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Oak Ridge National Laboratory Literature Review: Methods for Microgrid Protection

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OAK RIDGE NATIONAL LABORATORY
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Electrical and Electronics Systems Research Division

OAK RIDGE NATIONAL LABORATORY LITERATURE REVIEW: METHODS FOR MICROGRID PROTECTION

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ACRONYMS

3L	Three-Line
AEP	American Electric Power
ANSI	American National Standards Institute
BC	British Columbia
BCIT	British Columbia Institute of Technology
CA	California
CERTS	Consortium for Electric Reliability Technology Solutions
CND	Canada
DC/AC	Direct Current / Alternating Current
DERs	Distributed Energy Resources
DPMC	Diesel Plant Master Controller
EMS	Energy Management System
EPB	Electric Power Board
FDISR	Fault Detection, Isolation, and Service Restoration
FP	Feeder Protection
GOOSE	Generic Object-Oriented Substation Events
GTO	Guanajuato
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IIT	Illinois Institute of Technology
IL	Illinois
LACU	Los Alamos County Department of Public Utilities
LL	Line-to-Line
LLG	Line-to-Line-Ground
LP	Loop Protection
LWP	Load-Way Protection
MEX	Mexico
MP	Microgrid Protection
NAY	Nayarit
NC	North Carolina
NEDO	New Energy and Industrial Technology Development Organization
NLA	Newfoundland and Labrador
NM	New Mexico
OH	Ohio
PV	Photovoltaic
PWD	Palmdale Water District
QC	Quebec
SCADA	Supervisory Control and Data Acquisition
SEL	Schweitzer Engineering Laboratories
SLG	Single-Line-to-Ground
TN	Tennessee
TX	Texas
USA	United States of America
WDICS	Wind-Diesel Integrated Control System
WPMC	Wind Plant Master Controller

ABSTRACT

This study reviewed existing conventional and nonconventional protection schemes for grid-connected and islanded mode operations in North American microgrid projects. The microgrid projects investigated in this study used different types of distributed energy resources (DERs) and integrated hydropower/diesel generators, gas/steam/wind turbines, and photovoltaic systems with energy storage. In this work, conventional protection schemes were defined as those within the IEEE Standard C37.2-2008, while nonconventional schemes were those not defined within this standard. The pros and cons of conventional and nonconventional protection schemes applied in the microgrids were discussed in detail. The overvoltage, undervoltage, and frequency elements were the most common conventional protection schemes applied in microgrid projects in North America. These protection elements were used to detect the islanded conditions and faults that could not be sensed by overcurrent relays because of small fault currents contributed by low-inertia DERs and power-electronic sources. Directional overcurrent elements were used to distinguish between external (grid) and internal (microgrid) faults. Adaptive protection was the most popular nonconventional protection scheme applied to the microgrid projects. Adaptive protection detected when the microgrid was set in grid-connected or islanded modes and selected the relay settings for the actual microgrid conditions to avoid relay misoperation. In conclusion, the microgrid projects in this study used different types of DERs and operational modes that must be considered in order to address protection and control challenges specific to each microgrid and to obtain the best technical and economical solution. The protection scheme results and discussions for the North American microgrid projects collected in this report provide important information to guide protection and control engineers, designers, and researchers in defining the protection methods for microgrids based on the types of DERs and grid-connected or islanded operational modes.

1. INTRODUCTION

Oak Ridge National Laboratory has been assigned to formulate the protection schemes constraints for microgrid designs. These constraints feed into an optimization of microgrids, which could be applied to determine how, where, and what electrical designers should invest in protection and control equipment for networked microgrids to enhance and balance the reliability and cost, respectively, of new microgrid projects. This report reviews existing methods to protect microgrids while islanded and/or grid connected. This work focuses on current industry practices, as well as recent research projects. Grid-connected and islanded cases with hydropower generators (spinning inertia cases), modern wind turbines, and photovoltaic (PV) panels with energy storage systems (synthetic inertia cases) were evaluated. This report defines and presents a detailed review of conventional and nonconventional protection schemes applied in microgrid projects. Conventional protection schemes were defined as those described in the ANSI/IEEE Standard Device Numbers Standard, while nonconventional were those not included in this standard [1].

North American microgrids have been growing in number in an effort to provide a more reliable grid connectivity to our communities, and they have played an important role in supplying uninterrupted energy to utilities' customers in blackout situations. Microgrids can be operated in grid-connected or islanded modes, and they are designed based on different protection schemes to enhance their reliability, resilience, and power quality [2–5].

In previous publications, general aspects of microgrids were explained in detail [2, 6]. Hirsch et al. [2] described the technologies, key drivers, and outstanding issues about microgrids and focused on general microgrid definitions and functional classification schemes. The review article [2] explained what a microgrid is and provided a multidisciplinary portrait of today's microgrid drivers, real-world applications, challenges, and prospects. Bayindir et al. [6] presented an overview of North American microgrid facilities that described major microgrid projects, compared each one with the others, and provided circuit diagrams and comparative tables [6]. However, no protection schemes and industry practices for microgrid projects were described in detail in these publications [2, 6].

Other authors reviewed protection schemes [3, 4, 7–10]. Oudalov et al. [3] and Edwards and Manson [9] presented a detailed description of microgrid protection schemes published by relay original equipment manufacturers. Outdalov et al. [3] presented a novel adaptive microgrid protection system using digital relaying and advanced communication. This protection system was based on a centralized architecture where relay protection settings were modified according to microgrid operating conditions [3]. Edwards and Mason [9] explained how microprocessor-based protective relays were used to provide control and protection functions for small microgrids. This paper included automatic islanding, reconnection to the electric power system, dispatch of distributed generation, compliance to IEEE specifications, load shedding, volt/VAR control, frequency, and power control at the point of interface [9]. Haron et al. [7] described different protection functions and schemes focused on research publications instead of microgrid projects. This paper reviewed the available protection schemes and coordination techniques applied to address protection issues in microgrid distribution systems, discussing the implementation of methods, modes of operation, types of distributed generators, and availability of communication links [7]. Buigues et al. [4] and Laaksonen et al. [10] described microgrid protection challenges and future communication principles, respectively. Buigues et al. [4] presented a comprehensive overview of the existing microgrid protection methods based on research publications and described the most important technical challenges for existing techniques in microgrid protection schemes [4]. Laaksonen [10] presented a future protection concept for low-voltage microgrids using IEC-61850-based communication to achieve a fast, selective, and reliable operation for microgrid protection schemes. Shiles et al. [8] described different protection schemes for microgrid projects and provided an overview and analysis of protection schemes that have been implemented in major North American microgrid projects. This publication provides a brief overview of microgrid protection issues and potential solutions to help designers define protection requirements for practical microgrids [8].

In this study, a literature review of microgrid protection schemes for North American (USA, MEX, CND) major projects is presented. This report focused on finding the existing protection schemes at different microgrid scenarios, such as those grids connected and islanded with hydropower generators (spinning inertia cases), modern wind turbines, and PV panels with energy storage systems (synthetic inertia cases). The literature review focused on existing protection methods for current projects and industry practices. The role of original equipment manufacturers in protective relays for microgrid applications is discussed, describing their protection philosophy as applied in today's microgrid projects. The main goal of this literature review was to identify the constraints of protection schemes in microgrids and the philosophy of project designers and current industry practices. This review aids in understanding how new protection methods (nonconventional protection schemes) differ from existing protection methods (conventional protection schemes) and the challenges protection and control systems in microgrids currently face.

2. OVERVIEW OF MICROGRID PROTECTION SCHEME PROJECTS

2.1 ELECTRIC POWER BOARD (EPB) MICROGRID, CHATTANOOGA (TN) – USA

The Electric Power Board (EPB) microgrid is in Chattanooga (TN). This networked microgrid is based on an EPB currently installed and operating system [11]. The microgrid has 46/12.47 kV Ridgedale and Riverside substations. The Ridgedale substation is supplied by diesel generators that are located near the EPB Operations Building. The diesel generators are currently configured to provide emergency power to the Operations Building and isolate the rest of the microgrid when in use. A third 0.24/12.47 kV substation provides energy from a PV and energy storage system with a DC/AC inverter. This system has 4408 solar panels that can generate 1.3 MW to feed residential customers.

In this microgrid, the energy stored could be used to balance the generation and consumption, voltage, and frequency. All substations are connected to 12.47 kV distribution lines that supply energy to several feeders located between the three substations. The feeders are protected by 30T, 50T, and 100T ampere-rated fuses. The substations have SEL-751 protective relays, and several IntelliRupters are installed along the 12.47 kV distribution lines that can detect different types of faults in the system. The IntelliRupters use a PulseClosing technology to determine whether the fault is temporary or permanent. If the fault is temporary, the devices restore power in seconds without damaging equipment with fault currents. If the fault is permanent, the devices use the intelligence in the IntelliTeam SG software to isolate the faulted segment and reroute power from other available sources in a matter of seconds [12]. The IntelliRupters are directional overcurrent protection devices that can be set with inverse time overcurrent curves for forward and reverse directions. IntelliRupters can be coordinated with each other and with feeder fuses for currents flowing in reverse or forward direction, depending on the microgrid operation mode (grid connected or islanded).

2.2 DUKE ENERGY MICROGRID, MOUNT HOLLY (NC) - USA

The Duke Energy Microgrid is located in Mount Holly (NC) and was installed at the McAlpine Creek Substation. This microgrid is a 12.47/0.48 kV system that has a substation with a 50 kW PV DERs and a 240 kW (500 kWh) battery energy storage system [13]. These two systems are connected in parallel to import and export energy. The PV and the battery energy storage systems ensure reliable and resilient power during prolonged grid outages [13]. The microgrid also serves the critical load of the fire station.

The Duke Energy Microgrid demonstrates that a utility-owned microgrid can provide other distribution system benefits such as frequency regulation, circuit voltage support-VAR dispatch, demand response through islanding, and mitigation of solar intermittency at the source. The designed microgrid protection and control system has SEL-651R Advanced Recloser Relays and SEL Real-Time Automation Controllers installed [13]. The SEL-651R Advanced Recloser Relays were able to incorporate features such as an automatic synchronization check that interfaces at the point of common coupling between the microgrid and the bulk electric power system. In addition, the SEL-615R Advanced Recloser Relays have directional overcurrent, frequency, and voltage protection schemes that were applied for the microgrid.

2.3 UNIVERSITY OF CALIFORNIA MICROGRID, SAN DIEGO (CA) - USA

The microgrid at the University of California, San Diego, serves a campus community of more than 45,000 people. This microgrid generates 80% of the electricity used on campus annually [14]. The campus controls 42 MW of generation and then purchases power on the market. The microgrid has gas turbines (2 × 13.5 MW), a steam turbine (3 MW), PV panel system (3 MW), and a methane fuel power cell (2 MW). This microgrid provides significant benefits such as power generation, storage, transport, and electricity to the campus and can connect to the larger electric grid or work independently. It can “island” in a power emergency, disconnecting from the grid and maintaining its own critical functions. The University of California reports savings of more than $800,000 in power costs per month because of its microgrid [14].

More than 100 SEL devices were used [15] to provide a protection and control system for this microgrid. These devices ranged from protective relays to automation control and communication equipment [15], as well as other devices from other manufacturers. The protective relays used on this microgrid were SEL-311L Line Current Differential Protection and Automation System, SEL-751 Feeder Protection Relays, SEL-487B Bus Differential and Breaker Failure Relays, SEL-587Z High-Impedance Differential Relays, and SEL-700G Generator Protection Relays [15].

2.4 CONSORTIUM FOR ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS MICROGRID, COLUMBUS (OH) - USA

The Consortium for Electric Reliability Technology Solutions (CERTS) microgrid testbed is a 13.2/0.48 kV system operated by the American Electric Power (AEP). The CERTS testbed is a microgrid with natural gas DERs. This microgrid has three 60 kV inverter-based natural gas DERs. The inverter-based natural gas DER feeders and the utility grid are connected through an interface static switch [16]. The microgrid is protected with a symmetrical-component-based scheme. However, the interface static switch is equipped with conventional protection schemes such as overvoltage (59), undervoltage (27), overfrequency and underfrequency (81), and directional overcurrent (67). The interface static switch is capable of islanding the microgrid [17] during power quality incidents, based on protection function responses shown in Table 1 [8, 18]. However, the design of the CERTS microgrid has not considered a protection study against faults within the island in this project.

Table 1. Protection settings for the interface static switch [8, 18].

Protective functions of interface static switch	Setting ranges	Implemented values
Overvoltage (59)	105–115%	110%, 10 ms (Fast) 115%, 2 ms (Instantaneous)
Undervoltage (27)	95–50%	80%, 10 ms (Fast) 50%, 3 ms (Instantaneous)
Overfrequency (81)	60.1–63.0 Hz	60.5 Hz, 0.5 ms
Underfrequency (81)	59.9–57.0 Hz	59.5 Hz, 0.5 ms
Directional overcurrent (67)	0–500%	130%, 60 sec

2.5 SANTA RITA JAIL MICROGRID, DUBLIN (CA) – USA

The Santa Rita Jail Microgrid in Dublin (CA) provides energy to approximately 4,000 inmates [19]. This microgrid is a 12.47/0.48 kV system with a PV system (1.5 MW), a molten carbonate fuel cell (1.0 MW), backup diesel generators (2 × 1.0 MW), storage battery system (2.0 MW/4.0 MWh) and wind turbine generators (5 × 2.3 kW). The microgrid interconnection is enabled with an interface static switch, which permits fast isolation of the microgrid. The interface static switch has islanding and synchronization functions without the need for external signals and is set with conventional protection functions such as overvoltage (59), undervoltage (27), and overfrequency and underfrequency (81) that are used to detect islanding situations [8]. In addition, the directional overcurrent (67) elements are used to distinguish between external (grid) and internal (microgrid) faults. The overvoltage (59), undervoltage (27), and overfrequency and underfrequency (81) elements of the interface static switch and microgrid DERs are coordinated to ensure the DERs remain online during the islanding situations.

The interface static switch is capable of islanding the microgrid [17] during power quality incidents, based on protection function responses shown in Table 1 [8, 18], similar to the Consortium for Electric Reliability Technology Solutions Microgrid, Columbus (OH) – USA. The protection scheme of the Santa Rita Jail microgrid does not have selective coordination against faults within the islanded microgrid. Thus, a fault within the islanded microgrid leads to a shutdown of the entire island. In addition, a backup breaker is provided for the interface static switch. This backup device is a 12 kV standard vacuum circuit breaker with protective relays installed upstream from the interface static switch. The backup circuit breaker operates when the protection schemes of the interface static switch fail.

2.6 ILLINOIS INSTITUTE OF TECHNOLOGY MICROGRID, CHICAGO (IL) – USA

The Illinois Institute of Technology (IIT) Microgrid [20] is located in Chicago. It is a 12.47/4.16/0.48 kV system with natural gas (8 MW) and wind (8 kW) turbines, PV (300 kV) and flow battery (500 kWh) systems, and a backup generator system (4 MW). This microgrid is fed through two 12.47/4.16 kV transformer substations to ensure seamless operation of the system if one of the feeders fails. In the substations, transformers are installed with appropriate protective devices. However, the IIT microgrid uses a hierarchical protection scheme. This hierarchical protection scheme is based on localized differential protection in seven loops and four coordinated protection levels, which are implemented by communication-assisted digital directional relays [21]. Table 2 shows the conventional protection schemes and functions (primary, backup and others) of the four levels for the hierarchical protection scheme in the IIC microgrid.

Table 2. Hierarchical protection scheme.

Protection levels	Conventional protection schemes	Primary function	Backup function	Other functions
Load-Way Protection (LWP)	– Directional overcurrent – Voltage – Frequency	Directional overcurrent relays that detect the load-level faults	If level breakers fail, trip signals are sent to adjacent breakers	Voltage and frequency functions are implemented to enable load shedding and/other control schemes
Loop Protection (LP)	– Differential – Directional overcurrent – Breaker failure	Differential relays detect faults between two switches and isolate loop faults[a]	Provide backup protection for the LWP level	Provide breaker failure protection
Feeder Protection (FP)	– Differential – Directional overcurrent	Directional overcurrent relays with adaptive settings to detect faults at different microgrid modes	Provide backup protection for the LWP and LP levels if network comm. fails	
Microgrid Protection (MP)	– Overcurrent – Voltage – Frequency	Overcurrent, voltage and frequency relays to detect the grid faults	Provide backup protection for the LWP, LP, and FP levels	Voltage and frequency functions are implemented to enable the islanding

[a] Communication-assisted relays with directional functionality

2.7 SAN DIEGO GAS AND ELECTRIC COMPANY'S MICROGRID, BORREGO SPRINGS (CA) – USA

The Borrego Springs Microgrid, developed by the San Diego Gas and Electric Company, provides energy to 615 customers with a peak load of 4.6 MW. This microgrid is fed by a 69/12 kV substation from the utility grid side and has two diesel generators (2 × 1.8 MW), a PV (0.7 MW) system, and a substation battery (500 kW/1500 kWh) system with three feeders [22]. In the Borrego Springs Microgrid, the magnitudes of the fault currents in the island mode are so small that overcurrent relays cannot trip. As a result, a voltage-restrained overcurrent protection was designed for the islanded modes of the microgrid. The voltage restrained overcurrent protection provides improved sensitivity of overcurrent relaying by making the set overcurrent operating value proportional to the applied input voltage. The voltage restrained overcurrent protection improved the sensitivity of the overcurrent relays for small fault currents, but the selectivity of the protection system along the microgrid remains affected because of the small magnitude of the fault currents.

2.8 ONCOR MICROGRID, LANCASTER (TX) – USA

The ONCOR microgrid is a 12.47/0.48 kV system (1 MW) located in Lancaster (TX). This microgrid has four smaller operating zones. Two zones have diesel generators, one zone contains the battery energy storage, and the fourth zone has two PV systems, battery energy storage, and a microturbine. This microgrid is fed by a 12.47 kV overhead distribution line through an automatic isolation switch that provides the protection and control functions to operate as islanded or grid-connected modes. An S&C IntelliRupter was installed at this interconnection point to detect the voltage loss on one or more phases. The Intellirupter quickly isolates the microgrid to perform islanding. When the source is suitable for reconnection, the IntelliRupter quickly reconnects to the grid [23]. Downstream from the IntelliRupter and serving the four microgrid zones, an S&C's SCADA-Mate Switching System was applied on the overhead lines [23]. This system provides the isolating and sectionalizing functionality to have automatic fault isolation and circuit restoration capabilities.

In this microgrid, issues related to the protection scheme were addressed. When the microgrid was connected to the electric grid, the fault current magnitudes were detected by the protection scheme. However, when islanded, the fault current magnitudes on site were substantially reduced because of limited onsite generation. Hence, the microgrid required a protection scheme that would operate securely for both grid-connected and islanded operations. As a solution, a dynamic protection system was implemented by installing eight protective relays with assisted communication [23]. This protection system enabled the microgrid to alter its protection scheme according to the operating mode based on an adaptive protection scheme. The protective relays use the IEC 61850 Generic Object-Oriented Substation Events (GOOSE) messaging to perform protection setting decisions to protect the microgrid regardless of whether it was grid connected or islanded [23].

2.9 NEW ENERGY AND INDUSTRIAL TECHNOLOGY DEVELOPMENT ORGANIZATION MICROGRID, LOS ALAMOS (NM) - USA

The New Energy and Industrial Technology Development Organization (NEDO) Microgrid is in Los Alamos (NM). This project was developed by Los Alamos County Department of Public Utilities (LACU) through a collaboration with Japan. This microgrid has a Japanese PV system (2 × 1 MW) and battery storage (1.8 MW). The project is based on the integration and control of PV technology with Micro Energy Management System (EMS) on an American distribution system [24]. The PV system and battery storage are integrated into the Los Alamos power plant to work under diverse situations and to achieve a reliable power supply under unstable operational conditions by charging or discharging the batteries. This microgrid feeds power to approximately 1,900 customers.

The protection and control devices are optical fiber communication lines. The S&C Vista pad-mounted switchgear is used to integrate the NEDO and LACU generation sources [25]. The Vista utilizes bidirectional SEL 451 relays to accommodate the reverse power flow conditions from the battery and PV system. The fault current conditions of the electrical system change depending on the microgrid source of connectivity. Therefore, the SEL relays need to be set on either parallel mode (normal operation) or islanding mode (sole supply source). The Micro EMS has the functionality to provide islanding connectivity to part of the LACU distribution system but only after a complete feeder shutdown [25].

2.10 PALMDALE WATER DISTRICT MICROGRID, PALMDALE (CA) – USA

The Palmdale Water District (PWD) Microgrid Project has renewable and nonrenewable DERs that feed some external loads of a water treatment plant. This microgrid is a 0.48 kV system that has two backup diesel generators (1 × 1000 kW / 1 × 800 kW), a wind turbine (950 kW), and hydro (250 kW) and gas (200 kW) generators with an ultra-capacitor (450 kW). This microgrid decreased energy expenses, improved the energy system dependability, and enhanced the power quality [26]. The ultra-capacitor (450 kW), DC/AC power conversion and static switch is known as the "EnergyBridgeTM EB 450," which is the energy storage system for the PWD microgrid. The EnergyBridgeTM EB 450 system has a static switching and PowerRouter controls that are combined with Maxwell Technologies [26]. The system provides energy for critical load demand and high-quality power to protect loads during utility disturbances and seamlessly transitions to a backup generator in the event of a grid outage. It can support loads up to 450 kW for 30 seconds [26].

2.11 GUASIMAS DEL METATE (NAY) / TIERRA BLANCA DEL PICACHO (GTO) SOLAR MICROGRIDS – MEX

The Guasimas del Metate and Tierra Blanca del Picado microgrids are located in the states of Nayarit (NAY) and Guanajuato (GTO) in Mexico. These microgrids are part of the "White Flag Program" sponsored by the Electrical Federal Commission of Mexico [27]. The objective of this program was to provide energy to isolated communities by using renewable energy systems. The microgrids of Guasimas del Metate and Tierra Blanca del Picacho are identical and feed a load composed of approximately 52 households. Each microgrid includes an integrated protection, control, and monitoring system. The system collects and processes data from the microgrid substations and sends the data to the supervisory control and data acquisition (SCADA) master of two remote control centers. The PV system (45.9 kW) for each microgrid has solar arrays with a DC/AC inverter and a battery with a DC/AC inverter [27]. This PV system can collect and store energy that is consumed by residential customers. The PV system is connected to a 0.22/13.8 kV transformer (75 kVA) that supplies energy to the community by a radial distribution network of 13.8 kV.

The microgrid protection schemes have Schweitzer Engineering Laboratories (SEL) protective, control and communication devices. The control systems of the solar array and battery bank inverters include an undervoltage protection algorithm that detects DC and AC circuit faults and automatically shuts down the inverter in approximately 5 ms. The undervoltage protection algorithm for the inverter control systems provides the primary protection for faults in the DC and AC circuits. The relay that performs the protection scheme for the microgrid trips the breaker located at the transformer low-voltage side.

In this microgrid, the behavior of the phase overcurrent (50/51), ground overcurrent (51N), undervoltage (27), voltage balance (60), and volts-per-hertz (24) relay elements was studied. The volts-per-hertz (24) element was evaluated for failures at the inverter control system [27]. Table 3 shows the protective relay elements response for single-line-to-ground (SLG), line-to-line (LL), line-to-line-ground (LLG), and three-line (3L) faults on the 13.8 kV network. In Table 3, elements 27 and 60 trip to all (SLG-LL-LLG-3L) and unbalanced (SLG-LL-LLG) faults, respectively. The elements 27 and 60 were enabled as a backup protection scheme, and element 24 provided redundant backup protection for the inverter control system failures [27].

Table 3. Protection element response to faults on the 13.8 kV network [27].

Protection elements	Type of faults			
	Single-line-to-ground (SLG)	**Line-to-line (LL)**	**Line-to-line-ground (LLG)**	**Three-line (3L)**
Phase overcurrent (50/51)	Does not trip	Does not trip	Does not trip	Does not trip
Ground overcurrent (51N)	Sometimes trips	Does not trip	Does not trip	Does not trip
Undervoltage (27)	Trips	Trips	Trips	Trips
Voltage balance (60)	Trips	Trips	Trips	Does not trip

2.12 WIND-DIESEL MICROGRID, RAMEA (NLA) – CND

The Ramea Wind-Diesel Microgrid is located at the Newfoundland and Labrador area in Canada. This microgrid system was installed to provide energy to isolated communities. The microgrid is not connected to a grid because it is located on a small island 10 km from the south shore of Newfoundland, with a population of 700 (conventional fishery neighborhood). This project is a 4.16 /0.48 kV microgrid system with three CAT 3512 diesel generators (3 × 925 kW) and six wind turbines (6 × 65 kW) [28]. This project is a self-ruling diesel-based system with a medium-scale wind plant. The energy system has a peak demand and annual energy generation of 1.2 MW and 4,556 MWh, respectively. If the power generation of the diesel plant decreases to 30% of its capacity, the control mechanism recovers the lost potential by integrating wind turbines into the system until the diesel generator again supplies over 30% of its capacity [6]. The average and minimum load of the system are 528 kW and 202 kW, respectively.

The microgrid has two dissemination feeders (4.16 kV) that are controlled with WOODWARD controls, and modicon PLC [29]. A wind-diesel integrated control system (WDICS) is used to control and supervise the operation of the wind turbines and to facilitate their integration into the system, which is controlled and primarily supplied by the diesel generator plant. The WDICS configuration is composed of a diesel plant master controller (DPMC), a wind plant master controller (WPMC), and a SCADA system with internet access for monitoring and data acquisition. The DPMC is a fully integrated and digital automatic controller that supervises the overall wind-diesel network operation as well as synchronization, load sharing, and load following control of the diesel generators. The WPMC performs automatic control and protection of the wind power plant including start-up and shutdown of the wind turbines. The WPMC also has communication with the DPMC to report power generation of the turbines and to update the maximum limit for wind power import. The communication link between DPMC and WPMC is a 1 km wireless connection [28].

2.13 BRITISH COLUMBIA HYDRO MICROGRID, BOSTON BAR (BC) – CND

The British Columbia Hydro Microgrid is in Boston Bar (BC), Canada. This microgrid is a 4.16/25/69 kV system that has two hydropower generators (2 × 3.5 MW) joined by a single bus. The system also has a 4.16/25 kV and 69/25 kV substations that are connected to the hydropower generators and utility grid, respectively. In this microgrid, if the high-voltage feeder encounters any deficiency, the microgrid can work in island mode. It allows a 3 MW peak load and 8.6 MVA of hydroelectric generation in the islanded mode [30]. The hydro microgrid has the capacity to include the substation level or island mode immediately utilizing remote auto-synchronization without bringing on load shedding. This proving ground and genuine system operation has automatic and manual synchronization, and it was tested with step load and dead load with black-start competence utilizing a 55 kW diesel generator [31, 32]. This microgrid can supply one or more feeders during power outages.

The protection methods applied to this project are based on an adaptive protection schemes to change the overcurrent protection settings in the islanded mode and a positive-voltage field control used in the excitation system to enable high fault currents for feeder faults [31]. A remote auto-synchronization is applied to reconnect the microgrid in island mode. The communication is implemented by a leased telephone line [30] that is used to monitor the substation breakers and protection settings changes for the adaptive protection scheme.

2.14 BRITISH COLUMBIA INSTITUTE OF TECHNOLOGY MICROGRID, BURNABY (BC) – CND

The British Columbia Institute of Technology (BCIT) Microgrid is located on campus in Burnaby (BC), Canada. This project represents a scaled-down microgrid that is used for research and instructional activities. This 1.2 MW microgrid system has two wind turbines (2 × 5 kW), a PV system (300 kW), steam turbine (250 kW), and Li-particle battery (550 kW) [6]. This microgrid feeds four areas, the Canada-way receiving station, Goard-way receiving station, residential serving area, and small load centers [33]. In this microgrid, the areas are connected to the 12.47 kV feeders, with the exception of the small load centers. Seventy percent of total campus energy is consumed by the Canada-way and Goard-way receiving stations.

In this microgrid, a communication-aided fault detection, isolation, and service restoration (FDISR) strategy was implemented that employs a differential protection to detect and locate faults within the microgrid for grid-connected and islanded modes. This differential protection scheme continuously monitors the three-phase currents at both ends of each 12.47 kV feeder. When a fault is detected between the feeders, the currents at the beginning and end of the feeders are not identical. If this current difference is sustained for three consecutive cycles (50 ms), a fault is declared by the protection devices. This time delay (50 ms) does not allow tripping to occur for temporary faults or short-term disturbances [33]. Once a fault is detected, a trip signal is sent to the corresponding breakers. If the fault isolation results at the island mode, the distribution management system sends a signal to the DER controllers to switch the control mode from the active/reactive power to voltage/frequency mode such that the service for the islanded mode is guaranteed at the microgrid [33].

2.15 BORALEX PLANNED ISLANDING MICROGRID, SENNETERRE (QC) – CND

The Boralex Planned Islanding Microgrid is in Senneterre (QC), Canada. It is a privately owned thermal power plant that feeds the Hydro-Quebec network through the Senneterre substation. This microgrid is a 13.8/120/25 kV system that supplies energy to 3,000 customers [34]. The Senneterre substation (120/25 kV) is connected to a 31 MVA steam turbine (26.35 MW), 120 kV transmission line (grid-link), and three 25 kV feeders (1 × 7 MVA /2 × 4 MVA). The steam turbine demonstrates a stable operation in isochronous mode under differing loads when the peak load is about 7 MW [34].

In this microgrid, the steam turbine is used to island the Senneterre substation during a possible restoration of the 120 kV transmission line. Its islanding capacity allows the continuity of energy supply to Hydro-Quebec customers [35]. This microgrid operates in islanded mode only for planned maintenance. In such cases, the radial topology of the system is preserved, and the protection coordination at the islanded mode has shown that the protection settings of protective devices do not need to change due to the large size of the steam turbine that allows the same fault current magnitudes to be maintained during the islanded mode [35]. This project showed that each microgrid needs to be studied individually to determine its protection schemes because not all microgrids need to adapt their protection schemes to the grid-connected and islanded modes.

3. CONVENTIONAL AND NONCONVENTIONAL PROTECTION SCHEMES FOR MICROGRIDS

Microgrids are complex power systems that have DERs, power lines, and feeders, and they need to adapt different conventional protection schemes that are usually implemented in generation, transmission, and distribution power systems. Microgrids use conventional and nonconventional protection schemes. Understanding the impact of conventional and nonconventional protection schemes on current microgrid projects is crucial in order to adapt current protection schemes to new applications. The conventional protection schemes were defined here as those protection devices described in the ANSI/IEEE Device Numbers Standard [1]. The most common conventional protection schemes used in microgrid projects are undervoltage (27), overvoltage (59), voltage balance (60), volts per Hertz (24), frequency (81), impedance (21), differential (87), instantaneous overcurrent (50), inverse time overcurrent (51), and directional overcurrent (67). Table 4 shows the advantages and disadvantages of conventional protection schemes based on current microgrid projects.

Table 4. Conventional protection schemes for microgrid projects.

Functions (Device Nº)	Advantages	Disadvantages
Undervoltage (27)	- Does not depend on fault current magnitude and direction	- Does not allow a good selectivity coordination - Susceptible to transient incidents (load operations)
Overvoltage (59)	- Does not depend on fault current magnitude and direction - Protects inverters	- Does not allow a good selectivity coordination - Susceptible to transient incidents (load operations)
Voltage Balance (60)	- Detects blown voltage transformer fuses to protect generators	- Does not allow selectivity coordination
Volts per Hertz (24)	-Protects inverters	- Does not allow a good selectivity coordination - Susceptible to transient incidents (load operations)
Frequency (81)	- Protects inverters	- Does not allow a good selectivity coordination - Susceptible to transient incidents (load operations)
Impedance (21)	- Provides solution for islanded microgrids	- Lacks sensitivity to measure apparent impedances at fault situations with distributed energy resource contributions. - Needs communication
Differential (87)	- Does not depend on fault current level - Does not depend on distributed energy resource type, location and size	- Does not allow a backup protection from other zones - Needs communication
Instantaneous Overcurrent (50)	-Allows an instantaneous trip but it is used with the inverse time and definite time overcurrent relays	-Does not allow coordination with fuse curves -Needs to be used when coordination is not required (last relay application)
Inverse Time Overcurrent (51)	-Allows coordination of relays with feeder fusses	-Needs to be complemented with directional and/or adaptive overcurrent protections -Needs communication
Directional Overcurrent (67)	- Provides proper solution to coordinate protectives devices for different microgrid circuit paths	- Needs forward and reverse coordination - Needs adaptive settings

Alternatively, the nonconventional protection schemes are protection functions that are not set in the ANSI/IEEE Device Numbers Standard [1] but are applied in current microgrid projects. The most common nonconventional protection schemes applied in microgrid projects are adaptive, voltage-restrained, hierarchical, and symmetrical component protection schemes. The nonconventional protection schemes are based on traditional protection schemes but apply additional functions that protect and control the distributed energy resources, DC/AC inverters, energy storages, transformers, power lines, and feeders for different operation modes and/or circuit path applications for the microgrids. Table 5 shows the advantages and disadvantages of nonconventional protection schemes based on current and ongoing microgrid projects.

Table 5. Nonconventional protection schemes for microgrid projects.

Functions	Advantages	Disadvantages
Adaptive protection	- Allows sensitivity and selectivity based on microgrid operation conditions	- Needs communication - Needs large amount of data for real-time adaptation of protection settings - Complicated design
Voltage-restrained	- Enhances fault detection that could not have overcurrent relays - Detects low fault currents	- Difficult coordination - Lacks success to detect high-impedance faults
Hierarchical	-Allows to coordinate differential protection schemes at different protection levels.	-Needs communication
Symmetrical component	- Allows to detect asymmetrical faults	- Unable to detect type of faults - Needs to be implemented with other protection elements

4. RESULTS AND DISCUSSIONS: MICROGRIDS AND PROTECTION SCHEMES

Microgrids are classified as small or large systems, depending on their size. In small microgrids, protective relays are used for control, metering, and protection. However, large microgrids are controlled by one or more centralized controllers connected to metering and protection devices. The metering and protection devices are controlled by a central device that can be connected to more than 100 distributed protective relays. The majority of microgrid projects in Canada and Mexico have hydro and solar DERs, respectively, whereas the majority of microgrid projects in the USA have solar, wind, diesel, thermal and gas DERs. Most microgrids allow islanded and grid-connected modes. The microgrid projects in the USA and Mexico have inverter- and rotation-based DERs because PV systems and rotative generators are used. However, most microgrid projects in Canada are focused on rotation-based DERs instead of PV systems because solar energy projects are usually not technically or economically feasible in Canada. The microgrid projects use PV, wind, hydro, diesel, fuel cells, steam and gas turbines. Figure 1 shows the real power in MW supply by the DERs for the microgrid projects. The DERs that provide most of the power supply for these microgrid projects are represented by the hydro and gas turbines. Table 6 shows the operation modes, types of DERs, and power supply for the microgrid projects collected in this literature review for the USA, Mexico, and Canada.

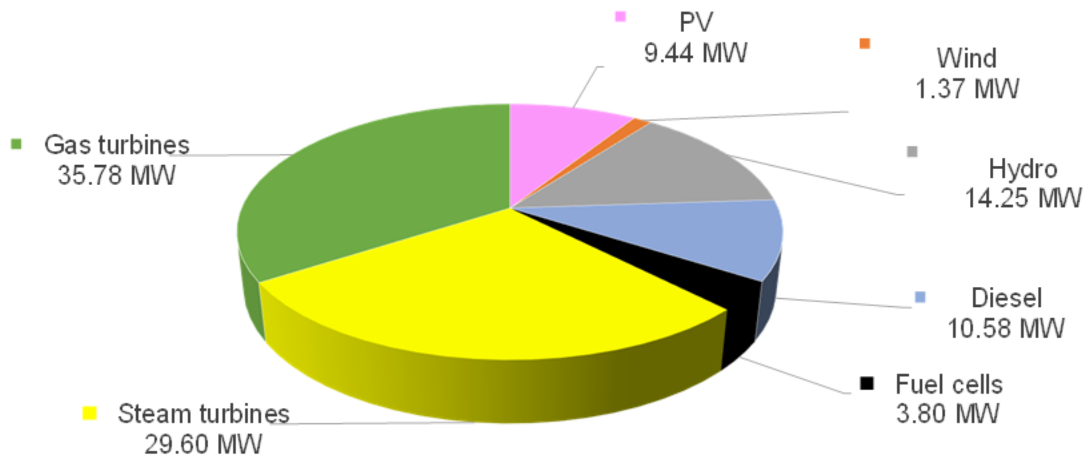

Figure 1. Real power (MW) supply by distributed energy resources.

The EPB (Chattanooga, TN, USA) and ONCOR (Lancaster, TX, USA) microgrids use IntelliRupters that have a directional overcurrent protection function that allows the inverse time overcurrent curves to be set in forward and reverse directions. These IntelliRupters work with neighboring IntelliRupters and with feeder fuses for currents flowing in reverse or forward directions, depending on the microgrid operation mode (grid-connected or islanded). In addition, the IntelliRupters allow temporary or permanent faults to be detected by using the PulseClosing technology. If the fault is temporary, the devices restore power within seconds without damaging equipment with fault currents. If the fault is permanent, the devices use the intelligence in the IntelliTeam SG software to isolate the faulted segment and reroute power from other available sources in a matter of seconds. The CERTS (Columbus, OH, USA) and Santa Rita Jail (Dublin, CA, USA) microgrids have interface static switches with conventional protection schemes such as overvoltage (59), undervoltage (27), overfrequency and underfrequency (81), and directional overcurrent (67). The interface static switch is capable of islanding the microgrid after having power quality incidents, based on protection functions responses shows in Table 1.

The IIT microgrid (Chicago, IL, USA) has a hierarchy protection scheme with four differential protection levels (load-way, loop, feeder, and microgrid protection levels). The feeder protection level has an additional adaptive protection scheme with directional overcurrent relay settings to detect faults at different microgrid modes. The ONCOR (Lancaster, TX, USA) microgrid perform both grid-connected and islanded operations by an adaptive protection scheme with assisted communication with relays using IEC 61850 GOOSE messaging to perform protection setting decisions. The BC hydro microgrid (Boston Bar, BC, CND) has an adaptive protection scheme to change the overcurrent protection settings in the islanded mode. Communication is provided via a leased telephone line, which is used to monitor the substation breakers and protection setting changes for the adaptive protection scheme.

Table 6. Operation modes, types of DERs, and power supply for microgrid projects.[a]

COUNTRY	Microgrid Project Names	Microgrid Operation				Power Supply						
		Operation Modes		Types of DERs		PV	Wind	Hydro	Diesel	Fuel Cells	Steam turbines	Gas turbines
		Grid-connected	Islanded	Inverter based (PV)	Rotation based	MW	MW	MW	MW	MW	MW	MW
USA	Electric Power Board Microgrid, Chattanooga (TN)	X	X	X		1.3						
USA	Duke Energy Microgrid, Mount Holly (NC)	X	X	X		0.05						
USA	UC Microgrid, San Diego (CA)	X	X	X	X	3.0				2.8	3.0	27.0
USA	Consortium for Electric Reliability Technology Solutions, Columbus (OH)	X			X							0.18
USA	Santa Rita Jail Microgrid, Dublin (CA)	X	X	X	X	1.5	0.011		2.0	1.0		
USA	Illinois Institute of Technology Microgrid, Chicago, IL	X	X	X	X	0.3	0.008					8.0
USA	San Diego Gas and Electric Company's Microgrid, Borrego Springs (CA)	X	X	X	X	0.7			3.6			
USA	ONCOR Microgrid, Lancaster (TX)	X	X	X	X	0.2			0.4			0.4
USA	NEDO Microgrid, Los Alamos (NM)	X	X	X		2.0						
USA	Palmdale Water District Microgrid, Palmdale (CA)	X	X		X		0.95	0.25	1.8			0.2
MEX	Guásimas del Metate (NAY) Solar Microgrid		X	X		0.046						
MEX	Tierra Blanca del Picacho (GTO) Solar Microgrid		X	X		0.046						
CND	Wind-Diesel Microgrid, Ramea, Newfoundland (NLA)		X		X		0.39		2.775			
CND	BC Hydro Microgrid, Boston Bar (BC)	X	X		X			14.0				
CND	British Columbia Institute of Technology Microgrid, Burnaby (BC)	X	X	X	X	0.3	0.01				0.25	
CND	Boralex Planned Islanding Microgrid Senneterre (QC)	X	X		X						26.35	

[a] USA: United States of America, MEX: Mexico, CND: Canada, DERs: Distributed Energy Resources

The Guasimas del Metate (NAY, MEX) and Tierra Blanca del Picado (GTO, MEX) microgrids have rather small fault currents that overcurrent relays cannot trip because of solar arrays and battery bank inverters. The application of undervoltage protection algorithm detects DC and AC circuit faults and automatically shuts down the inverter in approximately 5 ms. The undervoltage (27) and voltage balance (60) elements are enabled as backup protection scheme, and the volts-per-Hertz (24) element is provided as redundant backup protection for the inverter control system failures. The SDGEC (Borrego Springs, CA, USA) microgrid also has small fault currents that overcurrent relays cannot trip. Consequently, a voltage-restrained overcurrent protection was designed for the islanded modes of the microgrid. The voltage-restrained overcurrent protection provides improved sensitivity of overcurrent relaying by making the set overcurrent operating value proportional to the applied input voltage, but the selectivity of the protection system along the microgrid is affected because of the small magnitude of the fault currents. The ONCOR (Lancaster, TX, USA) microgrid has small fault currents as well when the microgrid is islanded. As a solution, a dynamic protection system was implemented by installing eight protective relays with assisted-communication that enabled the microgrid to alter its protection scheme according to the operating mode based on an adaptive protection scheme. However, at the Boralex Planned Islanding microgrid (Senneterre, QC, CND), protection coordination at the islanded mode showed that the protection settings of protective devices did not need to change due to the large size of the steam turbine that allowed the same fault current magnitudes to be maintained during islanded mode. In conclusion, each microgrid needs to be studied individually to determine its protection schemes because not all microgrids need to adapt their protection schemes to the grid-connected and islanded modes.

The conventional protection schemes applied in North American projects are shown in Figures 2-a. The power quality is represented by the voltage and frequency ranges. The overvoltage (59), undervoltage (27), and frequency (81) elements were the most common conventional protection schemes related to the power quality of the microgrids. In addition, the overvoltage (59), undervoltage (27), and frequency (81) elements were used to detect the islanding conditions. The directional overcurrent (67) elements played an important role in microgrid projects because they allowed external (grid) faults to be distinguished from internal (microgrid) faults. In addition, the directional overcurrent (67) elements were set in forward and reverse direction by using inverse time (51) and instantaneous (50) overcurrent curves. The nonconventional protection schemes applied in actual North American projects are shown in Figures 2-b. The adaptive protection scheme was the most common nonconventional protection scheme applied in the microgrids. The scheme could detect if the microgrid was set in grid-connected or islanded mode and select the relay settings for the actual microgrid conditions and avoid relay misoperations. The voltage-restrained overcurrent protection scheme was also used for the islanded modes of the microgrid. The scheme provided improved sensitivity of overcurrent relaying by making the set overcurrent operating value proportional to the applied input voltage. The voltage-restrained overcurrent protection improved the sensitivity of the overcurrent relays for small fault currents.

Table 7 shows the conventional and nonconventional protection schemes for the microgrid projects collected in this literature review for USA, Mexico and Canada. The microgrid protection systems depend on integrating the conventional and nonconventional protection schemes, to keep a balance between the protection system cost and technical complexity to operate the microgrid.

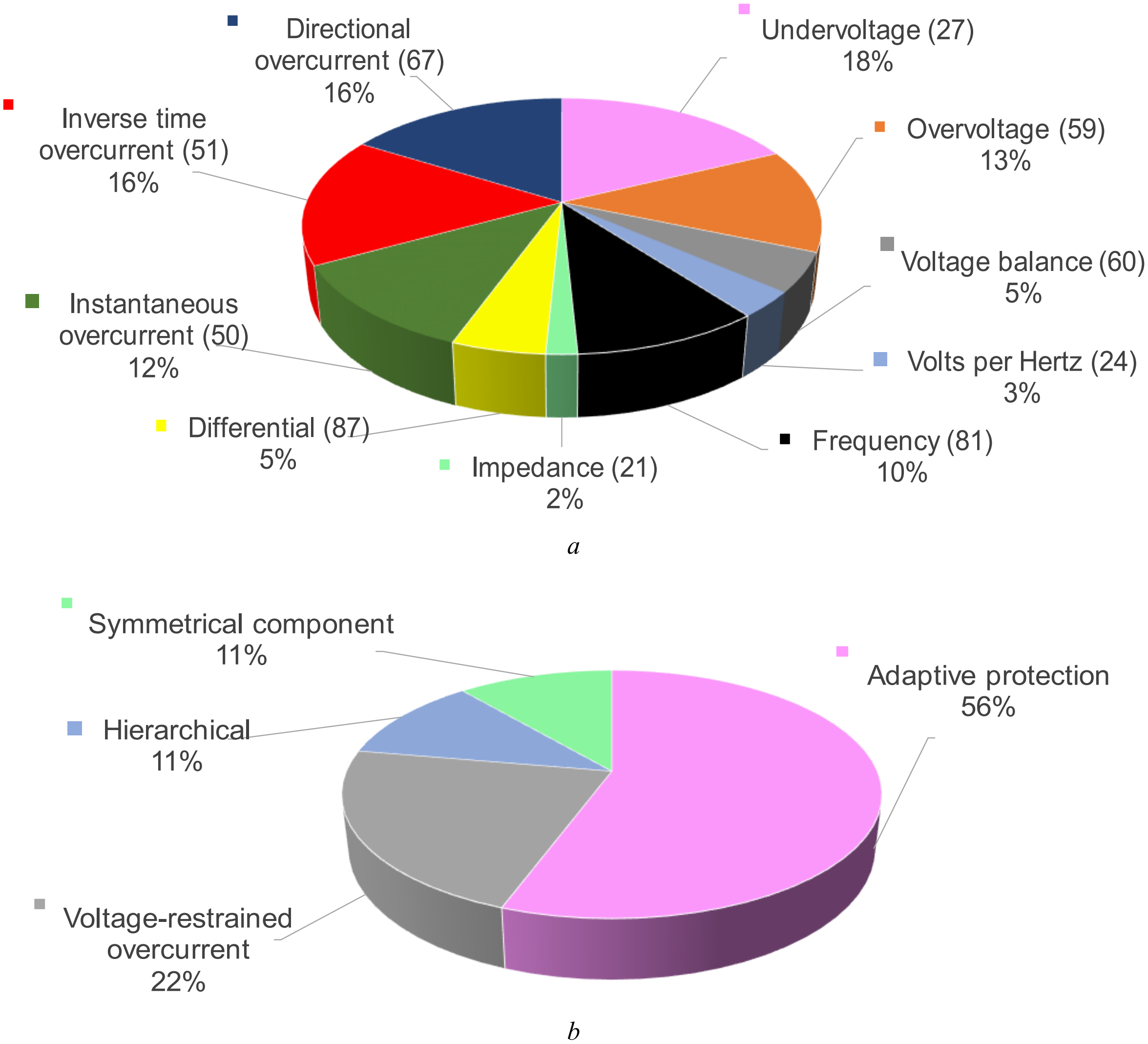

Figure 2. Conventional (a) and nonconventional (b) protection schemes for microgrids.

Table 7. Conventional and nonconventional protection schemes for North American microgrid projects.[a]

COUNTRY	Microgrid Projects	Conventional Protection Schemes										Non-Conventional Protection Schemes			
		27	59	60	24	81	21	87	50	51	67	Adaptive protection	Voltage-restrained overcurrent	Hierarchical	Symmetrical component
USA	Electric Power Board Microgrid, Chattanooga (TN)										X	X			
	Duke Energy Microgrid, Mount Holly (NC)	X	X			X					X				
	UC Microgrid, San Diego (CA)						X	X	X	X	X				
	Consortium for Electric Reliability Technology Solutions, Columbus (OH)	X	X			X					X				X
	Santa Rita Jail Microgrid, Dublin (CA)	X	X			X					X				
	Illinois Institute of Technology Microgrid, Chicago, IL	X	X			X		X		X	X	X		X	
	San Diego Gas and Electric Company's Microgrid, Borrego Springs (CA)												X		
	ONCOR Microgrid, Lancaster (TX)									X	X	X			
	NEDO Microgrid, Los Alamos (NM)								X	X	X	X			
	Palmdale Water District Microgrid, Palmdale (CA)	X	X	X					X	X	X				
MEX	Guásimas del Metate (NAY) Solar Microgrid	X		X	X				X	X					
	Tierra Blanca del Picacho (GTO) Solar Microgrid	X		X	X				X	X					
CND	Wind-Diesel Microgrid, Ramea, Newfoundland (NLA)	X							X	X	X				
	BC Hydro Microgrid, Boston Bar (BC)	X	X							X		X	X		
	British Columbia Institute of Technology Microgrid, Burnaby (BC)	X	X			X		X							
	Boralex Planned Islanding Microgrid Senneterre (QC)	X	X			X			X	X					

[a] Undervoltage (27), Overvoltage (59), Voltage Balance (60), Volts per Hertz (24), Frequency (81), Impedance (21), Differential (87), Instantaneous Overcurrent (50), Inverse Time Overcurrent (51), Directional Overcurrent (67)

The inertia of DERs in microgrids limits the frequency variations in the case of sudden load or generation changes. The penetration of DERs based on renewable energy can reduce the inertia of the grid, and the synthetic inertia can be introduced using smart grid techniques to overcome this problem [36]. In the standard operation of a power system, the frequency is regulated within strict limits by adjusting the electrical supply to meet the demand. If the balance between generation and demand is not reached, the system frequency changes at a rate initially determined by the inertia of the total system. The total system inertia comprises the combined inertia of most of the spinning generation and load connected to the power system [37]. The low levels of rotational inertia in microgrids by an inverter connected to DERs, such as wind turbines and PV panels, do not provide any rotational inertia and have some effect on the microgrid's frequency dynamics [36]. By the way, the loss of rotational inertia, and its increasing time variance, leads to frequency instability phenomena in microgrids [38]. The wind turbines are asynchronous machines that do not have inherent inertia. However, several wind turbine suppliers enabled the rotating mass of the blades to be used to create synthetic inertia and feed additional power into the microgrid to support loss of generation [36]. In addition, wind turbines are variable in nature and may not be able to provide energy for frequency support during times of low production. Therefore, energy storage systems based on providing primary and long-term support energy can also provide the synthetic inertia or dynamic support for microgrids. Although many microgrids with storage systems installed do not have a means of communication between all devices in the network [36], the interconnection and communication between all microgrid protection and control devices is a feature that will allow effective use of distributed energy storage systems to provide frequency support [39].

This report focused on both current industry practices and the ongoing projects examining new methods of protecting microgrids. In this study, microgrids were considered in grid-connected and islanded modes with hydropower/diesel generators, gas/steam turbines that are typically spinning inertia cases where the fault current magnitudes can be detected for islanded modes, and modern wind turbines and PV panels with energy storage systems that can generate the synthetic inertia to provide frequency support during the load-connected and islanded mode operations.

Overvoltage (59), undervoltage (27), frequency (81), volts-per-hertz (24), and voltage-restrained overcurrent protection schemes were applied to the islanded modes with DERs that had small fault current magnitudes. These protection schemes improved the sensitivity for small fault currents, but the selectivity of the protection system along the microgrid was affected because of the small magnitude of the fault currents. In addition, the directional overcurrent (67) elements played an important role in microgrid projects because the directional overcurrent (67) elements could distinguish between external (grid) and internal (microgrid) faults, and the directional overcurrent (67) elements were set in forward and reverse direction by using inverse time (51) and/or instantaneous (50) overcurrent curves. The interface static switch had also an important function because it islanded the microgrid after having power quality incidents [17], based on protection functions, setting ranges, and clearing times provided by Table 1 [18].

Of the nonconventional protection schemes, using adaptive protection to change the overcurrent protection settings in the islanded and grid-connected modes was the most common practice for the majority of the microgrid projects. Adaptive protection also needs to implement a communication system to monitor the substation breaker states and set the protection settings changes for the microgrid operation modes.

5. CONCLUSIONS

The microgrid projects examined in this report used different types of distributed energy resources (DERs) and operational modes in various configurations. Microgrid protection schemes must therefore be considered on a case-by-case basis in order to address the specific protection and control challenges of each microgrid and to obtain the best technical and economical solution. Conventional protection schemes are used in microgrid projects, but new protection schemes (nonconventional protection schemes) are also needed to integrate different DERs, such as hydropower/diesel generators, gas/steam/wind turbines, and PV systems, with energy storage into grid-connected and islanded modes.

The main goal of this study was to examine each microgrid individually based on its operational modes and types of DERs, the results of which are critical to designing the best technical and economical solutions for the protection and control system of microgrid projects. The protection scheme results and discussions of North American microgrid projects presented in this report provide crucial information that can be used to guide protection and control engineers and/or researchers in defining protection schemes for microgrids based on the types of DERs and microgrid operational modes.

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