each of the 3 Network themes that can be demonstrated and showcased on the BCIT Microgrid, including those from Theme 1 (Microgrid Operation and Control), Theme 2 (Microgrid Planning and Optimization) and Theme 3 (Communications). The raw information will be drawn from the work carried out in Project 2.5.
- Identify and assemble the BCIT Microgrid systems and subsystems on which the technologies can be implemented.
- Test the identified Network technologies on the BCIT Microgrid.
- Compile recommended system configurations and approaches deployed on the BCIT Microgrid that could be implemented in Canadian microgrids and based on the research deliverables.

Up to 12 graduate students from NSMG-Net will participate in the Project, completing 3-month internships at BCIT during which they will work with BCIT research staff to implement the technologies developed by Network Research. The internships will take place over the course of a no-cost extension year for the Network (Year 6).

BCIT campus in Burnaby *(Photo credit: Wikimedia-Grassbag)*

Theme Research Reports

The next generation Smart Grid is the convergence of Information and Communication Technology with Power System Engineering.

The three research themes of NSGM-Net reflect this interdisciplinary nature.

Theme 1 is led by Dr Reza Iravani at University of Toronto. The four projects in this theme are focused on the electrical engineering issues involved in Canadian urban, rural and remote microgrids.

Theme 2 is led by Dr Geza Joos at McGill University. The four projects in this theme are focused on the overall technical and economic justification of microgrids, and their interactions with the main grid.

Theme 3 is led by Dr Julian Meng at the University of New Brunswick. The four projects in this theme are focused on innovative network architectures to support seamless exchange of data and commands between participants in the smart grid network.

Theme 1: Microgrid Operation and Control

(Dr Reza Iravani, Theme Leader)

Theme Overview

The four projects in this theme are focused on the electrical engineering issues involved in Canadian urban, rural and remote microgrids. Unlike their European counterparts, Canadian grids operate a large number of weak, long, radial distribution systems and have little or no experience operating microgrids. The research in this theme seeks to overcome operation, control and protection challenges that are required to enable deployment of distributed generation units and integration of electric vehicles in smart microgrids. Specific project goals are as follows:

Project 1.1 Remote Smart Microgrids (Yazdani, Ryseron University)

- Development of a robust and fault tolerant control strategy for remote microgrids
- Development of a supervisory control to maximize depth of penetration of DER units
- Iidentification of reliable ICT and back-up algorithms to ensure reliability of supply

Project 1.2 Distributed and Hybrid Control (Iravani, University of Toronto)

- Delivery control strategies for single and cluster microgrids
- Development of improved interfaces and decision support systems
- Optimization of operational microgrid scenarios, based on sensing and metering

Project 1.3 Disturbance Detection, Diagnosis and Protection (Xu, University of Alberta)

- Provide strategies monitor signals and extract information at distributed nodes
- Identify status and operational requirements at the microgrid PoCC
- Specify advanced technologies for active islanding detection

Project 1.4 Operational Strategies to Address High Penetration of DG Units in Microgrids (Joos, McGill)

- Identification of technical issues and constraints of existing standards
- Development of models for assessment of the various electrical and thermal issues
- Development of strategies to maximize overall efficiency

Summary of Theme Progress

Project 1.1 (A. Yazdani - Ryerson University)

Milestones Progress during year-5:

i. Research and develop coordinated control, supervisory and operational strategies (2012)—Started in Sept 2011; 90% complete.
ii. Research and Develop protection strategies (2013); 100% complete.
iii. Develop simulation test cases and benchmark models (2011-2013) - started Sept 2012; 80% complete
iv. Perform test cases and evaluation studies and identify the beta site and specify requirements and test cases (2014); 50% complete
v. Perform beta test cases (2015); Not started

The project progress during year-5 has been according to the schedule. The project has been extended to March 2016 at no cost and the will achieve the following during the extended period:

In addition to the research advanced by K. Akbari, F. Kazempour, and R. Oliveira, two Masters students, Mr. Marcos Aguirre and Ms. Nikoo Kouchakipour, have been admitted and will start research as of Sept, 1, 2015. These students will work on the following two milestones:

vi. Develop simulation test cases and benchmark models
vii. Perform test cases and evaluation studies and identify the beta site and specify requirements and test cases

Also, an experimental setup for verifying the developed control techniques is being worked on by R. Oliveira and a summer undergraduate student, Nebi Cicek. This setup will be completed with the help of Marcos Aguirre in the remaining months of the project, to contribute towards the last milestone, i.e., *Perform beta test cases*

Project 1.2 has in particular collaborated with project 1.2, 2.2, and 1.4. Project 1.1 has been collaborating with Project 1.4 on the development of control strategies that ensure stable operation, and enablement of a high degree of penetration of renewable energy, of off-grid microgrids. The project has also been collaborating with Project 1.2 on the development of centralized, decentralized, and hybrid control strategies for remote microgrids. Also, since October 2014, the project has tried to collaborate with Schneider Electric on the development of experimental set-ups for evaluation of the control strategies developed under the project for remote microgrids.

Project 1.2 (R. Iravani - University of Toronto)

In continuation of Year-1 to Year-4 program, the project progress in Year-5 includes:

- Investigated the impact of cyber layer on the microgrid controllers developed during year-2 to year-4 of the program. (100% complete)
- Identified and formulated hierarchial robust control approaches for urban and rural Microgrids based on the use of pre-specified communication infrastructure. (100% complete)
- Developed linear dynamic models for the design of centralized and distributed controls for benchmark microgrid systems. (100% complete)
- Develop strategies and algorithms for the cotnrol of multiple Intelligent Microgrids, and specify the required ICT. (100% complete)
- Developed performance criteria for control strategies including ICT. (100% complete)
- Developed HIL-RTDS environment for real-time testing realization and performance evaluation of the control systems. In progress. (80% complete)
- Identify beta site test cases for selcted scenarios to validate the R&D results. In collaboration with Hatch and HydroOne we are finanilizing the test site and developing the detailed simulation models of these site for pre-installation testing of hardware-based control/protection/EMS. In progress. (100% completed)
- Develop developed hardware-in-the-loop test-bed for performance evaluation/validation of the control of multiple Intelligent Microgrids, including the required ICT. In progress. (80% complete)
- Developed of supervisory control and EMS for multi-microgrid system based on distributed robust control of individual microgrids (using local measurement at the PCC and within each microgrid)) and ICT-based supervisory control appraoch for multiple microgrids. In progress. (80% complete)
- The project results are being implemented in two exisiting microgrids and can be readily tailored for implenetation in the BCIT microgrid.

The project progress in year-5 has met all the objectives as was envisioned in the original plan. Project 1.2 has been closely collboarted with Project 1.1 (as discussed above), Project 1.3 in terms of adopting protection strategies of microgrids, projects of Theme 2 (particularly 2.2) in terms of control and protection of multiple microgrids, and Project 3.1 for real-time Hybrid simulation of ICT and physical layers of microgrids.

The project has been extended to March 2016 at no additional cost and objectives include:

- Developed of multi-layer real-time-based HIL plartform in which

  (i) local controllers within each microgrid are operated based on local measurements within the microgrid,
  (ii) local controllers within each microgrid are coordinated by the microgrid EMS,
  (iii) EMS' of muliple microgrids are coordinated by the upper-level EMS/supervsiory-control, using communication and measurements at the PCCs of the multiple microgrids.

  All controls and EMS entities will be in NI-CRIO or NI-PXI platforms and the power circuits of the microgrids will be in an FPGA- enhanced RTDS platform.

- Development of HMI system for "remote" monitoring, parameter adjustment, and data logging of the upper-layer EMS/supervisory-control.

These two items are in continuation and the extension/generalization of the developments of the last four items of the year-5 activites.

Project 1.2 has managed to establish international collaborations in the field with multiple universities in Brazil, France, and China and also secured funding (outside the NSMG-Net) for exchange of students/PDFs with France and China. Project 1.2 has established close collaborative projects with multiple entities, e.g., Hydro One, Hatch Associates, Toronto Hydro, and OpusOne, which will continue beyond March 2016.

Project 1.3 (W. Xu - University of Alberta)

The milestone progress of Project 1.3 in year-5 includes:

- Research work on the low voltage ride through (LVRT) capability of inverter based DGs has been completed. LVRT has become a major requirement for microgrid DGs. This research work developed an analytical method to evaluate the performance of several key LVRT control schemes and proposed new methods to improve LVRT performances of inverter based DGs. Two papers have been submitted and one M.Sc. student graduated.
- Research on novel methods for open loop synchronization of a microgrid to system. The methods are based on the idea of reducing synchronization transients using techniques such as impedance insertion and synchronous closing. The impedance insertion method has been found effective. The synchronous closing based method is not found as effective. A strategy that allows open-loop implementation of the impedance insertion scheme has been finished. Recently, we have completed the design method for the impedance insertion scheme, including the selection of impedance value and the impact on microgrid stability. The student has started to write a report. The proposed method has been presented to Hydro One and a few other companies.
- In view of the availability of funds, we expanded the above research by investigating the idea of "thyristor-based synchronizer" for micro-grids. This concept may be useful for MGs without extensive power electronic control capability. "Thyristor-based synchronizer" is similar to the thyristor-based motor starter.
- Since May 2015, I Project 1.3 has been in collaboration with Prof. Y. Jing of U of A on a general purpose disturbance detection method for both microgrid and regular systems. The new idea here is the use of automatic and "soft" thresholds for disturbance detection.

The project progress has been according the original plan and the objectives of year five have been achieved. The results of Project 1.3 has been widely used to achive the objectives of Project 1.2 and Project 2.2 , and there has been significant degree of collaboration between the corresponding teams. Project 1.3 also has colsely collaborated with Project 2.1, and also established collaboration with the University of Sao Paulo in Brazil. Project 1.3 has been extended to March 2016 at no additional cost. The objectives the project during the extended period include:

1. Complete the research on impedance insertion based synchronization scheme. A paper will be submitted and the student is expected to complete thesis defense.
2. Determine the feasibility and technical issues of "Thyristor-based synchronizer" for microgrid synchronization.
3. Complete the research on a general purpose distance detection method. Submit a paper if the results are promising.

Project 1.4 (G. Joos - McGill University)

The milestones progress of Project 1.4 in year-5 includes:

A. Implementation of the microgrid controller algorithms into an online physical controller for hardware-in-the-loop and physical integration, including a rule based and a hierarchical optimization algorithm based controller

The main goal is to implement the hierarchical Microgrid controller (as described in the recently accepted transaction journal) for online studies. The focus thus far has been to develop the central optimization algorithm, and a common interface for the distributed controllers. A common interface has been established between the central controller and the distributed controllers; this is employed to reduce the communication requirements and to facilitate the integration of a variety of Distributed Energy Resources. An algorithm has been developed in the central hierarchical controller (based on the interface model) to amalgamate the distributed resources' valuation functions to create a unified virtual plant whose optimal dispatch can be directly determined in a distributed manner either through cost signals (when grid-connected), or frequency (when islanded). Any deviation from the nominal set points is along the optimal curves. Preliminary results demonstrate that the proposed algorithm yields identical results to a central optimization algorithm, and it facilitates distributed intelligence and a novel distributed approach to unit commitment in the microgrid.

Furthermore, in terms of the distributed controllers, the focus has been to develop a common interface and distributed intelligence into the storage controller to facilitate the integration of a time-dependent resource in the optimization algorithm. This algorithm considers past market prices to determine the net present value of the stored energy, and its post-processing interface to the central controller is identical to other resources in the Microgrid. Results show that the employed back casting approach yields savings that are approximately 71.3% that of the perfect offline forecasting algorithm. Results are expected to be submitted for a transaction paper (Michael Ross, PhD candidate).

An alternate, simpler solution, will also be implemented, based on the same requirements and objectives, offering and easier and more robust implementation of microgrid controller functions, with simpler adaptation. It consists of a rule based controller (Farah Awan, PhD candidate).

B. Developing real-time models of the real test microgrid for the online implementation

The approach is to initially test the controller on the OPAL-RT real time simulator at McGill. This may be followed by testing on the 25kV Distribution Test Line at Varennes through collaboration with our Network partner IREQ. The results of this work may be extended towards implementation on the BCIT microgrid.

In keeping with the project milestones for this year, a model of the IREQ Distribution test line has been developed on the Matlab/Simulink platform. The model includes inverter interfaced DGs, synchronous machines, storage and loads. Control loops are in place to ensure the capabilities of the test line generators are captured. The model includes a communication infrastructure to allow for real time dispatch. The next milestone is to implement the real time model on the McGill OPAL-RT simulator.

C. Online implementation of the microgrid controllers in a real time simulation environment and on the real microgrid test system

The approach is to initially test the controller on the OPAL-RT real time simulator at McGill. This may be followed by testing on the 25kV Distribution Test Line at Varennes through collaboration with our Network partner IREQ.

The results of this work may be extended to an implementation on the BCIT microgrid.

The project progress has been according to the schedule and the objectives have been achieved. The project has been closely collaborating with the industrial partners and other projects of Theme 1. Project 1.4 has been extended to the March 2016 at no additional cost and the objectives/milestones during the extension period include:

Implementation of the two microgrid controllers and their respective algorithms, first on the McGill real time simulator (OPA-RT) and subsequently on the IREQ test microgrid (with the help on industrial partner Hydro-Quebec IREQ, see below):

(a) a rule based (expert system based) controller, with rules developed and optimized off line (Farah Awan, PhD candidate);

(b) a controller based on an optimization algorithm, which meets specified constraints related to the cost of energy and emissions, and optimizing the on-site resources, including renewable generation and storage (Michael Ross, PhD candidate).

Overall Conclusions of Theme 1 Progress During Year-5:

All four projects of theme 1 have met the objectives and their milestones progress has been according to the original plans without major changes/deviations.

All four projects of Theme 1 have been extended to the end of March 2016 with no additional cost. Each project has identified the objectives and milestones for October 1, 2015 to March 31, 2016, as described above section.

There has been a significant increase in the level of collaboration among the Theme 1 projects, collaboration with the other theme's projects, collaboration with universities/institutions outside Canada, and collaboration with the industry during year-5. Some of these collaborative efforts, specifically with the industry, will continue beyond March 2016.

Table 1: Theme 1 Publications in Year 5

Project	Citation *(Click on link to access article where available)*	Refereed Journal Article	Non-refereed Journal Article	Invited Conference Presentation	Non-invited Conference Presentation	Other
1.1	A. Haddadi, B. Boulet, A. Yazdani, and G. Joos, "A µ-Based Approach to Small-Signal Stability Analysis of An Interconnected Distributed Energy Resource Unit and Load," IEEE Trans. on Power Delivery, vol. 30, no. 4, pp. 1715-1726, Aug. 2015.	x				
1.1	M.B. Delghavi and A. Yazdani, "A Simple Passive Voltage-Balancing Scheme for Three-Phase Induction Generators Interfaced with Single-Phase Grids in Micro Hydroelectric Systems," Elsevier Electrical Power and Energy Systems, 74 (2016), pp. 42-48, Jul. 2015.	x				
1.1	O. Alizadeh and A. Yazdani, "A Control Strategy for Power Regulation in a Direct-Drive WECS with Flexible Drive-Train," IEEE Trans. on Sustainable Energy, vol. 5, no. 4, pp. 1156-1165, Oct. 2014.	x				
1.1	F. Bhuiyan, A. Yazdani, and S.L. Primak, "Optimal Sizing Approach for Islanded Microgrids," IET Renewable Power Generation, vol. 9, no. 2, pp. 166-175, 2015.	x				
1.2	A. Etemdai, E.J. Davison, R. Iravani, "A generalized decentralized robust control of islanded microgrids", IEEE Trans. on Power Systems, Vol. 29, No. 6, pp. 3102-3113, Nov 2014.	x				
1.2	A. Etemdai, R. Iravani, "Smooth Transition Between Consecutive Microgrid Control Schemes", accepted for publication for IEEE Trans. on Power Delivery.	x				
1.2	S. Helmy, R. Iravani, "A supervisory control and energy management system for microgrid under high-depth of renewable resources", under review by the IEEE Trans on Industrial Electronics.	x				
1.2	K. Samarasekera, R. Iravani, "Coordinated fault ride-through characteristics of multiple microgrids", under review to the IEEE Trans on Power Systems.	x				
1.2	A. Khorsandi, M. Ashourloo, H. Mokhtari, Reza Iravani, "An Automatic Droop Control for a Low Voltage Microgrid", accepted for publication in the IET on Gen/Tran/Dist.	x				
1.2	A. Etemdai, R. Iravani, "Smooth Transition Between Consecutive Microgrid Control Schemes", accepted for publication for IEEE Trans. on Power Delivery	x				
1.2	C. Marnay, B. Kroposki, M. Mao, H. Xu, A. Chong, S. Chong, R. Hara, T. Ise, R. Iravani, M. Albu, N. Hatziargyrious, T. Funabashi, J. Reilly, J. Driesen, G. Jimenez, X. Vallve, "The Tianjin 2014 Symposium on microgrids", **Invited paper**, IEEE Electrification Magazine, vol. 3, no. 1, pp. 79-85, March 2015.	x				
1.2	R. Iravani as one the members of CIGRE WG SC-6-22 "Microgrid Road Map", CIGRE Report, to be published in early 2016.					x
1.3	R. Torquato, Q. Shi, W. Xu and W. Freitas, "A Monte Carlo Simulation Platform for Studying Low Voltage Residential Networks", IEEE Trans. on Smart Grid, vol.5, no.6, pp. 2766-2776, Nov.2014	x				
1.3	M. M. Shabestary, Y. A. I. Mohamed, and W. Xu, "A Comparative Study on Low-Voltage Ride-Through Reference-Current-Generation (LVRT-RCG) Strategies in Grid Converters", submitted to IEEE Transactions on Sustainable Energy, 2014.	x				
1.3	M. M. Shabestary, Y. A. I. Mohamed, and W. Xu, "Analytical Study of LVRT Reference-Current-Generation Strategies and a Novel Method to Obtain Their Best Allowable Performance", submitted to IEEE Transactions on Sustainable Energy, 2014.	x				
1.3	Zhou, P. "Application of Synchronous Closing in Generator Synchronization for				x	

	Reducing Transients", Poster Presentation at PES General Meeting, 2015.		
1.3	Xu, W. et al. "Open-loop Synchronization of Islanded Systems", Centre for Energy Advancement through Technological Innovation (CEATI) webinar presentation (technology transfer for the impedance insertion based synchronization scheme), May 2015.		x
1.3	Xu, W. et al. Demonstrated of research results at the 2014 Annual Power & Energy Innovation Forum organized by the Alberta Power Industry Consortium.		x
1.4	M. Ross, C. Abbey, F. Bouffard, and G. Joós, "Multi-Objective Optimization Dispatch for Microgrids with a High Penetration of Renewable Generation," IEEE Transactions on Sustainable Energy, vol. 6, no. 4, pp. 1306-1304, June 2015.	x	

Table 2: Highly Qualified Personnel in Theme 1 since Inception (listed by Project #)

Project	Name	Program	Start	End	Employer (if graduated)
1.1	Akbari, K.	PhD	January 2014	Ongoing	
1.1	Kazempour, F.	PhD	April 2013	Ongoing	
1.1	Oliveira, R.	PhD	September 2013	Ongoing	
1.1	Syed, I.	PhD	January 2013	February 2014	
1.1	Kouchakipour, N.	MSc	September 2015	Ongoing	
1.1	Aguirre, M.	MSc	September 2015	Ongoing	
1.1	El-Tayb, M.	MSc	September 2011	October 2012	CIMA+
1.1	Cicek, N.	UG	May 2015	September 2015	
1.1	Kaler, S.	UG	May 2014	September 2014	
1.1	Lin, H.	UG	May 2013	September 2013	
1.2	Badrkhani, F.	PhD	September 2011	Ongoing	
1.2	Helmy, S.	PhD	September 2013	Ongoing	
1.2	Hernandez, G	PhD	September 2008	November 2011	Assistant Professor - Mexico Polytechnique University
1.2	Huzayin, A.	PhD	September 2014	December 2011	Assistant Professor - Cairo University
1.2	Kazempour, F.	PhD	September 2012	Ongoing	
1.2	Kobravi, A.	PhD	August 2009	December 2012	Design Engineer - US Hybrid - CA
1.2	Mehrizi-Sani, A.	PhD	August 2008	September 2011	Assistant Professor - Washington State University
1.2	Mirzahosseini, M.	PhD	January 2013	Ongoing	
1.2	Ramadan, M.	PhD	January 2012	Ongoing	
1.2	Paradis, D.	MASc	September 2011	December 2013	US Hybrid
1.2	G. Gumusteking	MASc	October 2013	Ongoing	
1.2	Samarakera, K.	MASc	September 2013	August 2015	BNL, USA
1.3	Gao, P.	PhD	September 2010	Ongoing	

1.3	Salles, D.	PhD	September 2011	May 2012	
1.3	Yazdanpanahi, H.	PhD	September 2009	December 2013	
1.3	Polzl, A.	PhD	September 2011	Left program	
1.3	Shabestary, M.	MSc	January 2013	Ongoing	
1.3	Zhou, Y. (Peter)	MSc	September 2013	Ongoing	
1.3	Yong, Hyunjung	MSc	September 2014	Ongoing	
1.3	Li, Benzhi	MSc	September 2013	Ongoing	
1.3	Shi, Q.	MSc	September 2011	March 2014	
1.3	Torquato, R.	MSc	May 2013	April 2014	
1.3	Tian, Y.	MSc	September 2011	September 2013	
1.3	Jiang, C.	MSc	September 2009	December 2012	
1.4	Elkasrawy, A.	PhD	September 2011	January 2013	
1.4	Haddadi, A.	PhD	April 2011	April 2015	PDF, Polytechnique Montreal
1.4	Farah, A.	PhD	January 2013	Ongoing	
1.4	Ross, M.	PhD	October 2010	Ongoing	
1.4	Saadeh, O.	MSc	January 2012	December 2013	Greentech Media
1.4	Wang, M.	MSc	January 2011	December 2012	GE Energy
1.4	Milicevich, M.l	UG	May 2013	August 2013	

Theme 2: Microgrid Planning, Optimization and Regulatory Issues

(Dr Geza Joos, Theme Leader)

Theme Overview

The four projects in this theme are focused on the overall technical and economic justification of microgrids, and their interactions with the main grid. The direct benefits to Canada of this theme are in providing tools to quantify the benefits of implementing microgrids, while the indirect benefits are the reduction of greenhouse gas emissions through enabling new renewable generation, and improved flexibility and resilience of the distribution grid. Theme 2 relies on the knowledge provided by Theme 1 on the internal operation of the microgrid, and on tools and systems supplied under Theme 3 related to information and communication technologies. Specific project goals are as follows:

Project 2.1 Cost-Benefit Framework: Secondary Benefits and Ancillary Services (Joos, McGill)

- establishment of a comprehensive list of all primary and secondary benefits, and a framework for quantifying benefits
- development of a methodology for allocating the economic value to benefits to various stakeholders
- development of mechanisms to exploit the operational and financial value of these benefits

Project 2.2 Energy and Supply Security Considerations (Iravani, University of Toronto)

- quantification of the impact of a large penetration of microgrids on the performance of interconnected power systems
- determination of new regulatory guidelines required for a large penetration of microgrids

Project 2.3 Demand Response Technologies and Strategies (Bhattacharya, University of Waterloo)

- determination of the overall sustainability of microgrid deployment
- design of energy-aware scheduling algorithms
- optimization of internal microgrid load balancing

Project 2.5 Microgrid design guidelines and use cases (Joos, McGill)

- benchmark models for microgrids and microgrid elements, particularly for integrated power system and communication/control infrastructures
- modeling strategies for making planning and operation case studies for different microgrid structures and operating strategies
- case studies and use cases allowing a structured approach to analyzing microgrid operation and specifying appropriate microgrid structures

Summary of Theme Progress

Project 2.1 – Cost-Benefit Framework

The focus of the work ever this last period was on the application of the methodologies previously developed in this project to representative microgrids and on applying the Use Case approach to formulating the problem for the first two microgrids listed below:

- a microgrid for a remote mining site in Quebec
- an urban microgrid in a Canadian city (Calgary)
- remote communities with compressed air energy storage associated with wind energy

Project 2.2 – Energy and Supply Security Considerations

The focus was on investigating the impact of cyber layer failure/malfunction/hacking on the microgrid controllers developed in year-2 to year-4 of the program. The work, based on off-line simulation studies previously completed, involved hybrid real-time simulation of both physical and cyber layers in RTDS and Opnet platforms, respectively.

In particular, a methodology is being developed to quantify the impact of high-depth of penetration of renewable resources on the reliability of supply, the life-time reduction of legacy components subject to the intermittency of renewables (switched capacitors, on-load tap changers), and the resiliency of the complete system.

This work was extended to the mutual impacts of parameters in systems with multiple microgrids. Information was gathered from a number of utilities in terms on maintenance scheduling and failures history of components of apparatus to determine the costs associated the operation of system components.

Input to the analysis engine was provided by power flow, transient stability, and electromagnetic transient programs and the results were correlated.

Project 2.3 – Demand Response and Technologies and Strategies – Energy Management and Metering

Work in this period dealt with proposing energy-aware scheduling algorithms for internal microgrid load balancing capability. In addition, microgrid impact analysis for various demand response models were analyzed.

Project 2.5 – Integration Design Guidelines and Performance Metrics

This project, initiated in the fall of 2014, and replaces Project 2.4. Work carried out during the period included:

- Compiling the work done in the 3 themes, including Microgrid Operation and Control, Microgrid Planning, Optimization and Regulatory Issues, Microgrid Communication and Information Technologies, based on site visits, analysis of annual reports and direct interactions with project leaders and researchers
- Compiling microgrid models, including the power systems and the control and communications systems, based on the collected information
- Defining microgrid system studies, through among others, discussions with the BCIT microgrid development team; data is being collected for the application and implementation of technologies developed within the Network projects

- Defining case studies and use cases, based on information available on on-going projects within Canada and the USA, and using the expertise developed within the Network projects

HIGHLIGHTS

1) Overall progress – Year 5 – opportunities

All projects under Theme 2 have been active and delivered research results in accordance with the original mandate and scope of work of the Network. The exception is Project 2.4, which was replaced in the fall of 2014 by Project 2.5. Below is an explanation on how projects 2.4 and 2.5 are related. In some cases, namely Project 2.2, the work was extended beyond the original scope to new issues arising from the deployment of microgrids, particularly multiple microgrids within larger distribution systems. In general, and particularly in the USA, microgrids are attracting increased interest on the part of regulators as a means to increase the resiliency of distribution systems to extreme atmospheric events, and offer an alternative to reconfiguring distribution systems.

2) Achievement of objectives in the original application

Most of the objectives set out in the initial application were met in one form or another during the course of the 5-year mandate of the Network. Project 2.4, Integration design guidelines and performance metrics, which was initially structured to deal with issues common to all projects, in the areas of microgrid benchmarks, microgrid component modeling and system studies, was replaced by Project 2.5, Integration Design Guidelines and Performance Metrics. This new project deals with the same topics and collates the research results developed during the mandate of the Network. In addition, it brings together all the applicable technologies and investigates how they can be applied to and implemented on the one of the more developed Canadian microgrid, the BCIT Campus Microgrid. Project 2.5 will also provide the framework for the student internship program to be implemented at BCIT and described in Project 2.6, BCIT Microgrid demonstration project. These internships will allow the participating students to apply their research results on and in the context of the BCIT microgrid.

3) Priorities – remaining 6 months

The work proposed in this period consists essentially in completing and in some cases extending the work proposed in the original application.

a) Project 2.1 – Cost-benefit framework

- Developing Use Cases and compiling case studies of representative microgrids
- Real time Implementation of the developed methodologies – Real Time simulator (OPAL-RT)

b) Project 2.2 - Energy and Supply Security Considerations

The following tasks will be carried out: application, performance evaluation, and verification of the developed strategies and corresponding algorithms to a real large-size interconnected power system with multiple microgrids. The selected system is the New-York/New-England interconnected system which includes nine microgrids, in close electrical proximity, in the New-York city area. The test cases include:

- Impact of high-depth penetration of bulk intermittent generation, e.g., up to 35% wind power, on the dynamic behavior and dynamic interactions of the multiple microgrids

- Impact of a major loss of generation or transmission which triggers a cascading failure event, on the ability of microgrids to properly island and continue islanded operation to enhance resiliency and continuity of supply for selected and/or partial load scenarios,
- Evaluation of the system dynamics on the assets in terms of loss of life and quantification of "tear and wear" due to generation intermittency and multi-mode operation; evaluation of the degree of asset utilization

c) Project 2.3 – Demand response and technologies and strategies – energy management and metering

Environmental impact analysis of demand response using and developing appropriate mathematical models, and quantification of the savings, both from emissions and cost perspectives, for the microgrid, the customers and the society.

d) Project 2.5 – Integration Design Guidelines and Performance Metrics

- Analyzing and providing a critical assessment of the modeling detail and the model detail trade-offs, and recommending modeling details as appropriate for the type of study to be performed
- Defining a modeling approach that combines the power and communication systems, allowing a complete system study
- Defining typical system studies and requirements associated with the operation of the microgrid, in grid connected and islanded operation, based on the work carried out in other Network projects in all three Themes, and identifying the systems required for case studies, including the appropriate benchmark systems and components
- Determining sets of system sample case studies required for the study of the various microgrid operating scenarios and contingencies, for real time operation (voltage and frequency control, protection, islanding and reconnection), and energy management of the generation, storage and loads within the microgrid, in islanded and grid connected modes
- Developing use cases for the sample case studies defined above
- Validating the models and approaches with field tests and results from BCIT microgrid and the Hydro-Quebec Test-line (as applicable).

4) Additional information

The information relevant to synthesizing microgrids that would have been produced in Project 2.4, was included in Project 2.5. In addition, this new project offers an opportunity to:

- Collect, categorize and synthesize the research results delivered by the Network during its 5-year term
- Identify the research results that could be made available to industrial and utility partners and industry and utility in general, and applicable to the Canadian participating benchmark microgrid, the BCIT Campus Microgrid
- Identify the research results that could be the object of technology transfer and be patentable
- structure student projects that are based on the ideas they have brought to fruition in their research projects and that could be implemented on the BCIT microgrid, projects in the form of internships funded through Project 2.6

Table 3: Publications by Theme 2 Projects in Year 5

Project	Citation *(Click on link to access article where available)*	Refereed Journal Article	Non-refereed Journal Article	Invited Conference Presentation	Non-invited Conference Presentation	Other
2.1	M. Quashie, Use Case for Mining Microgrid Business Case - Technical Report (internal), McGill University, Oct 2014.					x
2.1	M. Quashie, Optimal Planning of an Urban Microgrid Use Case - Technical Report (internal), McGill University, Oct 2014.					x
2.1	P. Tiwari, Compressed Air Energy Storage – a Business Case for Remote Communities – Technical Report (internal), McGill University, Aug 2015.					x
2.2	A. Mohamed, R. Iravani, X. Wang, "Definitions and evaluation of multiple microgrids on reliability, continuity of supply and resiliency", submitted to the IEEE Transactions on Power System.	x				
2.2	S. Chuangpishite, R. Iravani, A. Niaki, "Impact of Wear and Tear on the power system apparatus due to high-depth of penetration of renewable in multiple microgrids", submitted to the IEEE Tran on Power Delivery.	x				
2.2	R. Mirzahosseini, A. Mohamed, R. Iravani, "Real-time simulation of large cyber-physical layers of a large electrical system", accepted for publication in the IEEE Trans on Power Systems.	x				
2.3	A. Mossadegh, C. Canizares, K. Bhattacharya and H. Fan, "Distributed computing architecture for optimal control of distribution feeders with smart loads", IEEE Transactions on Smart Grid, in review.	x				
2.3	M. Farrokhabadi, C. Canizares and K. Bhattacharya, "Frequency control in isolated/islanded microgrids through voltage regulation", IEEE Transactions on Smart Grid, in revision.	x				
2.3	B. Solanki, A. Raghurajan, K. Bhattacharya and C. Canizares, "Including smart loads for optimal demand response in integrated energy management systems for isolated microgrids", IEEE Transactions on Smart Grid, in revision.	x				
2.3	M. Pirnia, C. Cañizares, K. Bhattacharya and A. Vaccaro, "A novel affine arithmetic method to solve optimal power flow problems with uncertainties", IEEE Transactions on Power Systems, Vol.29, Issue 6, Nov 2014, pp.2775-2783.	x				
2.3	S. Shetty and K. Bhattacharya, "A stochastic distribution operations framework to study the impact of PEV charging loads", 47th North American Power Symposium, Charlotte, NC, USA, Oct 2015.				x	
2.3	Mosaddegh, C. Canizares and K. Bhattacharya, "Distributed computing approach to solve unbalanced three-phase DOPFs", IEEE Canada Electrical Power and Energy Conference (EPEC) 2015, London, Ontario, Canada, October 2015.				x	
2.3	M. Farrokhabadi, C. A. Canizares, K. Bhattacharya, "Evaluation of droop-based controls in an islanded microgrid with electronically interfaced distributed energy resources", Proc. IEEE PowerTech 2015, Eindhoven, The Netherlands, June 2015.				x	
2.3	R. Kundu, C. Cañizares and K. Bhattacharya, "Smart operation of centralized temperature control system in multi-unit residential buildings", 2014 CIGRE Canada Conference, Toronto, Canada, Sept 2014.				x	

Table 4: Highly Qualified Personnel in Theme 2 since Inception (listed by Project #)

Project	Name	Program	Start	End	Employer (if graduated)
2.1	Quashie, M.	PhD	September 2011	Ongoing	
2.1	Ross, M. (partial)	PhD	October 2010	Ongoing	
2.1	Tiwari, P.	PhD	September 2014	Ongoing	
2.1	Elkasrawy, A. (partial, scholarship)	PhD	September 2011	January 2013	Ryerson (PhD student)
2.1	Qin, S.	MSc	September 2012	June 2015	
2.1	Clavier, J.	MSc	January 2012	December 2013	GE Energy (CA)
2.1	Morris, G. (partial)	MSc	September 2011	May 2012	
2.1	Rifkin, D.	UG	May 2012	August 2012	
2.2	Akbari, K.	PhD	January 2014	Ongoing	
2.2	Jedrzejczok, J.	PhD	September 2013	Ongoing	
2.2	Mohamed, A.	PhD	April 2014	Ongoing	
2.2	Azad, S.	PhD	September 2009	November 2013	PDF - KU Leuven - Belgium
2.2	Etemadi, A.	PhD	September 2014	August 2012	Assistant Professor - George Washington University - USA
2.2	Kamh, M.	PhD	January 2008	October 2011	Senior Engineer - Atlanta Power - Calgary
2.2	Gumusteking, G.	MASc	September 2013	Ongoing	
2.2	Hayhoe, G.	MASc	September 2014	Ongoing	
2.2	Chunagpishite,S.	MASc	September 2012	March 2015	HydroOne
2.2	Annakkage, M.	MASc	September 2013	December 2013	
2.2	Wang, S.	MASc	September 2011	November 2013	Engineer - Siemens Canada
2.2	Tobia, J.	UG	September 2014	April 2015	HydroOne
2.3	Padmanabhan, N.	PhD	May 2015	Ongoing	
2.3	Mosaddegh, A.	PhD	January 2015	Ongoing	
2.3	Solanki, B.	PhD	January 2014	Ongoing	
2.3	Farrokhabadi, M.	PhD	September 2014	Ongoing	
2.3	Nasr-Azadani□E.	PhD	September 1, 2011	May 2014	
2.3	Pirnia, M.	PhD	May 1, 2011	February 2014	California ISO
2.3	Shubhalakshmi, S.	MSc	May 2015	Ongoing	
2.3	Raghurajan, A.	MSc	May 1, 2013	April 2014	GM Canada
2.3	Gaete, F. R.	MSc	September 1, 2011	September 2013	
2.3	Jain, R.	MSc	September 1, 2011	December 2012	METSCO Energy Solutions
2.3	Kundu, R.	MSc	September 1, 2011	May 2013	

2.3	Le, B.	MSc	September 1, 2011	April 2012	IESO
2.3	Madhavan, A.	MSc	May 1, 2011	April 2012	Robertson and Associates
2.5	Brooer, T.	PDF	October 2014	March 2015	
2.5	Mascarella, D.	Res. Assoc.	July 2015	October 2015	
2.5	El Arroudi, K.	Res. Assoc.	July 2015	October 2015	

Theme 3: Microgrid Communication and Information Technologies

(Dr Julian Meng, Theme Leader)

Theme Overview

The four projects in this theme are focused on innovative network architectures to support seamless exchange of data and commands between participants in the smart grid network. Unlike traditional grid control strategies based on hierarchical models, Canada's smart grid will rely on a distributed system of command and control. Given the enormity of data produced by arrays of sensors, smart meters, intelligent electronic devices (IEDs) and substation equipment it would no longer be practical to rely on a centralized control hierarchy. Instead, the required intelligence is inserted at the appropriate nodes of the system, so that operational and control decisions can be taken at the node level, based on local data and global control attributes. Theme 3 supports the establishment of cost effective and efficient communication infrastructure for Canada's intelligent microgrid future. Theme 3 projects are focused on the following:

Project 3.1 Universal Communication Infrastructure (LaBeau, McGill)

- Developing a media-agnostic topology for smart grid networks and associated protocols
- Focusing on seamless exchange of data and command through hybrid technologies
- Researching robust authentication methods associated with various access functionality

Project 3.2 Grid Integration Requirements, Standards, Codes and Regulations (Le-Ngoc, McGill)

- Suitable communication technologies for smart microgrids
- Standards for end-to-end messaging
- Efficient protocols for distribution automation within and across integrated microgrids

Project 3.3 Distribution Automation Communications (Meng, UNB)

- Developing a technology-agnostic topology for intelligent sensor networks
- Assessing of cost-effective technologies for intelligent sensor networks
- Developing an optimal real-time operating system (RTOS) to support the sensor network profile

Project 3.4 Integrated Data Management and Portals (Farhangi, BCIT)

- The structure of intelligent agents at various command and control layers within and across smart microgrids
- Scalable multi-port database architecture to support energy management applications
- Platform-dependent architectures for user and utility portals.

Summary of Theme Progress

Project 3.1 (Universal Communication Infrastructure), led by Dr. Fabrice Labeau, has continued to focus on the impact of noise at 1800 and 700 MHz with respect to electric substations. This work continues in close collaboration with Hydro-Quebec for substation data collection, and includes impulse noise modeling and optimal receiver design in the presence of significant electromagnetic interference. The final research push will focus on the use of optimal receiver models to create cooperative, relay-based systems for transmission in substations.

Project 3.2 (Grid Integration Requirements, Standards, Code and Regulatory Considerations), led by Dr. Tho Le-Ngoc, continues to meet project requirements. This project is focused on the investigation of networking protocols, standards (such as IEC 61850) and coding schemes suitable for the diverse nature of the smart grid information infrastructure. Recent progress includes research into routing protocols for relatively low availability wireless devices such as wireless smart meters and a comprehensive survey of coding and candidate schemes for microgrid deployment scenarios. Also investigated is the utilization of Software-Defined Radio Access Network (SD-RAN) techniques for microgrid communications. SD-RAN research will facilitate cost effective and flexible deployment of wireless access networks. Targets will include network architecture design and the implementation of reconfigurable software/firmware in wireless devices and network protocols. Extension research will include: Research and development of SDNs for microgrid applications and requisite simulations to model various microgrids utilizing SDNs to evaluate their performance.

Project 3.3 (Distribution Automation Communications: Sensors, Condition Monitoring and Fault Detection), led by Dr. Julian Meng and Dr. Eduardo Castillo Guerra, is moving towards achieving designated milestones. Recent developments include: 25 sensor nodes have been constructed and will be deployed with industry partners and research labs for testing; 4 gateway access nodes with cellular capabilities have been constructed; A higher layer software application has been developed using Thingspeak for cloud network configuration, data collection, data management and data visualization; implemented and tested a fault detection relay algorithm (Phase lock loop, DQ transform, Wavelet transform) on a sensor node with line to ground & line to line fault testing completed; developed and tested an Earliest Deadline First Prioritization algorithm for the gateway node for the purposes of prioritization data stream from various nodes; assessed of minimum transmission power and latency times that ensures effective communication and a basic wireless network simulation of an IEEE 802.15.4 based WSN with prioritized end devices and cellular communication. Extension work will focus on software development for WSN networks, deployment and testing.

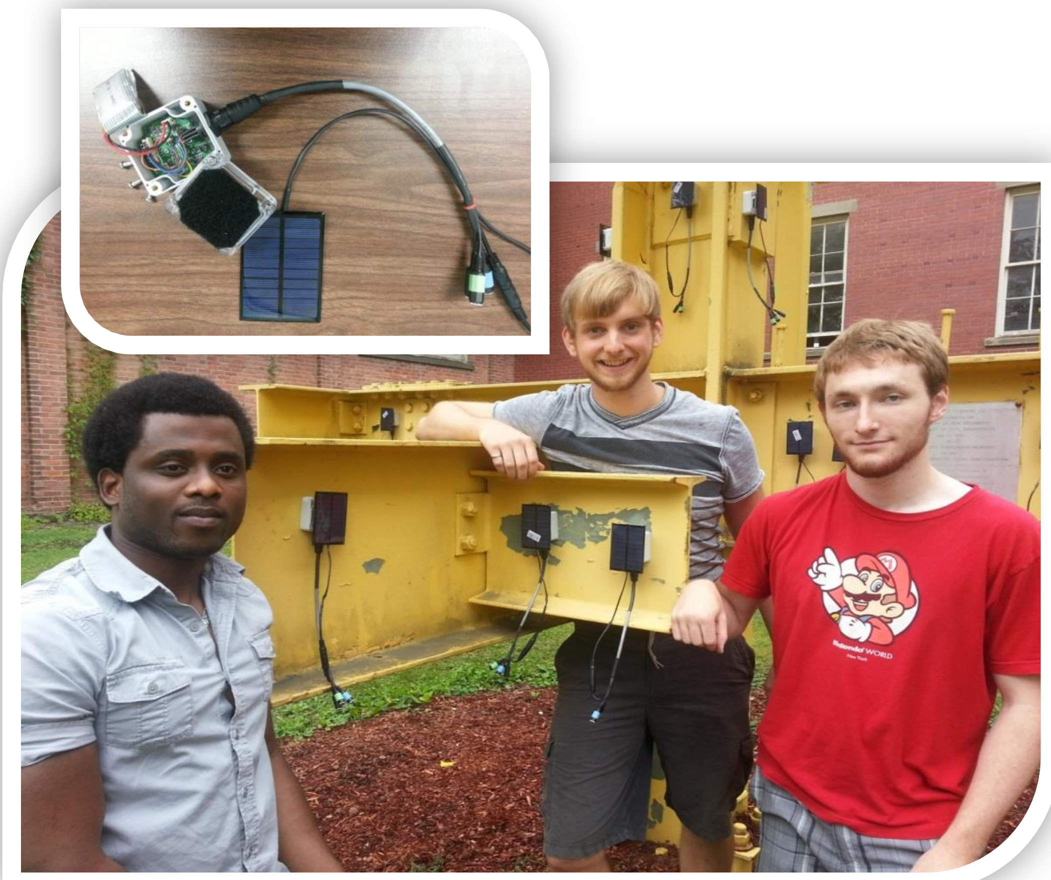
Finally, project 3.4 (Data Management/Communications), led by Dr. Hassan Farhanghi, considers VVO and CVR optimization control and residential load modeling. Some milestone highlights include: design of Quasi Real-time Smart Grid-based Volt-VAR Optimization Engine; completed design of Predictive VVO Engine able to optimize distribution grids; completed working on Maintenance Scheduling issue of Volt-VAR Control Assets; completed studies related to V2G, EV, Micro-CHP/PV penetration impacts on AMI-Based VVO and CVR analysis; finalized proposed VVO engine and models have been validated through a real-time co-simulation environment comprised of real-time digital simulator (RTDS), VVO engine, Volt-VAR control component's model and reliable communication platform working with DNP.3 protocol or IEC-61850 MMS and GOOSE. In terms of AMI data disaggregation, accomplishments include: an appliance inference algorithm is developed based on AMI data measured at 1-hour frequency, Canadian appliance ownership survey, and surveys on appliance usage patterns. Given the hourly power consumption, dwelling type, heating type, and etc. of a residence, the algorithm is able to discern different appliances and their power characteristics. Also, an electric load disaggregator is developed based on the appliance inference algorithm. The disaggregator is able to disaggregate loads in a

residence with moderate accuracy by only referring to the 1-hour AMI data.
The main short-term action item in the extension year is to focus on assessing a collection of projects that can be used for the P2.6 demonstration project on the BCIT campus.

Overall Conclusions of Theme 3 Progress During Year-5:

Projects 3.2, 3.3 and 3.4 continue to meet the original plans without major changes/deviations. Projects 3.2 and 3.4 have been especially strong in the area of dissemination of knowledge with numerous journal and conference papers submitted or published. Project 3.3 has met milestones of developing wireless sensor technology for micro-grid applications with novel fault detection algorithms being implemented and tested. A special case is Project 3.1 led by Dr. Fabrice Lebeau, which has focused on assessing the wireless environment in noisy sub-stations. The original intent of this project was to investigate a universal communications infrastructure that would encompass various physical media including wireless, fiber, copper etc. That said, it should be noted that Dr. Lebeau took over the project late in the Network timeline and is utilizing the momentum of pre-existing research to contribute to Network research goals. Although not an exact fit, it is the opinion of this Theme leader that this research is of value to the area of microgrid communications, especially given Dr. Lebeau's strong connection with Quebec Hydro.

The level of collaboration in Theme 3 projects has improved in year-5 with a Theme 2/Theme 3 Montreal workshop taking place in August of 2014 and will continue into the extension year. All four projects of Theme 1 have been extended to the end of March 2016 with no additional cost and it is expected that more collaborative work during this time will focus on the final demonstration project in BCIT.



Wireless sensor nodes constructed by Project 3.3 researchers using a Zigbee development platform. (Left to right: students Gift Owhuo, Ryan MacDonald and Erik Hatfield)

Table 5: Publications by Theme 3 in Year 5

Project	Citation *(Click on link to access article where available)*	Refereed Journal Article	Non-refereed Journal Article	Invited Conference Presentation	Non-invited Conference Presentation	Other
3.1	S. Ghazanfari Rad and F. Labeau, "Formulation and Analysis of LMS Adaptive Networks for Distributed Estimation in the Presence of Transmission Errors", accepted for publication in IEEE Journal on Internet of Things, June 2015.	x				
3.1	H. Mahboubi, M. Vaezi and F. Labeau, "Sensors Deployment Algorithms Under Limited Communication Range and Measurement Error", in Proc. IEEE Vehicular Technology Conference (Spring), March 2015, 5 pages.				x	
3.2	Quang-Dung Ho, Yue Gao, Gowdemy Rajalingham and Tho Le-Ngoc, "Geographic-based Routing in Smart Grid's Neighbor Area Networks", REV Journal on Electronics and Communications (REV-JEC), vol. 3, no. 3-4, July December 2013, pp. 110-115.	x				
3.2	S. P. Herath, Nghi H. Tran, Tho Le-Ngoc, "Optimal Signalling Scheme and Capacity Limit of PLC under Bernoulli Gaussian Impulsive Noise", IEEE Transactions on Power Delivery, Vol. 30, No.1, February 2015,pp. 97-105.	x				
3.2	Hung V. Vu, Nghi H. Tran, Mustafa Cenk Gursoyz, Tho Le-Ngoc, S. I. Hariharan, "Capacity-Achieving Input Distributions of Additive Quadrature Gaussian-Mixture Noise Channelsaccepted in IEEE Transactions on Communications.	x				
3.2	Quang-Dung Ho, Yue Gao, Gowdemy Rajalingham and Tho Le-Ngoc, "Robustness of the Routing Protocol for Low-power and Lossy Networks (RPL) in Smart Grid's Neighbor-Area Networks", IEEE International Conference on Communications (ICC 2015), London, United Kingdom, 8-12 June, 2015.				x	
3.2	Gowdemy Rajalingham, Quang-Dung Ho, and Tho Le-Ngoc, "Multiple-instance Low-power and Lossy Networks (RPL) Routing Protocol for QoS Differentiation in Microgrid Communications Networks – the Burwash Landing (Yukon, Canada) Case Study", Technical Report, Broadband Communications Lab, McGill University, July 2015.					x
3.2	Gowdemy Rajalingham, Quang-Dung Ho, and Tho Le-Ngoc, "Network-coded Low-power and Lossy Networks (RPL) Routing Protocol for Converge-casting in Microgrid Communications Networks", Technical Report, Broadband Communications Lab, McGill University, March 2015.					x
3.2	Quang-Dung Ho and Tho Le-Ngoc, Network Architecture, Signaling Protocols, and Experimental Platform for the Integration of Software-Defined IEEE 802.11/WiFi Access Technologies into Intelligent Microrgrid,Technical Report , Broadband Communications Lab, McGill University, May 2015.					x
3.4	M. Manbachi, H. Farhangi, A. Palizban, S. Arzanpour, "Quasi Real-Time ZIP Load Modeling for Conservation Voltage Reduction of Smart Distribution Networks using Disaggregated AMI Data", Sustainable Cities and Society Journal, vol. 19, pp. 1-10, December 2015.	x				
3.4	M. Manbachi, H. Farhangi, A. Palizban, S. Arzanpour," Volt-VAR Optimization of Smart Distribution Networks utilizing Vehicle to Grid Dispatch", International Journal of Electrical Power and Energy Systems, vol 74, pp. 238-251, January 2016.	x				
3.4	M. Manbachi, H. Farhangi, A. Palizban, S. Arzanpour, "A Novel Approach for Maintenance Scheduling of Volt-VAR Control Assets in Smart Distribution Networks", submitted to Canadian Journal of Electrical and Computer Engineering, March 2015.	x				
3.4	M. Manbachi, H. Farhangi, A. Palizban, S. Arzanpour, "Smart Grid Adaptive Volt-VAR Optimization Engine utilizing Particle Swarm Optimization and Fuzzification", submitted to Canadian Journal of Electrical and Computer Engineering, May 2015.	x				
3.4	M. Manbachi, H. Farhangi, A. Palizban, S. Arzanpour, "Conservation Voltage Reduction Plans of the Future", submitted to The Electricity Journal, May 2015.	x				
3.4	M. Manbachi, H. Farhangi, A. Palizban, S. Arzanpour, "Impact of Micro-CHP/PV Penetrations on Smart Grid Adaptive Volt-VAR Optimization of Distribution Networks using AMI data", submitted to IEEE Transactions on Power Delivery, June 2015.	x				

3.4	M. Manbachi, A. Sadu, H. Farhangi, A. Monti, A. Palizban, F. Ponci, S. Arzanpour, "Real-Time Co-Simulation Monitoring and Control Platform for AMI-based Volt-VAR Optimization of Smart Distribution Networks", submitted to IEEE Transactions on Power Delivery, June 2015.	x	
3.4	M. Manbachi, A. Sadu, H. Farhangi, A. Monti, A. Palizban, F. Ponci, S. Arzanpour, Real Time Co-"Simulation Platform for Smart Grid-based Volt-VAR Optimization using IEC61850 MMS and GOOSE Messaging", submitted to IEEE Transactions on Industrial Informatics, June 2015.	x	
3.4	M. Manbachi, H. Farhangi, A. Palizban, S. Arzanpour, " Impact of EV Penetration on Volt-VAR Optimization of Distribution Networks using Real-Time Co-Simulation Monitoring Platform", submitted to IEEE Transactions on Industrial Electronics, June 2015.	x	
3.4	M. Manbachi, A. Sadu, H. Farhangi, A. Monti, A. Palizban, F. Ponci, S. Arzanpour, "Real-Time Communication Platform for Smart Grid Adaptive Volt-VAR Optimization of Distribution Networks", Accepted in IEEE International Conference on Smart Energy Grid Engineering, May 2015.		x
3.4	M. Manbachi, A. Sadu, H. Farhangi, A. Monti, A. Palizban, F. Ponci, S. Arzanpour, Real-Time Co-"Simulated Platform for Novel Volt-VAR Optimization of Smart Distribution Network using AMI Data", Accepted in IEEE International Conference on Smart Energy Grid Engineering, May 2015.		x
3.4	M. Manbachi, H. Farhangi, A. Palizban, S. Arzanpour, "Real-Time Co-Simulated Platform for Energy Conservation of Smart Distribution Network using AMI-based VVO Engine", Accepted in 2015 CIGRE Canada Conference, April 2015.		x
3.4	Guanchen Zhang, Hassan Farhangi, Ali Palizban, and Gary Wang, "Residential Electric Load Disaggregation for Low-Frequency Utility Applications", 2015 IEEE PES General Meeting, Denver, July 2015.		x

Table 6: Highly Qualified Personnel in Theme 3 Since Inception (listed by Project #)

Project	Name	Program	Start	End	Employer (if graduated)
3.1	Sacuto, F.	PhD	May 1, 2014	Ongoing	
3.1	Ghazanfari Rad, S.	PhD	June 2015	Ongoing	
3.1	Khosravirad, S.	PhD	February 2015	Ongoing	
3.1	Alam, S.	PhD	April 2015	Ongoing	
3.1	Nabaee, M.	PhD	April 2015	Ongoing	
3.1	Monier, E.	UG	May 2014	August 2014	
3.2	Mudiyanselage, S.	PhD	October 2010	Ongoing	
3.2	Herath, S.	PhD	October 2010	Ongoing	
3.2	Leung, C.r	PhD	January 2011	August 2012	
3.2	Hazarika , P	MEng	June 2015	Ongoing	
3.2	Wang, X.	MEng	Sept 2015	Ongoing	
3.2	Jumba, V.	MEng	June 2015	Ongoing	
3.2	Chen, F.	MEng	January 2015	Ongoing	
3.2	Rajalingham, G.	MEng	January 2012	Ongoing	
3.2	Gao, Y.	MEng	October 2010	May 2014	
3.2	Ghosh, S.	MEng	October 2010	August 2012	

3.2	Burke, D.	UG	May 2015	Ongoing	
3.2	Wang, X.	UG	May 2015	Ongoing	
3.2	Mai, R.	UG	May 2015	Ongoing	
3.2	Santorelli, J.	UG	May 2011	August 2011	
3.2	Chao, C.-W.	UG	May 2011	August 2011	
3.3	Jia, J.	PhD	2012	Ongoing	
3.3	Morales, D.	PhD	2012	Ongoing	
3.3	Owhuo, G.	MSc	2014	Ongoing	
3.3	Kar, A.	MSc	2010	2014	Smart Skin Technologies
3.3	Losier, T.	MSc	2011	Ongoing	
3.3	Hatfield, E.	UG	2015	Ongoing	
3.3	MacDonald, R.	UG	2015	2015	
3.3	Harrington, M.	UG	2014	2014	
3.3	MacDonald, R.	UG	2013	2014	
3.3	MacNearney, D.	UG	2012	2012	
3.3	Khammash, T.	UG	2011	2011	
3.4	Manbachi, M.	PhD	September 2011	Ongoing	
3.4	Nasri, M.	PhD	August 2011	2015	
3.4	Zhang, G.	MSc	October 2013	Ongoing	
3.4	Shahabi, B.	MSc	August 2011	Apr. 2013	Alpha Tech.

Finance

The following section details NSMG-Net's finances in Year 5.

The **Statement of Accounts** provides an overview of the revenues and expenditures of NSERC (p. 34) and Industry (p. 35) funds for the period October 1, 2014 – August 24, 2015. Not that this period is approximately 1 month short of the full fiscal year, which runs October 1-September 30 annually. (Financial statements were requested early from BCIT to allow sufficient time to prepare the Financial Report prior to Board of Directors meeting on October 4, 2015.)

Statements of Account

A) NSERC Funds at BCIT at August 24, 2015

(All financial data collected from account statements prepared by BCIT).

Balance at start of Y5 (Oct 1, 2014)	438,463	1
REVENUE		
NSERC payments	739,500	2
Funds recovered from P2.4 (Gole)	16,161	3
Funds recovered from P3.1 (Michelson)	3,560	4
Total NSERC funds available in Y5	**1,197,684**	
EXPENDITURES		
Disbursements to Universities		
Y4H2 transfers	248,850	5
Y5H1 transfers	318,850	6
Y5H2 advance	32,400	7
Total Expenditures	**600,100**	
Balance at August 24, 2015	**597,584**	

Notes

1 Total NSERC revenue minus disbursements up until Sept 30, 2014 (end of Y4).

2 Includes payments 4b and 5a.

3 Funds returned by U Manitoba for terminated project.

4 Funds returned by UBC for Michelson (resigned from Network).

5 Y4H2 payments made in October and November 2014.

6 Y5H1 payments made in April and May 2015.

7 Y5H2 advance for P3.1 as approved by Farhangi and NSERC.

B) Partner Funds at BCIT at August 24, 2015

Balance at start of Y5 (Oct 1, 2014)	113,777	
REVENUE		
BC Hydro	20,000	
HydroOne	30,000	
NRCan	12,500	[1]
Schneider Electric	5,000	
Endurance Wind	1,000	
Nebula Networks	1,000	
UBC (Project 3.1 funds recovered)	7,154	
Total Y5 Revenue	76,654	
Total Partner Funds available in Y5	**190,431**	
EXPENDITURES		
Y4 AGM Costs (Montreal, 2014)	-27,905	
Administration	-511	[2]
Project 2.5 Travel (PDF)	-5,926	[3]
HQP Exchange (International)	-2,070	[4]
AGM Costs for Y5 meeting (to date)	-1,356	[5]
Total Expenditures	-37,768	
Balance at August 24, 2015	**152,663**	

Notes

[1] Additional Year 6 contribution of $10k granted due to Network extension + $2,500 holdback from Y5 contribution.

[2] Website hosting and IT assistance (under budget; $2,000 approved for admin).

[3] Travel for PDF reimbursed directly by BCIT (was originally budgeted as part of NSERC funds, billed by BCIT to Partner account).

[4] P3.4 student to Achen, Germany for international exchange. $2,070 paid directly by BCIT + $3,636 paid by P3.4 budget at SFU and then invoiced to BCIT. This $3,636 payment was included in the disbursements to universities from Partner funds in Year 4.

[5] Hotel deposit; flight bookings for 2 students.

Appendix:

Individual Project Reports

Project 1.1: Control, Operation, and Renewables for Remote Intelligent Microgrids

Project Leader: Amirnaser Yazdani, Ryerson University

Project Started: September 2011

Expected Completion Date: March 2016

Milestones Progress in Year 5

- Research and develop control strategies and algorithms (2012)—started in Sept 2011; 100% complete.
- Research and develop coordinated control, supervisory and operational strategies (2012)—started in Sept 2011; 90% complete.
- Research and develop protection strategies (2013)—100% complete.
- Develop simulation test cases and benchmark models (2011-2013)—started Sept 2012. 80% complete
- Perform test cases and evaluation studies and identify the beta site and specify requirements and test cases (2014)—50% complete
- Perform beta test cases (2015)— Not started

Research Plans for No-Cost Extension Period

In addition to the research advanced by K. Akbari, F. Kazempour, and R. Oliveira, two Masters students, Mr. Marcos Aguirre and Ms. Nikoo Kouchakipour, have been admitted and will start research as of Sep. 1, 2015. These students will work on the following two milestones:

i. Develop simulation test cases and benchmark models
ii. Perform test cases and evaluation studies and identify the beta site and specify requirements and test cases

Also, an experimental setup for verifying the developed control techniques is being worked on by R. Oliveira and a summer undergraduate student, Nebi Cicek. This setup will be completed with the help of Marcos Aguirre in the remaining months of the project, to contribute towards the last milestone, i.e., *Perform beta test cases.*

Collaborations in Year 5

Project 1.1 has been collaborating with Project 1.4 on the development of control strategies that ensure stable operation, and enablement of a high degree of penetration of renewable energy, of off-grid microgrids. The project has also been collaborating with Project 1.2 on the development of centralized, decentralized, and hybrid control strategies for remote microgrids. Also, since October 2014, the project has tried to collaborate with Schneider Electric on the development of experimental set-ups for evaluation of the control strategies developed under the project for remote microgrids.

Project 1.2: Distributed Control, Hybrid Control and Power Management for Intelligent Microgrids

Project Leader: Reza Iravani, University of Toronto

Project Started: October 2010

Expected Completion Date: March 2016

Milestones Progress in Year 5

In continuation of Year-1 to Year-4 program, in Year-5 we:

- Investigated the impact of cyber layer on the microgrid controllers developed during year-2 to year-4 of the program. *(100% completed)*
- Identified and formulated hierarchial robust control approaches for urban and rural Microgrids based on the use of pre-specified communication infrastructure. *(100% complete)*
- Developed linear dynamic models for the design of centralized and distributed controls for benchmark microgrid systems. *(100% complete)*
- Develop strategies and algorithms for the cotnrol of multiple Intelligent Microgrids, and specify the required ICT. *(100% complete)*
- Developed performance criteria for control strategies including ICT. (100% complete)
- Developed HIL-RTDS environment for real-time testing realization and performance evaluation of the control systems. *In progress (80% completed)*
- Identify beta site test cases for selcted scenarios to validate the R&D results. In collaboration with Hatch and HydroOne we are finanilizing the test site and developing the detailed simulation models of these site for pre-installation testing of hardware-based control/protection/EMS. *(100% completed)*
- Develop developed hardware-in-the-loop test-bed for performance evaluation/validation of the control of multiple Intelligent Microgrids, including the required ICT. *In progress (80% complete)*
- Developed of supervisory control and EMS for multi-microgrid system based on distributed robust control of individual microgrids (using local measurement at the PCC and within each microgrid)) and ICT-based supervisory control appraoch for multiple microgrids. *In progress (80% completed*)

Research Plans for No-Cost Extension Period

1) Developed of multi-layer real-time-based HIL plartform in which

(i) local controllers within each microgrid are operated based on local measurements within the microgrid,
(ii) local controllers within each microgrid are coordinated by the microgrid EMS,
(iii) EMS' of muliple microgrids are coordinated by the upper-level EMS/supervsiory-control, using communication and measurements at the PCCs of the multiple microgrids.

All controls and EMS entities will be in NI-CRIO or NI-PXI platforms and the power circuits of the microgrids will be in an FPGA- enhanced RTDS platform.

2) Development of HMI system for "remote" monitoring, parameter adjustment, and data logging of the upper-layer EMS/supervisory-control.

These two items are in continuation and the extension/generalization of the developments of the last four items of the year-5 activities as described in the above box.

Collaborations in Year 5

Research Partners
- University of Waterloo, Prof. Kankar Bhattacharya/Prof. Claudio Canizares
- Ryerson University, Prof. Amirnaser Yazdani
- University of Alberta, Profs. Wilsun Xu

Industrial Partners
- Hydro One
- Hatch Associates
- Toronto Hydro

International Collaboration
- North China Electric Power University, Beijing, China
- Tsinghua University, Beijing, China
- Imperial College, London, England

HQP Exchange
- Imperial College London, UK
- Ecole Polytechnique Grenoble, France
- North China Electric Power University, Beijing, China

Project 1.3: Status Monitoring, Disturbance Detection, Diagnostics and Protection for Intelligent Microgrids

Project Leader: Wilsun Xu (University of Alberta)

Project Started: October 2010

Expected Completion Date: March 2016

Milestones Progress in Year 5

The research work on the low voltage ride through (LVRT) capability of inverter based DGs has been completed. LVRT has become a major requirement for microgrid DGs. This research work developed an analytical method to evaluate the performance of several key LVRT control schemes and proposed new methods to improve LVRT performances of inverter based DGs. Two papers have been submitted and one M.Sc. student graduated.

We are continuing research on novel methods for open loop synchronization of a microgrid to system. The methods are based on the idea of reducing synchronization transients using techniques such as impedance insertion and synchronous closing. The impedance insertion method has been found effective. The synchronous closing based method is not found as effective. A strategy that allows open-loop implementation of the impedance insertion scheme has been finished. Recently, we have completed the design method for the impedance insertion scheme, including the selection of impedance value and the impact on microgrid stability. The student has started to write a report. The proposed method has been presented to Hydro One and a few other companies.

In view of the availability of funds, we expanded the above research by investigating the idea of "thyristor-based synchronizer" for micro-grids. This concept may be useful for MGs without extensive power electronic control capability. "Thyristor-based synchronizer" is similar to the thyristor-based motor starter.

Since May 2015, I have been in collaboration with Prof. Y. Jing of U of A on a general purpose disturbance detection method for both microgrid and regular systems. The new idea here is the use of automatic and "soft" thresholds for disturbance detection.

Research Plans for No-Cost Extension Period

1. Complete the research on impedance insertion based synchronization scheme. A paper will be submitted and the student is expected to complete thesis defense.

2. Determine the feasibility and technical issues of "Thyristor-based synchronizer" for microgrid synchronization. (This is a difficult research project. I don't expect the M.Sc. student can complete the project beyond this stage) .

3. Complete the research on a general purpose distance detection method. Submit a paper if the results are promising.

Collaborations in Year 5

Research Partners

- University of Toronto, Prof. Reza Iravani
- University of Waterloo, Prof. Kankar Bhattacharya
- University of Alberta, Profs. Y. Li, Y. Mohammed and Y. Jing

Industrial Partners

- Hydro One
- Powertech Labs

International Collaborations

- Prof. W. Freitas, University of Campinas, Brazil

Exchanges by HQP

- A. P. Grilo, Visiting PDF from State University of Sao Paulo, Brazil
- R. Torquato, Visiting MSc student from University of Campinas, Brazil

Other

- Research results presented at the Annual Power & Energy Innovation Forum organized by the Alberta Power Industry Consortium in November 2014.

Project 1.4: Operational Strategies and Storage Technologies to Address Barriers for Very High Penetration of DG Units in Intelligent Microgrids

Project Leader: Geza Joos (McGill University)

Project Started: October 2010

Expected Completion Date: March 2016

Milestones Progress in Year 5

Milestone name: Evaluate performance of the strategies based on computer simulation test cases, and validate the generation and storage dispatch and the ICT performance in the BCIT beta site

The progress made towards this milestone is divided into the following realizations.

A. Implementation of the microgrid controller algorithms into an online physical controller for hardware-in-the-loop and physical integration, including a rule based and a hierarchical optimization algorithm based controller

The main goal is to implement the hierarchical Microgrid controller (as described in the recently accepted transaction journal) for online studies. The focus thus far has been to develop the central optimization algorithm, and a common interface for the distributed controllers. A common interface has been established between the central controller and the distributed controllers; this is employed to reduce the communication requirements and to facilitate the integration of a variety of Distributed Energy Resources. An algorithm has been developed in the central hierarchical controller (based on the interface model) to amalgamate the distributed resources' valuation functions to create a unified virtual plant whose optimal dispatch can be directly determined in a distributed manner either through cost signals (when grid-connected), or frequency (when islanded). Any deviation from the nominal set points is along the optimal curves. Preliminary results demonstrate that the proposed algorithm yields identical results to a central optimization algorithm, and it facilitates distributed intelligence and a novel distributed approach to unit commitment in the microgrid.

Furthermore, in terms of the distributed controllers, the focus has been to develop a common interface and distributed intelligence into the storage controller to facilitate the integration of a time-dependent resource in the optimization algorithm. This algorithm considers past market prices to determine the net present value of the stored energy, and its post-processing interface to the central controller is identical to other resources in the microgrid. Results show that the employed back casting approach yields savings that are approximately 71.3% that of the perfect offline forecasting algorithm. Results are expected to be submitted for a transaction paper (Michael Ross, PhD candidate).

An alternate, simpler solution, will also be implemented, based on the same requirements and objectives, offering and easier and more robust implementation of microgrid controller functions, with simpler adaptation. It consists of a rule based controller (Farah Awan, PhD candidate).

B. Developing real-time models of the real test microgrid for the online implementation

The approach is to initially test the controller on the OPAL-RT real time simulator at McGill. This may be followed by testing on the 25kV Distribution Test Line at Varennes through collaboration with our Network partner IREQ. The results of this work may be extended towards implementation on the BCIT microgrid.

In keeping with the project milestones for this year, a model of the IREQ Distribution test line has been developed on the Matlab/Simulink platform. The model includes inverter interfaced DGs, synchronous machines, storage and loads. Control loops are in place to ensure the capabilities of the test line generators are captured. The model includes a communication infrastructure to allow for real time dispatch. The next milestone is to implement the real time model on the McGill OPAL-RT simulator.

C. Online implementation of the microgrid controllers in a real time simulation environment and on the real microgrid test system

The approach is to initially test the controller on the OPAL-RT real time simulator at McGill. This may be followed by testing on the 25kV Distribution Test Line at Varennes through collaboration with our Network partner IREQ.

The results of this work may be extended to an implementation on the BCIT microgrid.

Research Plans for No-Cost Extension Period

Implementation of the two microgrid controllers and their respective algorithms, first on the McGill real time simulator (OPA-RT) and subsequently on the IREQ test microgrid (with the help on industrial partner Hydro-Quebec IREQ, see below):

(a) a rule based (expert system based) controller, with rules developed and optimized off line (Farah Awan, PhD candidate);

(b) a controller based on an optimization algorithm, which meets specified constraints related to the cost of energy and emissions, and optimizing the on-site resources, including renewable generation and storage (Michael Ross, PhD candidate).

Collaborations in Year 5

1. Modelling the IREQ test line in collaboration with Diego Mascarella (Research Engineer, McGill) and Martine Chlela (PhD candidate, McGill) and with the help of Marthe Kassouf (Researcher) from Hydro-Quebec IREQ (Network partner)

2. Developing microgrid controller requirements with guidance from Chad Abbey from SmarterGrid Solutions formerly from Hydro-Quebec IREQ and PhD co-supervisor of Michael Ross (PhD candidate, McGill), and Yves Brissette from Hydro-Quebec IREQ (Network partner).

3. Developing microgrid controller energy management algorithms, including generation dispatch and load management, in 2 implementable on-line executable versions: (a) a rule based controller, with rules developed and optimized off line (Farah Awan, PhD candidate); (b) an optimization algorithm, which meets specified constraints related to the cost of energy and emissions, and optimizing the on-site resources, including renewable generation and storage (Michael Ross, PhD candidate). Yves Brissette from Hydro-Quebec IREQ (Network partner) participates in this work, along with Diego Mascarella (Research Engineer, McGill). IREQ intends to implement the controllers and their algorithms on its test real microgrid.

Project 2.1: Cost-benefits Framework: Secondary Benefits and Ancillary Services

Project Leader: Geza Joos (McGill University)

Project Started: October 2010

Expected Completion Date: March 2016

Milestones Progress in Year 5

- Planning and optimization approaches to maximize Microgrid benefits (2014) - *Completed*
- Application of the methodology to Microgrid demonstrations in commercial, industrial and remote community settings (2015) – *In Progress*

Work done over the year was to apply the developed methodologies under this project to representative microgrids:

- A business case for a mining microgrid in Quebec was developed through the implementation of the above methodologies (M Quashie)
- A use case for an Optimal Planning of an urban microgrid in Calgary was also developed based on the above methodologies (M Quashie)
- A business case for the use of compressed air energy storage in combination with wind energy for remote communities (P Tiwari)

Future work

Real time Implementation of the above methodologies – Real Time simulator (OPAL-RT)

Final verification of developed methodologies under this project with the commercial software (DERCAM, RETSCREEN)

Research Plans for No-Cost Extension Period

Project 1

- Finalizing and validating, using an alternate software, the software package developed at McGill that establishes the business case for isolated microgrids, with specific applications to remote communicates and remote mining installations
- Extending the use of the software to grid connected microgrids, with a focus on including the provision for ancillary services

Work carried out by PhD candidate Mike Quashie, with the inclusion of the work of MEng student Shijie Qin (thesis finalized June 2015)

Project 2

- Extending the methodology to develop a business case specifically for different storage approaches applied to microgrids, particularly battery technologies developed by industrial partner Hydro-Quebec and an alternative, compressed air technologies developed by another McGill industrial partner, with applications to both isolated and remote microgrids and grid connected microgrids

- Design of the controller for optimization of isolated power systems and implementation on a Real Time Simulator (OPAL-RT)

Work carried out by PhD student Prashant Tiwari based in part on the software described in the previous project

Collaborations in Year 5

1. Collaborating with Prof. Raad Jassim (Finance at McGill) to establish and verify financial models developed under this project.
2. On-going Collaboration with Prof. Francois Bouffard (McGill) to test and strengthen the optimization algorithm developed.
3. Collaboration with other members of the Network to develop business case for mining Microgrid grid and methodology to quantify benefit of ancillary services.
4. On-going collaboration with Dr. Steve Wong (NRCan-CANMET, Network partner) to optimize the quantified benefit of Ancillary services. Anticipated deliverable is a publication on co-optimization of microgrids to provide ancillary services.
5. On-going collaboration with Lawrence Berkeley National Laboratory (LBNL, USA) through the use of the commercial software DER-CAM to verify results of the EXCEL-based software tool developed under this project. Collaboration included 4 months training/internship for project student under the supervision of Dr. Stadler, Michael Stadler, Research Scientist, which provided student the opportunity to do preliminary comparison and validation of results of the developed optimization methodology under this project with acceptable packaged software. The student will apply the acceptable packaged software (DERCAM) in evaluating the planning and optimization strategies of demonstration microgrids particularly remote mines microgrid. The results of the application will be used as one of the validation mechanisms for the optimization tool developed under project 2.1. The student was also provided the opportunity to interact with other researchers/affiliates working in related research areas.

Project 2.2: Energy and Supply Security Considerations

Project Leader: Reza Iravani (University of Toronto)

Project Started: October 2010

Expected Completion Date: March 2016

Milestones Progress in Year 5

In Year-5, in continuation and according to the objectives/milestones of Year-1 to Year-4, we:

- Investigated the impact of cyber layer failure/malfunction/hacking on the microgrid controllers developed in the year-2 to year-4 of the program. The work based on off-line simulation studies is 100% complete, however, in year-5 we have initiated hybrid real-time simulation of both physical and cyber layers in RTDS and Opnet platforms, respectively. In progress (90% completed)
- Developed a methodology to quantify the impact of high-depth of penetration of renewable resources on
    a. reliability of supply (100% completed),
    b. life-time reduction of legacy components subject to intermittency of renewables, e.g., switched capacitors, on-load tap changers (100% completed),
    c. resiliency (90% completed).
- Collected data from multiple utilities to validate the strategy behind the methodology and verify the results. In progress (90% complete)
- Extended the methodology to investigate mutual impacts of multiple microgrids on each other in terms of items (i), (ii), and (iii) above. In progress (90% complete)
- Collected data from multiple utilities in terms of maintenance scheduling and failures history of components apparatus to determine cost associated with items (i), (ii) and (iii) above. In Progress (90% completed)
- Developed a data analytic approach based on PYTON software to handle massive data corresponding to the above item in an automated manner to (a) input to the analysis engine, e.g, power flow, transient stability, and electromagnetic transients types of programs, and (b) correlation of the study results. (100% complete)

Research Plans for No-Cost Extension Period

Application, performance evaluation, and verification of the developed strategies and corresponding algorithms of the milestones of year-5 (above box) to a real large-size interconnected power system with multiple microgrids. The selected system is the new-York/New-England interconnected system which includes nine microgrids, in close electrical proximity, in the New-York city area. The test cases include:

- impact of high-depth of bulk intermittent generation, e.g., up to 35% wind power, on the dynamic behavior and dynamic interactions of the multiple microgrids,
- impact of a major lose of generation or transmission which triggers a cascading failure event, on the ability of microgrids to properly island and continue islanded operation to enhance resiliency and continuity of supply for selected and/or partial load scenarios,
- evaluation of the system dynamics on the assets in terms of loss of life,
- evaluation of the degree of asset utilization,
- quantification of "tear and wear" due to generation intermittency and multi-mode operation.

Collaborations in Year 5

Research Partners

- University of Toronto, Prof. George Anders
- University of Waterloo, Prof. Claudio Canizares
- Ryerson University, Prof. Amirnaser Yazdani

Industrial Partners

- Hydro One
- Quanta Technology
- Toronto Hydro
- Power Stream

International Collaborations

- Norwegian Institute Science and Technology

Project 2.3: Demand Response Technologies and Strategies - Technologies and Metering

Project Leader: Kankar Battacharya (University of Waterloo)

Project Started: October 2010

Expected Completion Date: March 2016

Milestones Progress in Year 5

Milestone 2.3a: Sustainability consequences (environmental, economic and social impacts) of increased use of microgrids [2011-01-01 to 2011-12-31]: the sequence of this milestone has been moved to the period [2015-10-01 to 2016-04-30]. This milestone is now in progress. PhD student Bharatkumar Solanki is focussing on this aspect. Research is underway on environmental impact assessment of demand response schemes. A paper will be submitted for the forthcoming IEEE PES GM of 2016.

Milestone 2.3b: Modeling and scenario analyses, data collection [2012-01-01 to 2012-12-31]: Significant work has been carried out in this milestone. Data collection work was not undertaken, but we are using data from other sources to develop load estimation models for demand response studies. These models are being integrated with microgrid operations models and very interesting results have been obtained. A paper has been submitted to IEEE Transactions on Smart Grid based on this work. This milestone is almost complete.

Milestone 2.3c: Determining cost and benefits [2013-01-01 to 2013-12-31]: Significant work has been carried out in this milestone.

Milestone 2.3d: Energy-aware scheduling algorithms- proposing an algorithm for internal microgrid load balancing capability [2013-01-01 to 2013-12-31]: Significant work has been carried out, and some research is in progress. PhD student Mostafa Farrokhabadi is working on this problem and is the focus during the current year.

Milestone 2.3e: Formulation of the optimization problem with constraints on reliability and network capacity [2014-01-01 to 2014-12-31]: Comprehensive work has been carried out on microgrid modeling and optimization, as well as network modeling. This milestone was taken up earlier than proposed. Some further research is in progress with regard to microgrid impact analysis for various demand response models, but the milestone is completed.

Research Plans for No-Cost Extension Period

During the extension period, we will focus on Milestone 2.3a, which is environmental impact analysis from demand response by developing appropriate mathematical models and quantification of the savings, both from emissions and cost perspectives, for the microgrid, the customers and the society. We will examine various renewable sources for comparison and effectively determine the long-term penetration of demand response and renewables to achieve emission reduction targets.

Collaborations in Year 5

- Some models and parameters have been shared with other researchers in theme 3 (J. Meng group)
- Noise Measurements are being carried out with the collaboration of Hydro-Quebec, within their premises.

Project 2.5: Integration Design Guidelines and Performance Metrics

Project Leader: Geza Joos (McGill University)

Project Started: October 2014

Expected Completion Date: March 2016

Milestones Progress in Year 5

1. Compile microgrid models, including the power systems and the control and communications systems (2014) – on-going, report to be completed second quarter – most university partner and research laboratory visited and technologies developed compiled

2. Define system studies (2014) – on-going, report to be completed second quarter – discussion are ongoing with BCIT to obtained BCIT microgrid data to start the design and implementation of Network technologies

3. Compile the control systems and approaches implemented in the microgrids used in and meeting the requirements of Theme 1 (Microgrid Operation and Control) and Theme 2 (Microgrid Planning, Optimization and Regulatory Issues) – on-going

4. Compile the information and communication systems implemented in the microgrids used in and meeting the requirements of Theme 3 (Microgrid Communication and Information Technologies) – on-going

5. Define case studies and use cases (2015) – not started, due to start third quarter of 2015

Research Plans for No-Cost Extension Period

As per original scope of work:

- Analyze and provide a critical assessment of the modeling detail and the model detail tradeoffs, and recommend modeling details as appropriate for the type of study to be performed
- Define a modeling approach that combines the power and communication systems, allowing a complete system study
- Define typical system studies and requirements associated with the operation of the microgrid, in grid connected and islanded operation, based on the work carried out in other Network projects in all three Themes, identifying the systems required for case studies, including the appropriate benchmark systems and components
- Determine a set of system sample case studies required for the study of the various microgrid operating scenarios and contingencies, for real time operation (voltage and frequency control, protection, islanding and reconnection), and energy management of the generation, storage and loads within the microgrid, in islanded and grid connected modes
- Develop use cases for the sample case studies defined above
- Validate the models with field results from BCIT microgrid and Hydro-Quebec Test-line (as applicable).

Collaborations in Year 5

- University: the researchers have carried out site visits to all participating university laboratories (T Broeer), and are interacting closely with the BCIT team managing the BCIT microgrid to identify transferrable network research results and technologies; they will follow up with the university research project and theme leaders as they progress in completing the Network report so as to validate their findings and conclusions.
- Network partners.

Project 3.1: Distribution Automation Communication

Project Leader: Fabrice Labeau (McGill University)

Project Started: April 2014

Expected Completion Date: March 2016

Milestones Progress in Year 5

1) Use existing measurements taken in the framework of another project within Hydro-Quebec substations as a starting point. These measurements concerns wideband data, and we have started the operation of digitally filtering these measurements to give them a narrowband characteristic around 1800 MHz. Initial modeling.
2) Start a new measurement campaign around the 700 MHz (LTE) band. A first wave of measurements has been made with the help of Hydro –Quebec collaborators.
3) We have explored the design of optimal receivers for the most recently developed substation electromagnetic noise model, i.e. a multi-state partitioned Markov chain. A journal submission is in preparation to summarize this work.
4) Application of impulsive noise models and receivers to cooperative schemes.
5) Study of distributed algorithms in substation impulsive noise

Research Plans for No-Cost Extension Period

Use the optimal receiver models developed up to now to create cooperative, relay-based systems for transmission in substations.

Project 3.2: Grid Integration Requirements, Standards, Code and Regulatory Considerations

Project Leader: Tho Le-Ngoc (McGill University)

Project Started: October 2010

Expected Completion Date: March 2016

Milestones Progress in Year 5

Project 3.2 deals with the issues of grid integration requirements, standards, codes and regulatory considerations in intelligent microgrids. Specifically, it aims to study and to develop efficient transmission, information processing, and networking techniques and strategies suitable for a robust communications infrastructure that supports the integration of intelligent microgrids. The milestone set for the fifth year (2014-2015) is "Development and evaluation of integration strategies for transmission, information processing and networking architectures, based on available and emerging communications technologies". Progress highlights for the 12 months for October 1st 2014 to September 31st 2015 are given in the following:

1. After completing various studies on the performance and feasibility of Greedy Perimeter Stateless Routing (GPSR) and the Routing Protocol for Low Power and Lossy Networks (RPL) in microgrid communications networks [1], we have focused on the robustness and Quality-of-Service differentiation of the RPL. Firstly, since almost all smart meters and other microgrid communications devices are deployed in hash outdoor environment, they could fail or wireless links between them could be fluctuating over time. These dynamics could hinder the network connectivity and degrade the reliability of data communications. Therefore we proposed a cross-layer scheme, namely, Proactive Parent Switching (PPS), which effectively helps the RPL deflect network traffic from points of failures in microgrid communications networks. We have implemented the PPS in our network simulation platform. The robustness of the PPS in an IEEE 802.11-based microgrid communications networks with various levels of network availability has been evaluated by extensive simulations [3]. Secondly, we have investigated the capability of multiple-instance RPL for QoS differentiation in Microgrid Communications Networks (MCNs). The performance of multiple-instance RPL in various typical MCN scenarios are studied [4].
2. We have completed a comprehensive survey on network coding and selected candidate schemes that can be used jointly with routing protocols in microgrid scenarios. Basically, with network coding, intermediate nodes in the network transmit an algebraic combination of the received packets. Since each native packet can be disseminated throughout the network over space and time via coded packets, this diversity allows for enhanced throughput and/or reliability. We completed the implementation of candidate network coding schemes that could be used jointly with the RPL routing protocol. Currently, we are investigating the requirements (signaling overheads, computation and processing) versus performance gains (network throughput and transmission reliability) of those schemes in microgrid communications networks [5].
3. We are developing Software-Defined Radio Access Network (SD-RAN) techniques for microgrid communications. SD-RAN incorporates a number of emerging technologies that make wireless access networks programmable and less expensive to build and operate. This is achieved by separating the control and the data-forwarding functions of network equipment, and centralizing the control functions of multiple network elements. SD-RAN also enables automatic and efficient management of multiple access network elements. We are particularly working on network architecture, structure and implementation of reconfigurable software/firmware in wireless access

devices, and networking protocols to enable software-defined microgrid communications networks [6].

4. We studied the optimal signaling scheme and capacity of the Bernoulli–Gaussian impulsive noise channel to shed new light on the impact of impulsive noise on spectral efficiency of power-line communications systems. First, by focusing on the practically typical case with impulse power that is much higher than signal power, we developed a tight approximation to the differential entropy of Bernoulli–Gaussian noise. Closed-form tight lower and upper bounds on the capacity are then derived. By comparing these bounds, it is demonstrated that the capacity decreases with an increasing impulse occurrence rate and the Gaussian signaling scheme is nearly optimal. We then focus on the case with an impulse power lower than signal power to develop tight lower and upper bounds. We subsequently showed that the Gaussian signaling can approach the capacity in this region as well. In addition, channel erasure is shown to be very effective for the impulsive noise channel when impulse power is higher than signal power, but it introduces rate loss when impulse power is sufficiently lower than signal power. Illustrative simulation results confirm the analytical derivations and show their applications to estimate the maximum achievable rate of a power-line communication link with practical parameters [2]. We also further studied the characterization of the optimal input and the computation of the capacity of additive quadrature Gaussian-Mixture (GM) noise channels under an average power constraint. We demonstrated that the optimal input has discrete amplitude with a finite number of mass points, and developed a simple method to compute the discrete optimal input and the corresponding capacity. Our numerical examples show that in many cases, the capacity-achieving distribution consists of only one or two mass points [3].

[1] Quang-Dung Ho, Yue Gao, Gowdemy Rajalingham and Tho Le-Ngoc, "Geographic-based Routing in Smart Grid's Neighbor Area Networks", REV Journal on Electronics and Communications (REV-JEC), vol. 3, no. 3-4, July December 2013, pp. 110-115.

[2] S. P. Herath, Nghi H. Tran, Tho Le-Ngoc, "Optimal Signalling Scheme and Capacity Limit of PLC under Bernoulli Gaussian Impulsive Noise", IEEE Transactions on Power Delivery, Vol. 30, No.1, February 2015,pp. 97-105.

[3] Hung V. Vu, Nghi H. Tran, Mustafa Cenk Gursoyz, Tho Le-Ngoc, S. I. Hariharan, "Capacity-Achieving Input Distributions of Additive Quadrature Gaussian-Mixture Noise Channels," to appear in IEEE Transactions on Communications.

[4] Quang-Dung Ho, Yue Gao, Gowdemy Rajalingham and Tho Le-Ngoc, "Robustness of the Routing Protocol for Low-power and Lossy Networks (RPL) in Smart Grid's Neighbor-Area Networks", IEEE International Conference on Communications (ICC 2015) , London, United Kingdom, 8-12 June, 2015.

5] Gowdemy Rajalingham, Quang-Dung Ho, and Tho Le-Ngoc, "Multiple-instance Low-power and Lossy Networks (RPL) Routing Protocol for QoS Differentiation in Microgrid Communications Networks – the Burwash Landing (Yukon, Canada) Case Study", Technical Report, Broadband Communications Lab, McGill University, July 2015.

[6] Gowdemy Rajalingham, Quang-Dung Ho, and Tho Le-Ngoc, "Network-coded Low-power and Lossy Networks (RPL) Routing Protocol for Converge-casting in Microgrid Communications Networks", Technical Report, Broadband Communications Lab, McGill University, March 2015.

[7] Quang-Dung Ho and Tho Le-Ngoc, Network Architecture, Signaling Protocols, and Experimental Platform for the Integration of Software-Defined IEEE 802.11/WiFi Access Technologies into Intelligent Microrgrid, Technical Report, Broadband Communications Lab, McGill University, May 2015.

Research Plans for No-Cost Extension Period

Software-Defined Networking (SDN) and Software-Defined Networks (together with cloud computing) have been gaining a lot of attention in the last five years as the emerging communications technologies and a new service oriented communications network paradigm of future communications infrastructures. Numerous advantages including programmability, flexibility, collaborative resource management, and so on, given by SDN could have tremendous potential to address challenges in

Intelligent Microgrid communications networks due to their large-scale, heterogeneous, and distributed nature. Therefore, for the period from October 1st 2015 to March 31th 2016, the following tentative work items are the focus:

1. Studies and development of interworking and integration strategies to support the integration of Intelligent Microgrids over SDNs;

2. Simulation to model some illustrated realistic integration cases of Intelligent Microgrids over SDNs and evaluate their performance.

Collaborations in Year 5

- We met Torsten Broeer (December 2014) and had detailed discussions with him to help him have a better understanding about the ongoing research within the research network and to facilitate the inclusion of our work in the summary report.
- Also, we have been working with Researchers in Themes 2 and 3 to discuss, plan and coordinate various research subjects

Project 3.3: Distribution Automation: Sensors and Condition Monitoring

Project Leader: Julian Meng (University of New Brunswick)

Project Started: October 2010

Expected Completion Date: March 2016

Milestones Progress in Year 5

- 1 PhD, 1 M Sc and 2 undergraduate students are currently working on the project.
- 25 sensor nodes have being constructed and will be deployed with industry partners and research labs for testing.
- 4 gateway access nodes with cellular capabilities have been constructed. This will provide an access point for sensor data.
- A higher layer software application is being developed using Thingspeak for cloud network configuration, data collection, data management and data visualization.
- Implemented and tested a simple, sample-by-sample data compression algorithm on sensor node.
- Application development: Implemented and tested a fault detection relay algorithm (Phase lock loop, DQ transform, Wavelet transform) on a sensor node. Performed line to ground & line to line faults. Result: successful performance as node detected and tripped a relay within 1/8 to 1/4 of a cycle (to standard).
- Built I_2C drivers for sensor nodes for logic output and relay control.
- Developed and tested an Earliest Deadline First Prioritization algorithm for the gateway node for the purposes of priotization data stream from various nodes.
- Analysis of communication performance of the current nodes and gateway architecture. Detection of minimum transmission power and latency times that ensures effective communication. The output will be the characterization of different communication scenarios, delays and throughputs.
- Wireless network simulation of an IEEE 802.15.4 based WSN with prioritized end devices and cellular communication.

Research Plans for No-Cost Extension Period

- Continued work on compression of Electrical Signals. The topic of compression of electrical signals using the computing capabilities of the sensor nodes. We will test several low-complexity, high performance compression algorithms and determine the computing complexity required.
- Continued improvement and calibration of current node applications, and development of new ones.

The nodes will be easily configured to allow deployment of arbitrary networks depending on the application.

- Continued evaluation the processing capabilities of the nodes using DSP libraries and specific algorithms for further migrogrid applications.
- Continued development of Thinkspeak-based sensor network configuration management.
- Deployment of sensor networks in microgrid laboratories and industry partner scenarios to assess operational capabilities.

Collaborations in Year 5

- NB Power
- Saint John Energy

Project 3.4: Integrated Data Management and Portals

Project Leader: Hassan Farhangi (BCIT/Simon Fraser University)

Project Started: October 2010

Expected Completion Date: March 2016

Milestones Progress in Year 5

The main objective of Project 3.4 is to investigate system level issues associated with microgrid applications which require access to real-time or quasi real-time data. To study this, Project 3.4 has chosen a typical Microgrid function such as Volt-VAR Optimization (VVO), as a vehicle to find an optimal system topology, capable of improving the functionality of an existing Microgrid/Smart-Grid function using new data streams.

P3.4.1 (VVO Engine)

1. Completed design of Quasi Real-time Smart Grid-based Volt-VAR Optimization Engine.
2. Completed design of Predictive VVO Engine able to optimize distribution grids.
3. Designed a Quasi-Real-time Sliding Window for proposed VVO optimization engine.
4. Designed a Selective VVO Engine in presence of different selective objective functions.
5. Completed working on Maintenance Scheduling issue of Volt-VAR Control Assets.
6. Completed studies related to V2G, EV, Micro-CHP/PV penetration impacts on AMI-Based VVO.
7. Completed Conservation Voltage Reduction (CVR) Analysis.
8. Studied impact of network re-configuration on proposed quasi real-time VVO.
9. Completed working on the optimization approach (Improved GA and Particle Swarm Optimization applied as optimization techniques).
10. Finalized proposed VVO engine: Checked performance of the engine in different operating conditions. The results have been validated through a real-time co-simulation environment comprised of real-time digital simulator (RTDS), VVO engine, Volt-VAR control component's model and reliable communication platform working with DNP.3 protocol or IEC-61850 MMS and GOOSE.
11. Studied DNP.3 protocol and IEC-61850 MMS & GOOSE for communication platform of VVO application though co-simulated environment.
12. Continue working on VVO in presence of community energy storage systems.
13. Continue working on VVO integration with short-term planning of distribution networks.
14. Continue working on cost/benefit analysis of proposed VVO.

P3.4.1 (AMI Data Disaggregation)

1. An appliance inference algorithm is developed based on AMI data measured at 1-hour frequency, Canadian appliance ownership survey, and surveys on appliance usage patterns. The algorithm implements parallel optimization of power matching and likelihood maximization in an iterative fashion to account for uncertainties in data. Given the hourly power consumption, dwelling type, heating type, and etc. of a residence, the algorithm is able to discern different appliances and their power characteristics.

2. An electric load disaggregator is developed based on the appliance inference algorithm. The disaggregator implements a multi-objective optimization of real power matching, reactive power matching, and on-probability maximization. Appliance dependency rules and seasonal variances are integrated to tune the optimization results. The disaggregator is able to disaggregate loads in a residence with moderate accuracy by only referring to the 1-hour AMI data.

Research Plans for No-Cost Extension Period

- Investigating Community Energy Storage (CES) impact on Smart Grid Volt-VAR Optimization of distribution networks. Designing a management system for VVO and CES in order to support reactive power compensation.
- Studying distribution network planning improvement using proposed VVO engine.
- Perform cost/benefit analysis as well as risk assessment for proposed VVO engine.
- Studying the impact of decentralized VVO on other parts of the grid (sub-transmission, transmission) and evaluating the robustness of proposed VVO in different operating conditions of microgrids such as islanding.
- Patenting proposed VVO.

Collaborations in Year 5

- Moein Manbachi was attached to ACS Lab of the University of Aachen during the reporting period to work with Prof. Monti on co-simulation technologies related to his VVO engine. The work was extremely successful, producing one conference and two journal papers jointly developed between NSMG-Net P3.4 researchers and the University of Aachen.
- NSMG-Net P3.4 worked closely with BC Hydro to develop a novel inference algorithm to be validated for AMI data disaggregation.

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