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Realizing a Smart MicroGrid - Pioneer Canadian Experience

Mohamed Zakaria Kamh, *Member, IEEE,* Reza Iravani, *Fellow, IEEE* and Tarek H.M. EL-Fouly, *Member, IEEE*

***Abstract*—This paper outlines the main accomplishments towards realizing a Smart Microgrid Testbed at the British Columbia Institute of Technology (BCIT), Burnaby, BC, Canada. The paper describes a methodology to optimally select, site, size, control, and integrate distributed generation and storage units with the existing Campus power system. The proposed approach enables optimal operation of the Campus power system in both grid-tied and autonomous modes of operation. Two control strategies are selected, implemented, and tested to permit the safe and efficient integration and operation of the on-site DER units into the Campus power system during the grid-tied and islanded modes of operation. Moreover, a smart and accurate fault detection, isolation, and service restoration (FDISR) algorithm is proposed and implemented, based on a bi-directional communication infrastructure, to support the Campus power system operation in the presence and absence of the utility bus. Finally, the results of a case studies are reported and analyzed to evaluate the impacts of the proposed power management and control strategies on the performance of the BCIT Microgrid as well as the interaction between different on-site DER units and the utility.**

***Index Terms*—Distributed Energy Resources, Smart grid, Microgrid, Dual-Mode Control**

I. Introduction

The British Columbia Institute of Technology (BCIT) Campus in Burnaby, BC, was selected to be the site of Canada's first intelligent microgrid testbed. A microgrid is a cluster of distributed energy resource (DER) units that are served by a section of distribution network and can operate in grid-connected mode, islanded (autonomous) mode, and the transition between the two [1], [2]. The BCIT microgrid testbed is an ideal environment for the integration, testing and qualification of technologies and solutions required for Canada′s future Smart Grid [3]–[6].

The scope of this research project is divided in two major phases. In phase-I, the objectives are to (i) model and simulate the BCIT Campus in a time-domain simulation platform, (ii) select the technologies for distributed energy resource (DER) units, (iii) optimally size and site the selected DER units to minimize the power exchange with the utility (BC Hydro), (iv) develop a power management approach to integrate the DER units in grid-tied and islanded modes of operation, and (v) to develop and implement efficient strategies to control and coordinate the multiple on-site DER units in both modes of operation [7]. In the second and final phase of the project, the scope is to deploy the sophisticated on-site sensors, meters, and protective and controls equipment to realize an intelligent Fault Detection, Isolation, and Service Restoration (FDISR) strategy that could be triggered in case of unhealthy microgrid operation to minimize the duration of service interruption, thus improve the system reliability [8].

This paper describes the proposed methodology to optimally select, site, size, control, and integrate distributed generation and storage units within the existing Campus power system. The rest of the paper goes as follows. In Section II, the existing Campus power system is described. In Section III, the DER technology selection criteria is stated along with the DER units' optimal siting, sizing, and power management strategies. Section IV outlines the DER control strategies that are implemented to enable the safe operation of the multiple on-site DER units during the grid-tied and autonomous modes as well as the transition between both. In Section V, a smart and fast FDISR algorithm is proposed and implemented, based on the IEC-based bi-directional communication infrastructure existing in the BCIT Campus, to support the operation in the presence or absence of the utility bus. Section VI presents the results of one of several case studies that have been conducted to evaluate the impacts of the proposed power management, control strategies, and FDISR algorithms on the performance of the BCIT Intelligent Microgrid as well as the interaction between different on-site DER units and the utility. The main conclusions are outlined in Section VII.

II. Existing BCIT Campus Power System

Figure 1 shows the BCIT Campus, with the main serving areas of the Campus power system.

The Campus power system comprises four main serving areas:

1) Canada Way Receiving Station Serving Area (marked in blue in Fig. 1) is fed from BC Hydro via a 12.47 kV feeder.
2) Goard Way Receiving Station Serving Area (marked in green in Fig. 1) is fed from BC Hydro via a 12.47 kV feeder.
3) Residential Serving Area (marked in red in Fig. 1) is fed from BC Hydro via a 12.47 kV feeder.
4) Small load centers fed from BC Hydro via dedicated BC Hydro-owned power transformers.

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M.Z. Kamh is with Hatch Ltd., 2800 Speakman Drive, Mississauga, Ontario, L5K 2R7 Canada. Email: mkamh@hatch.ca

R. Iravani is with the Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, Toronto, Ontario, M4Y 1R5, Canada. Email: iravani@ecf.utoronto.ca

T.H.M. El-Fouly is with CanmetENERGY, Natural Resources Canada, 1615 Lionel-Boulet Blvd., P.O. 4800, Varennes, Quebec, Canada J3X 1S6Email: telfouly@nrcan.gc.ca

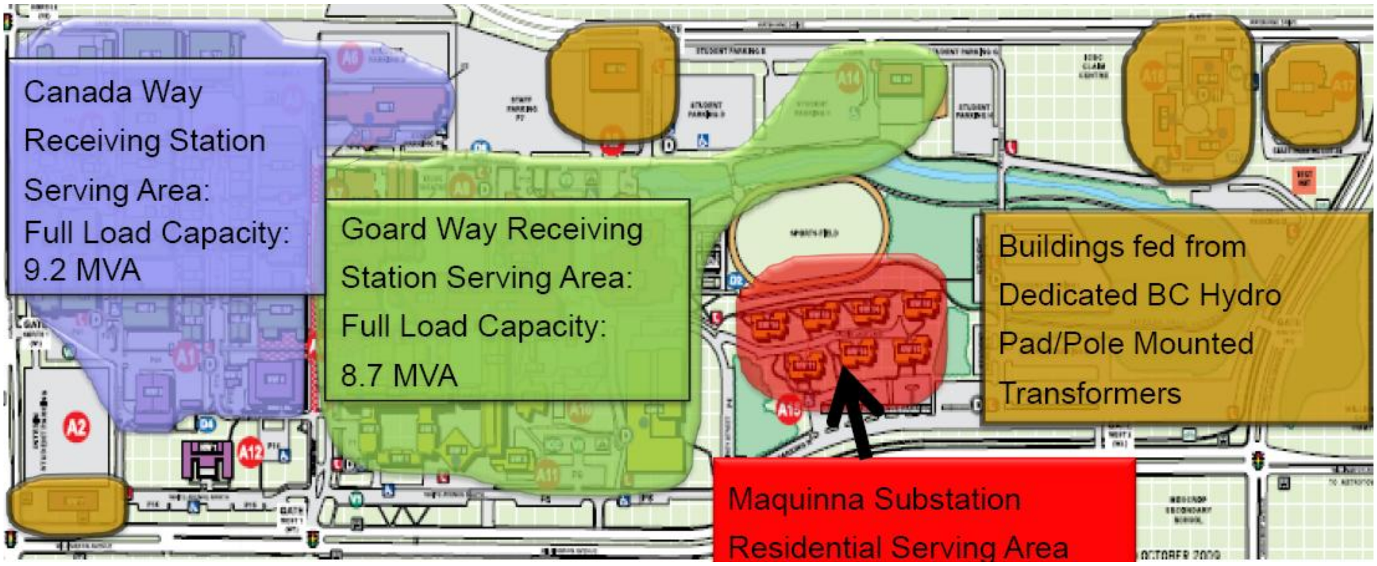


Fig. 1. BCIT Campus Plan and Microgrid Serving Areas.

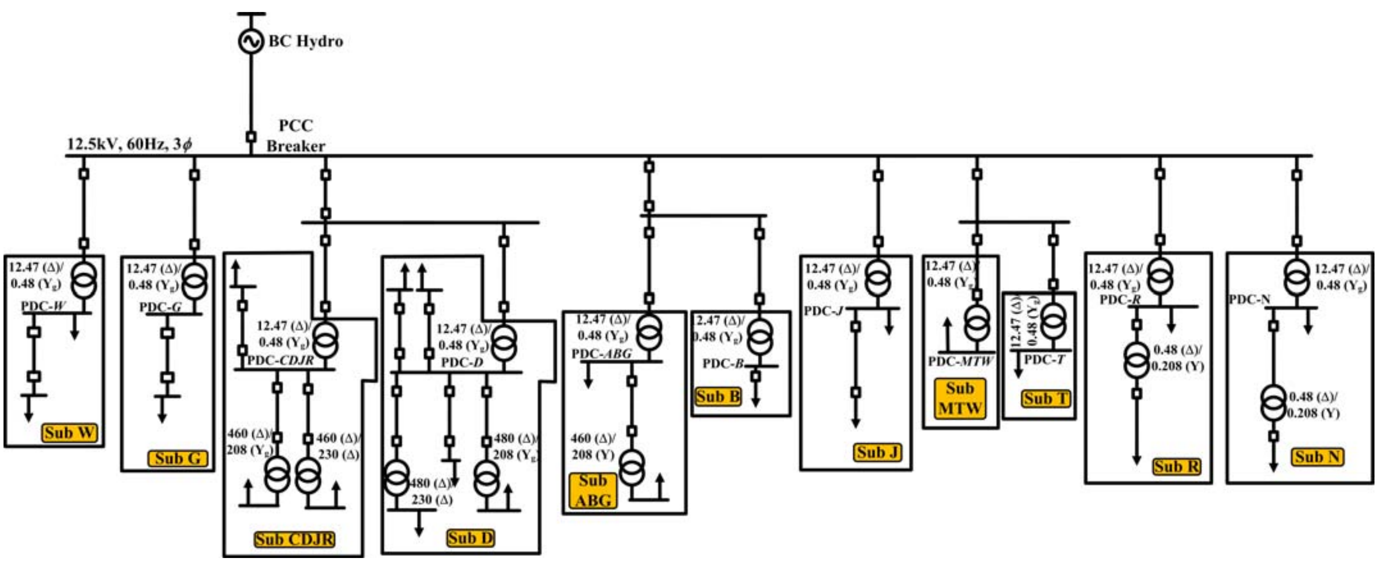


Fig. 2. Single Line Diagram of the Canada Way Receiving Station Serving Area

The largest Campus load centers are the Canada Way and Goard Way Receiving Stations Serving Areas. Their combined loads represent more than 70% of the total Campus electric load. The loads within each of these two serving areas are fed via BCIT-owned 12.5 kV distribution network, each of which is fed from an independent BC Hydro point of feed. Due to space limitation, the discussion throughout the rest of this paper will focus on the model and results associated with the Canada Way Receiving Station Serving Area. However, complete results and discussion can be found in [7] and [8]. Figure 2 represents the single line diagram of Canada Way Receiving Stations Serving Area.

III. Optimal Technology Selection, Sizing, and Siting of DER Units

A. DER Technology Selection

1) Distributed Generation (DG) Technology: Due to the site specific conditions and to realize the study scope, the most suitable DG units were selected based on the following selection criteria:

- Size Compactness: As such, wind turbine-generation units (WTGUs) are excluded.
- Dispatchability: Consequently, solar photovoltaic panels are excluded.
- Flexibility in Control and Islanding Detection: The conventional constant-speed synchronous machine-based units are excluded.

Based on this selection/exclusion criteria, the most suitable DG technology is found to be *the combined heat and power*

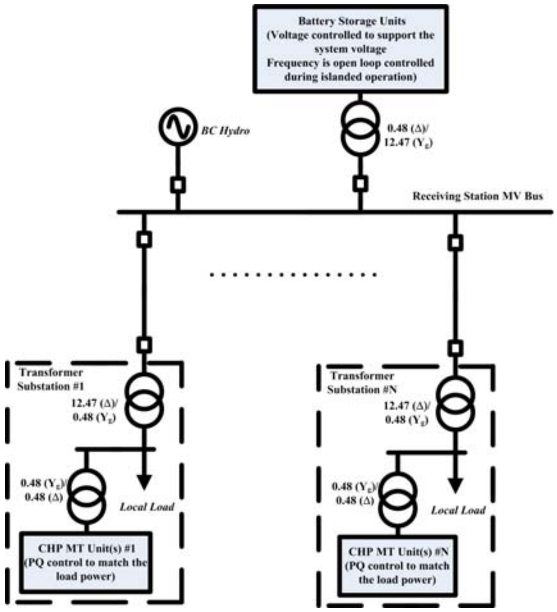


Fig. 3. Optimal location of DER units within each receiving station

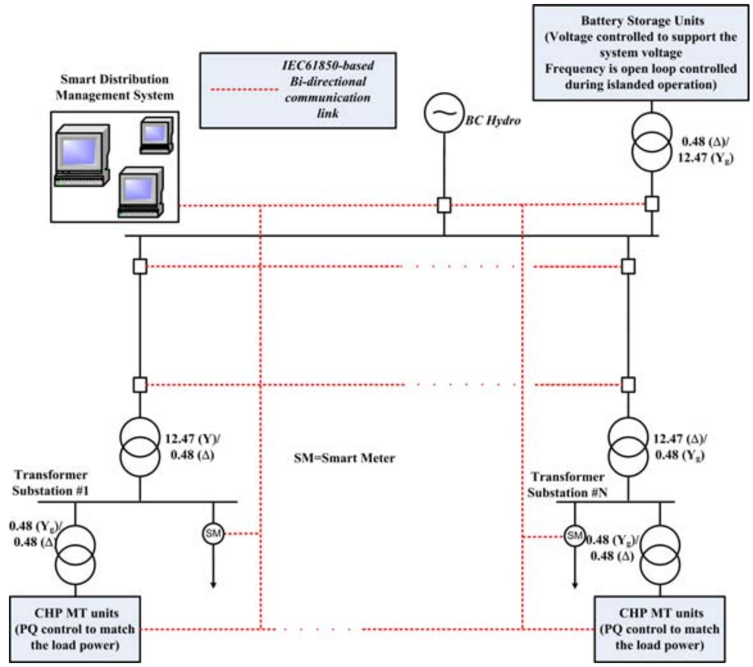


Fig. 4. IEC61850-based bi-directional communication link at the BCIT Intelligent Microgrid

(CHP) microturbines (MT) units. CHP-MT units are very efficient, compact in size (0.4 - 1 m^3), environmentally friendly, and commercially available at suitable ratings for microgrid applications. Commercial units are in the range of 30-100 kW) [9]. CHP-MT units are interfaced to the power system via voltage-sourced converters (VSCs), which are the norm of modern microgrid applications and provide flexibility in control and operation [10].

2) Distributed Storage (DS) Technology: To enable reliable operation during islanding, and minimize the power exchange with BC Hydro during the grid-tied operation, DS units should be deployed to absorb/supply any power mismatch that occurs between the campus load and DG units during different scenarios. *Deep cycle batteries* that support continuous charging and discharging were selected.

B. Optimal Siting and Sizing of DER Units

In this project, the optimality criteria are to minimize the overall system losses while guaranteeing a matched-power pre-planned islanding scenario. To realize these objectives:

- Each transformer substation will have a local DG unit connected to its low voltage primary distribution center (PDC) bus. The DG unit is rated at the substation peak load.
- The DS unit will be connected to the 12.5 kV bus of the receiving station. DS battery stations are to regulate the system voltage during islanding events. DS batteries are rated at 1.3 times the largest load fed from the receiving station to sustain potential power mismatches.

Figure 3 depicts the optimal location for the DER units within each receiving station.

C. Power Management Strategy

The following power management strategy is proposed to realize an intelligent microgrid at the BCIT Campus.

1) Grid-Connected Mode: The DG unit (CHP-Microturbine unit), connected to the low voltage bus (PDC bus) of each transformer substation, shall feed the local loads connected to its own substation. Simultaneously, the DS units, connected to the MV bus of each receiving station, shall be charged from the utility bus, and shall operate in the power-control mode.

To minimize the power exchange with the utility, these battery stations shall compensate the power mismatch arising from the loss of any of DG unit. However, in case the DS units are not appropriately charged or not in service, BC Hydro can pick up any sudden load increase or loss of DG unit.

2) Autonomous Mode: In case of loss of mains, an islanding signal is transmitted, over the bi-directional communication link already established in the Campus (Fig. 4), to the local controllers of the battery station to swicth the control strategy of the interface VSC to the voltage-controlled mode. The islanding signal is received based on communication with the Point of Common Coupling (PCC) breaker, located at each receiving end station. Once the islanding flag is raised, the battery station at each MV bus regulates the interface bus voltage at 1.0 pu. If any of the DG units is tripped out during the islanded operation, leading to significant power mismatch in the system, the DS battery stations can support the system voltage and ensure safe islanding operation, i.e., serve as the islanded system slack bus.

IV. DER Control Strategies

The on-site DER units, both DG and DS, are equipped with a dual-mode controller that can regulate either the DER unit's power exchange (PQ-control mode) or its terminal voltage and frequency (voltage-control mode), Figs. 5 and 6.

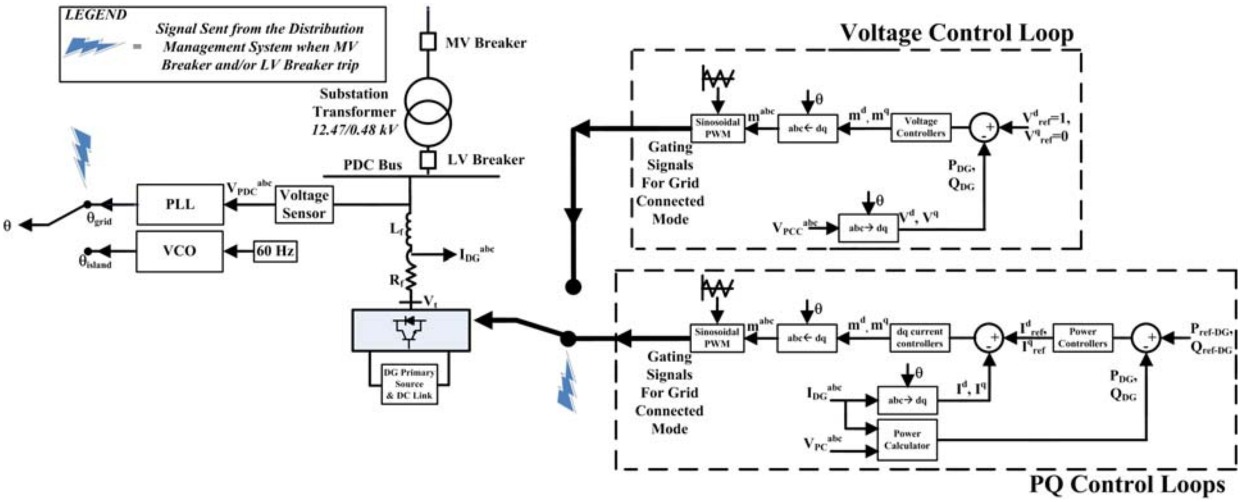


Fig. 5. Block Diagram for DG Dual-Mode Controller

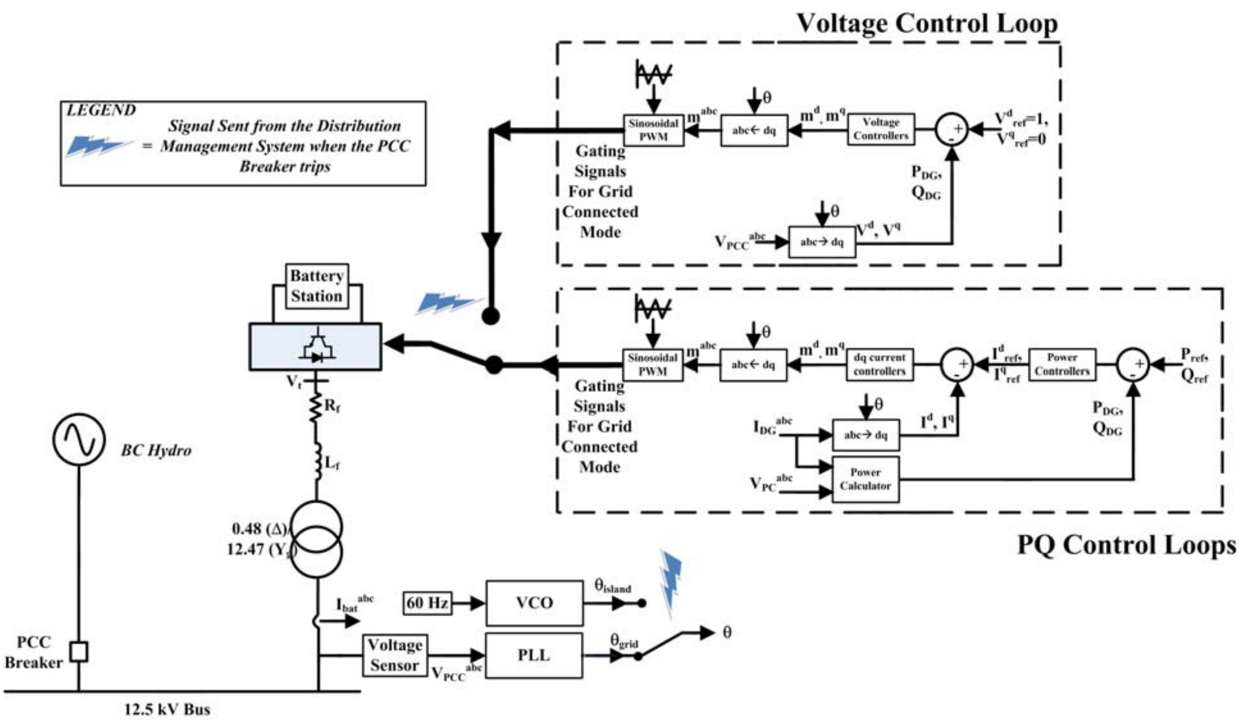


Fig. 6. Block Diagram for DS Dual-Mode Controller

In the PQ-control mode, the controller shall consist of two nested control loops [11]:

- An outer power control loop that regulates the DG real and reactive power output to track the reference power set point. This control loop dictates the reference real (d-) and reactive (q-) current components that are exchanged with the rest of the network.
- An inner dq current control loop that regulates the VSC currents by controlling the interface VSC generated voltage.

The real and reactive power set points shown in Figs. 5 and 6, P_{ref} and Q_{ref}, are dictated by a smart distribution management system to realize the power management strategy of Section III-C1. In addition, synchronization of each DER unit to the dq rotating frame at its local bus (PDC bus for DG units and the 12.5 kV bus at the receiving station for the DS unit) is based on a phase-locked loop [12]. The normal control mode is the PQ control.

In the BCIT Intelligent Microgrid, the smart distribution management system continuously monitors the status of and current through each MV breaker to instantaneously detect the islanding operation. Once the distribution management system detects that the local bus of any DER unit is isolated from the rest of the system, either intentionally or due to fault condition, it sends a signal, over an existing bi-directional communication link, to the controller of the corresponding DER unit. Once the

DER controller receives the islanding signal, the control mode is switched to voltage-control. In this mode, the interface VSC of each DER unit deploys an internal oscillator with a constant frequency of 60 Hz to generate the modulating signals, i.e., the frequency is controlled in an open loop fashion [13]. The VSC is then controlled to regulate the voltage of DER local bus at 1.0 pu. The voltage control mode and the internal oscillator are activated once the islanding status is declared.

Complete details of the controllers' parameters and PSCAD/EMTDC time-domain implementation of the BCIT Campus power system, incorporating the DG and DS units, distribution management system, and DG/DS controllers are reported in [7].

V. Fault Detection, Isolation, and Service Restoration Strategy

This section outlines the main features of the communication-based FDISR strategy for the BCIT Intelligent Microgrid.

In the BCIT Intelligent Microgid, the differential protection scheme is used to determine the faulty zones. The smart distribution management system monitors and compares, in real-time, the three-phase currents flowing through the circuit breakers at the beginning and end of each 15 kV feeder connecting a transformer substation to the receiving station bus, i.e., `Breaker_IN` and `Breaker_OUT` of Fig. 7, during both the grid-tied and islanded modes of operation.

During the normal (healthy) conditions, Fig. 7(a), currents through `Breaker_IN` and `Breaker_OUT` of each substation should be identical and in-phase. This equality also applies if a fault happens somewhere in the system but not on the feeders shown in Fig. 7(a).

Once a fault occurs somewhere on the 15 kV feeder connecting the transformer substation to the receiving station bus, the current distribution along the faulted feeder is disturbed, Fig. 7(b). If the current through the breaker `Breaker_IN-A` is not identical to that of `Breaker_OUT-A`, then a temporary flag is raised indicating a potential fault. A fault status is declared if this difference is sustained for three consecutive cycles (50 milliseconds). This delay is essential to avoid nuisance tripping due to any temporary faults or short-term disturbance.

Once the fault status is declared for any MV feeder, a trip signal is sent from the smart distribution management system to the corresponding breakers (`Breaker_IN` and `Breaker_OUT`), leading to the formation of an islanded microcell that consists of the Primary Distribution Center (PDC) bus, the local DG unit, and the local substation loads, Fig. 8. To restore the service for the islanded microcell, the smart distribution management system sends a simultaneous signal to the local DG controllers to switch the control mode from PQ control to voltage control. It should be noted that the DG voltage control mode is ONLY enabled if the PDC bus is disconnected from the rest of the Campus. Thus, during the islanded operation of the entire campus, the local DG units are PQ controlled as long as their corresponding MV feeders are healthy. A flow chart for the proposed FDISR strategy

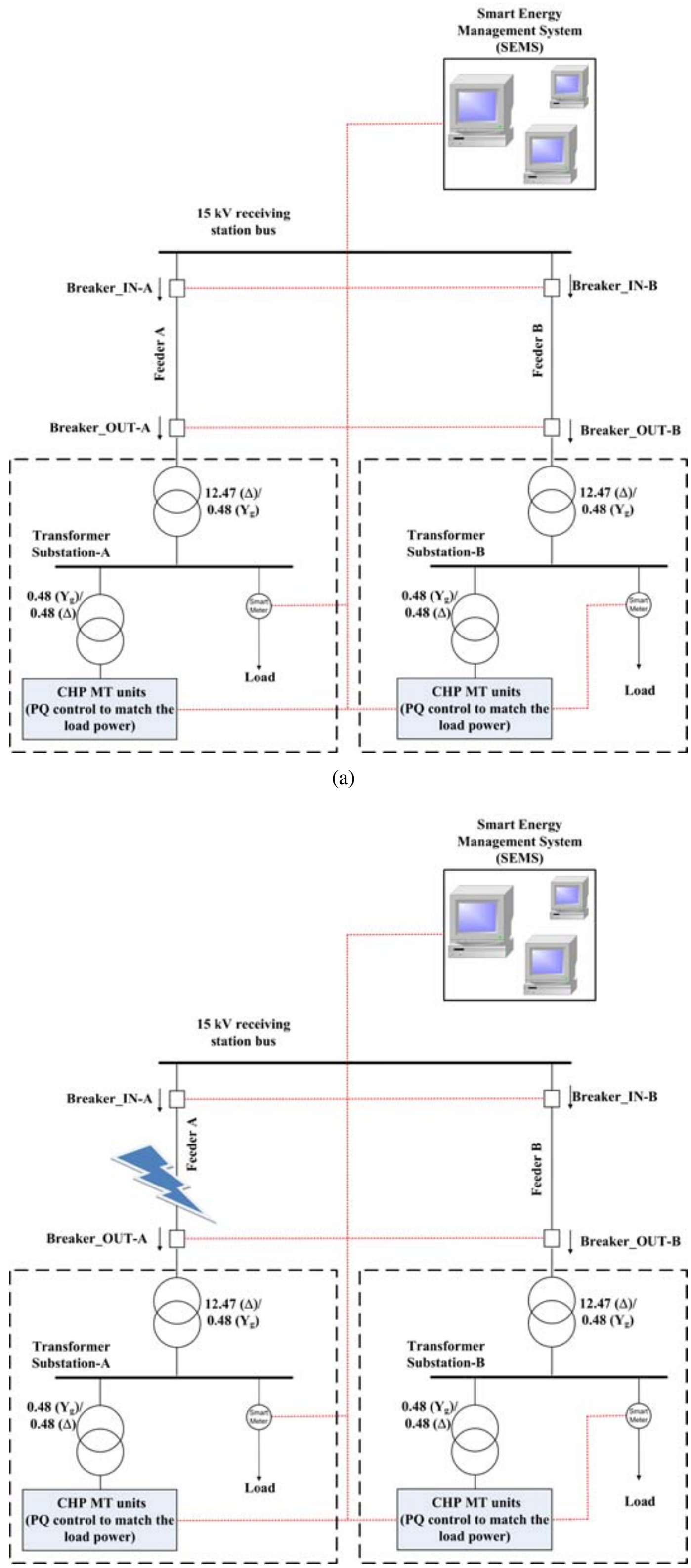


Fig. 7. Schematic representation of the Fault Detection Method; (a) healthy MV feeders and (b) one of the MV feeders is faulted

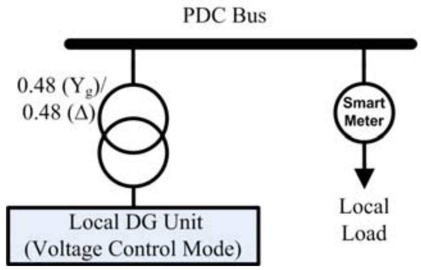


Fig. 8. Schematic diagram of an islanded Microcell formed subsequent to isolating a faulty MV feeder

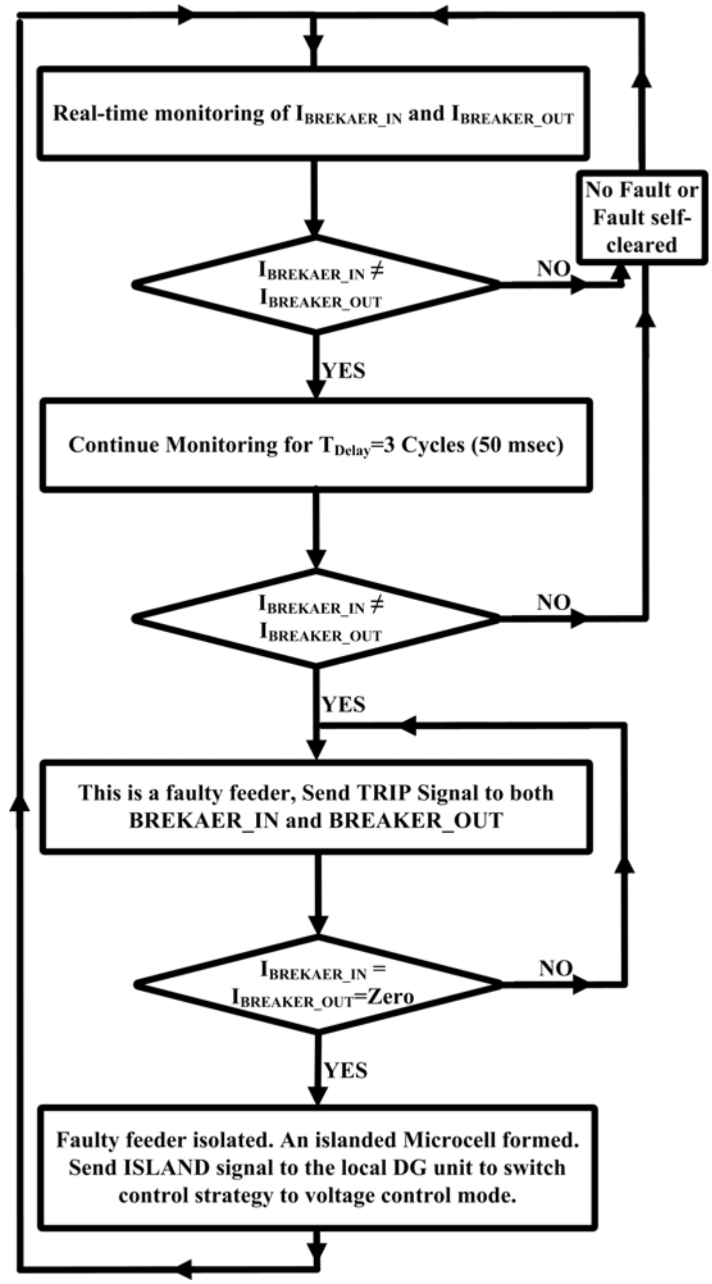


Fig. 9. Flow chart of the proposed FDISR algorithm

is depicted in Fig. 9. Complete testing and implementation details of the proposed FDISR, using the PSCAD/EMTDC platform, are presented in [8].

VI. Case Study

A detailed time-domain simulation model of the BCIT Intelligent Microgrid, including the DER units and the smart distribution management system, is built in PSCAD/EMTDC platform. The details of the model are presented in [7] and [8]. To verify (i) the efficiency of the optimal DER siting/sizing approach and the Microgrid power management strategy, (ii) the robustness of the DG/DS controllers, and (iii) the effectiveness and robustness of the proposed FDISR algorithm, a wide array of case studies and results are reported in the two final reports of the project [7] and [8]. The reported case studies cover all the possible combinations of operating scenarios during the utility-connected and autonomous modes including:

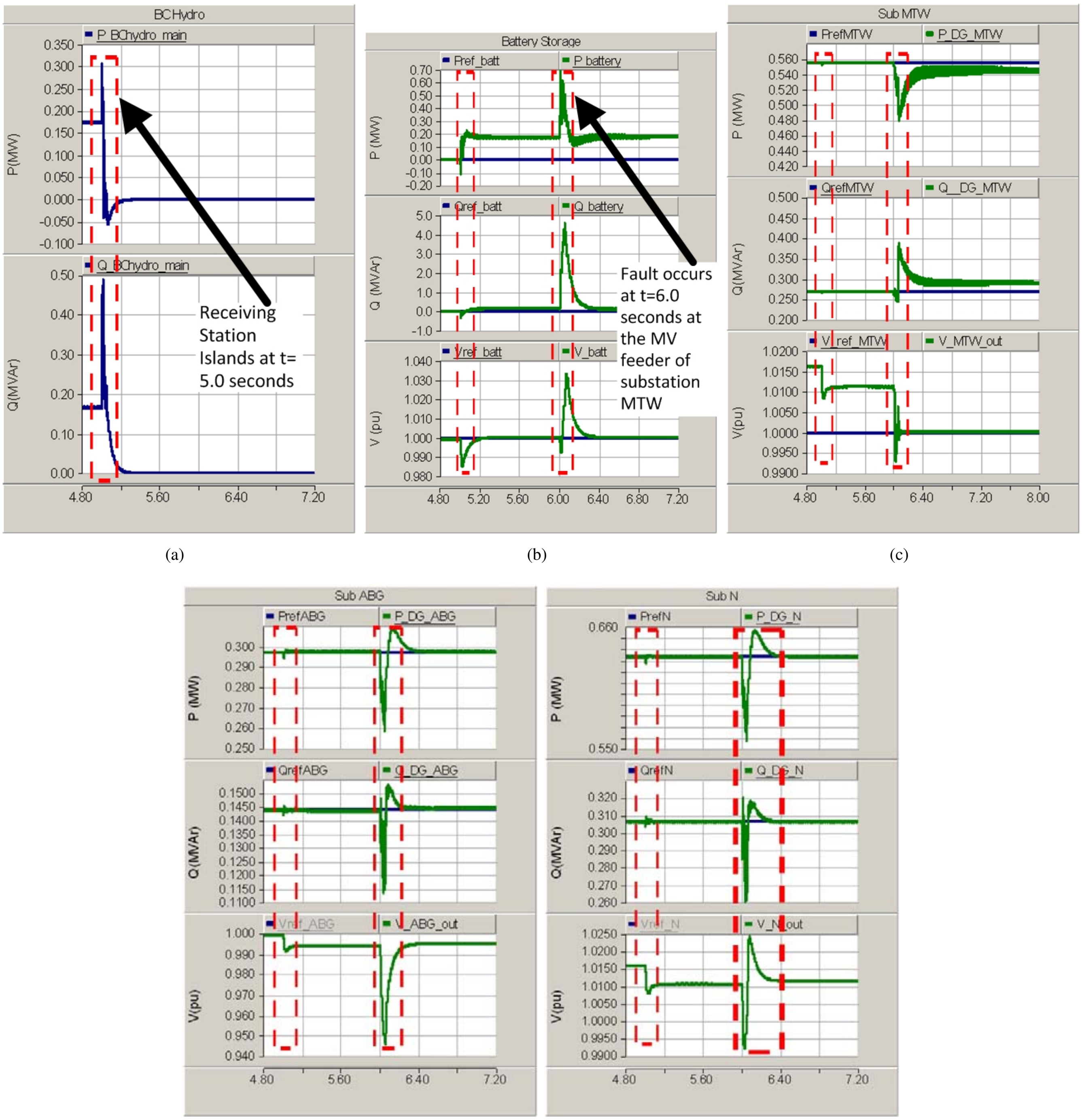
- Sudden load switching (increase/reduction)
- Preplanned load switching
- Changing the DG reference set-point
- Pre-planned DG outage
- Matched Power Islanding
- Preplanned unmatched power islanding
- Heavy loading during islanded operation
- Light loading during islanded operation
- Single phase-to-ground fault
- Double phase-to-ground fault
- Three phase-to-ground fault
- Temporary faults

The results obtained from all the above case studies verified that the performance of the DER controllers and the accuracy of the FDISR approach are independent of the BCIT Microgrid operating mode. Due to space limitations, the discussion in this paper is limited to one case study.

In the following case study, the Canada Way Receiving Station islands at t=5 seconds. Subsequently, a permanent single-line to ground fault occurs at the MV feeder to Sub *MTW*, Fig. 2, at t=6 seconds. This scenario is simulated, and some of the corresponding results are depicted in Fig. 10.

The results of Fig. 10 show that:

- During the grid-connected operation ($t < 5.0$ seconds), the real and reactive power exchange with BC Hydro, Fig. 10(a) does not exceed 4% of the total Campus load. This power exchange is essentially to compensate for the power losses in the feeders and transformers. As such, the deployed siting and sizing strategy of the DER units is efficient.
- At t=5.0 seconds, the smart distribution management system detects the islanding of the Canada Way Receiving Station, Fig. 10(a). Consequently, an islanding signal is sent to the DS dual-mode controller to switch to voltage-control mode. The DS voltage controller successfully tracks a reference set point of 1.0 pu voltage within 200 milliseconds, Fig. 10(b). However, all the DG units continue to operate in the PQ control mode. The DG power controllers reject the disturbance and quickly track their corresponding reference power set points within 150 milliseconds. Figs. 10(c)-10(e). In addition, the values of the overshoots in Figs. 10(b)- 10(e) are less than 2%.



(a) (b) (c)

(d) (e)

Fig. 10. Simulation results for a sustained single-phase-to-ground (phase A-G) fault at the MV feeder of substation MTW during the islanded operation of the Canada Way Receiving Station. The entire receiving station islands from BC Hydro at t= 5 seconds. The fault occurs at t=6 seconds. (a) power exchange with BC Hydro, (b) power and voltage output of the DS unit, (c) power and voltage output of the DG unit at Sub *MTW*, (d) power and voltage output of the DG unit at Sub *ABG*, (e) power and voltage output of the DG unit at Sub *N*.

- At t=6.0 seconds, a permanent single phase-to-ground fault occurs at the MV feeder of substation MTW. After three cycles, the intelligent FDISR algorithm, implemented within the distribution management system, detects the fault and trips the corresponding breakers to clear the fault. Consequently, an islanded microcell, consisting of the DG unit and the local loads of substation *MTW*, is formed. The smart distribution management system sends an islanding signal to the DG controller at this microcell to switch to the voltage control mode. Subsequent to fault clearing, the DG unit at substation *MTW* effectively regulates the voltage at its PDC bus at 1.0 pu within 200 milliseconds, Fig. 10(c). However, the remaining feeders remain in service, and the other DG units continue to operate in the PQ control mode after rejecting the disturbance within 200 milliseconds, Figs 10(d) and 10(e). Also, the DS voltage controller reject the disturbance within the same time frame and continue to support the voltage of the rest of the system Fig. 10(b).

The results of Fig. 10 show that (i) the power management strategy is efficient, (ii) the dual-mode controllers are robust and fast, and (iii) the FDISR is accurate. Readers can refer to the final reports of the project for further results and analysis [7] and [8].

VII. Conclusion

This paper presents the recent R&D activities to realize the first Canadian Smart Microgrid Testbed at the Burnaby Campus of British Columbia Institute of Technology (BCIT), BC, Canada. The paper outlines a design option for the Smart Microgird including: (a) DER technology selection, (b) DER siting and sizing, (c) the power management strategy, and (d) protection and control of the Microgrid during the presence and absence of the utility (BC Hydro) connection. A dynamic and transient simulation model of the Smart Microgrid is developed in a time-domain simulation platform, namely the PSCAD/EMTDC. The realization of the Smart Microgrid builds on the existing bi-directional communication infrastructure to support the Campus power system operation in the presence and absence of the utility bus. A sample case study is reported to evaluate the impacts of the proposed power management, protection and control strategies on the performance of the BCIT Microgrid.

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Mohamed Zakaria Kamh (S'08, M'11) received the B.Sc. (Honors) and M.Sc. degrees from Ain Shams University, Cairo, Egypt in 2003 and 2007 respectively, both in electrical power and machines engineering. In June 2011, he received his Ph.D. degree in electrical engineering from University of Toronto, Toronto, ON, Canada. He is currently with Hatch Ltd. where he provides technical consultations in the field of power system analysis, operation, and control. In addition, he is also a visiting scientist at the Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto. His research interests include power electronics and their applications in renewable energy resources and smart grids.

Reza Iravani (F'03) received the B.Sc. degree in electrical engineering from Tehran Polytechnic University, Tehran, Iran, in 1976, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Manitoba,Winnipeg, MB, Canada, in 1981 and 1985, respectively.
He is currently a Professor at the University of Toronto, Toronto, ON, Canada. His research interests include power electronics and applications of power electronics in power systems.

Tarek H.M. EL-Fouly (S97 M07) received his B.Sc. and M.Sc. degrees in Electrical Engineering from Ain Shams University, Cairo, Egypt, in 1996 and 2002, respectively. He received his Ph.D. degree in Electrical Engineering from the University Of Waterloo, Waterloo, Ontario, Canada, in 2008. He joined CanmetENERGY, Natural Resources Canada, in 2008, as a Transmission and Distribution Research Engineer, where he is conducting and managing research activities related to active distribution networks, microgrids and remote communities. In 2010, he was appointed as Adjunct Assistant Professor at the Electrical and Computer Engineering Department at the University of Waterloo. His research interests include protection and coordination studies, integration of renewable energy resources, smart microgrid, smart remote community applications, demand side management and forecasting.