

1 **Protection Schemes Used in North American Microgrids***

2
3 Emilio Carlos Piesciorovsky**, Travis Smith, Thomas Benjamin Ollis

4 Electrical and Electronics Systems Research Division, Oak Ridge National Laboratory,
5 Oak Ridge, Tennessee, 37830, USA.

6
7 *This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-
8 00OR22725 with the US Department of Energy (DOE). The US government retains and the
9 publisher, by accepting the article for publication, acknowledges that the US government
10 retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the
11 published form of this manuscript, or allow others to do so, for US government purposes.
12 DOE will provide public access to these results of federally sponsored research in accordance
13 with the DOE Public Access Plan (<http://energy.gov/downloads/doe-public-access-plan>).

14
15 ** Correspondence: Oak Ridge National Laboratory, Electrical & Electronics Systems
16 Research Division, Oak Ridge, TN, 37830, USA. Email address: piesciorovec@ornl.gov

17 18 **Summary**

19
20 This study reviewed existing conventional and nonconventional protection schemes for
21 grid-connected and islanded mode operations in North American microgrid projects. The
22 microgrid projects investigated in this study used different types of distributed energy

23 resources (DERs) and integrated hydropower/diesel generators, gas/steam/wind turbines, and
24 photovoltaic systems with energy storage. In this work, conventional protection schemes were
25 defined as those within the IEEE Standard C37.2-2008, while nonconventional schemes were
26 those not defined within this standard. The pros and cons of conventional and
27 nonconventional protection schemes were discussed in detail. The overvoltage, undervoltage,
28 and frequency elements were the most common conventional protection schemes applied in
29 microgrid projects in North America. These protection elements were used to detect the
30 islanded conditions and faults that could not be sensed by overcurrent relays because of small
31 fault currents contributed by low-inertia DERs and power-electronic sources. Directional
32 overcurrent elements were used to distinguish between external (grid) and internal (microgrid)
33 faults. Adaptive protection was the most popular nonconventional protection scheme applied
34 to the microgrid projects. In conclusion, different types of DERs and operational modes must
35 be considered in order to address the protection and control challenges of each microgrid and
36 to obtain the best technical and economical solution.

37

38 **Keywords:** microgrid, power system protection, relaying, distributed generators

39

40 **1. Introduction**

41

42 Oak Ridge National Laboratory has been assigned to formulate the protection schemes
43 constraints for microgrid designs. These constraints feed into an optimization of microgrids,
44 which could be applied to determine how, where, and what electrical designers should invest

45 in protection and control equipment for networked microgrids to enhance and balance the
46 reliability and cost, respectively, of new microgrid projects. This work focuses on current
47 industry practices, as well as recent research projects. Grid-connected and islanded cases with
48 hydropower generators (spinning inertia cases), modern wind turbines, and photovoltaic (PV)
49 panels with energy storage systems (synthetic inertia cases) were evaluated. This paper
50 reviews existing methods used to protect microgrids while islanded and/or grid connected and
51 defines and presents a detailed review of conventional and nonconventional protection
52 schemes applied in microgrid projects. Conventional protection schemes were defined as
53 those described in the ANSI/IEEE Standard Device Numbers Standard, while
54 nonconventional were those not included in this standard.¹ North American microgrids have
55 been growing in number in an effort to provide more reliable grid connectivity to our
56 communities, and they have played an important role in supplying uninterrupted energy to
57 utilities' customers in blackout situations. Microgrids can be operated in grid-connected or
58 islanded modes, and they are designed based on different protection schemes to enhance their
59 reliability, resilience, and power quality.²⁻⁵

60 General aspects of microgrids are explained in detail in previous publications.^{2, 6} Hirsch et
61 al.² described the technologies, key drivers, and outstanding issues of microgrids and focused
62 on general microgrid definitions and functional classification schemes. The review article,²
63 explained what a microgrid is and provided a multidisciplinary portrait of today's microgrid
64 drivers, real-world applications, challenges, and prospects. Bayindir et al.⁶ presented an
65 overview of North American microgrid facilities that described major microgrid projects,
66 compared each one with the others, and provided circuit diagrams and comparative tables.⁶

67 However, no protection schemes and industry practices for microgrid projects were described
68 in detail in these publications.^{2, 6} Other authors reviewed protection schemes.^{3, 4, 7-10} Oudalov
69 et al.³ and Edwards and Manson⁹ presented a detailed description of microgrid protection
70 schemes published by relay original equipment manufacturers. Oudalov et al.³ presented a
71 novel adaptive microgrid protection system using digital relaying and advanced
72 communication. This protection system was based on a centralized architecture where relay
73 protection settings were modified according to microgrid operating conditions³. Edwards and
74 Mason⁹ explained how microprocessor-based protective relays were used to provide control
75 and protection functions for small microgrids. This paper included automatic islanding,
76 reconnection to the electric power system, dispatch of distributed generation, compliance with
77 IEEE specifications, load shedding, volt/VAR control, frequency, and power control at the
78 point of interface.⁹ Haron et al.⁷ described different protection functions and schemes focused
79 on research publications instead of microgrid projects. This paper reviewed the available
80 protection schemes and coordination techniques applied to address protection issues in
81 microgrid distribution systems, discussing the implementation of methods, modes of
82 operation, types of distributed generators, and availability of communication links.⁷ Buigues
83 et al.⁴ and Laaksonen et al.¹⁰ described microgrid protection challenges and future
84 communication principles, respectively. Buigues et al.⁴ presented a comprehensive overview
85 of the existing microgrid protection methods based on research publications and described the
86 most important technical challenges for existing techniques in microgrid protection schemes.⁴
87 Laaksonen¹⁰ presented a future protection concept for low-voltage microgrids using IEC-
88 61850-based communication to achieve a fast, selective, and reliable operation for microgrid

89 protection schemes. Shiles et al.⁸ described different protection schemes for microgrid projects
90 and provided an overview and analysis of protection schemes that have been implemented in
91 major North American microgrid projects. This publication provides a brief overview of
92 microgrid protection issues and potential solutions to help designers define protection
93 requirements for practical microgrids.⁸

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

107

108 **2. Operation and Protection Schemes in North American Microgrids**

109

110 **2.1. Electric Power Board (EPB) Microgrid, Chattanooga (TN) – USA**

111

112 The Electric Power Board (EPB) microgrid is in Chattanooga, Tennessee. This networked
113 microgrid is based on an EPB currently installed and operating system.¹¹ The microgrid has
114 46/12.47 kV Ridgedale and Riverside substations. The Ridgedale substation is supplied by
115 diesel generators that are located near the EPB Operations Building. The diesel generators are
116 currently configured to provide emergency power to the Operations Building and isolate the
117 rest of the microgrid when in use. A third 0.24/12.47 kV substation provides energy from a
118 PV and energy storage system with a DC/AC inverter. This system has 4408 solar panels that
119 can generate 1.3 MW to feed residential customers.

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

133 flowing in a reverse or forward direction, depending on the microgrid operation mode (grid
134 connected or islanded). Figure 1 shows the EPB microgrid simplified one-line diagram.

135

136 **Figure 1.** Electric Power Board microgrid simplified one-line diagram.

137

138 **2.2. Duke Energy Microgrid, Mount Holly (NC) - USA**

139

140 The Duke Energy Microgrid is located in Mount Holly, North Carolina, and was installed
141 at the McAlpine Creek Substation. This microgrid is a 12.47/0.48 kV system that has a
142 substation with a 50 kW PV DERs and a 240 kW (500 kWh) battery energy storage system.¹³
143 These two systems are connected in parallel to import and export energy. The PV and the
144 battery energy storage systems ensure reliable and resilient power during prolonged grid
145 outages.¹³ The microgrid also serves the critical load of the fire station. Figure 2 shows the
146 online-diagram of Duke Energy microgrid.¹³

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

155 have directional overcurrent, frequency, and voltage protection schemes that were applied for
156 the microgrid.

157

158 **Figure 2.** Duke Energy microgrid one-line diagram.¹³

159

160 **2.3. University of California Microgrid, San Diego (CA) - USA**

161

162 The microgrid at the University of California, San Diego, serves a campus community of
163 more than 45,000 people. This microgrid generates 80% of the electricity used on campus
164 annually.¹⁴ The campus controls the generation and then purchases power on the market. The
165 microgrid has gas turbines (2×13.5 MW), a steam turbine (3 MW), a PV panel system (3
166 MW), and a methane fuel power cell (2.8 MW). This microgrid provides significant benefits
167 such as power generation, storage, transport, and electricity to the campus and can connect to
168 the larger electric grid or work independently. It can “island” in a power emergency,
169 disconnecting from the grid and maintaining its own critical functions. The University of
170 California reports savings of more than \$800,000 in power costs per month because of its
171 microgrid.¹⁴ Figure 3 shows a simplified microgrid diagram for the University of California,
172 San Diego.¹⁵ More than 100 SEL devices were used¹⁶ to provide a protection and control
173 system for this microgrid. These devices ranged from protective relays to automation control
174 and communication equipment,¹⁶ as well as other devices from other manufacturers. The
175 protective relays used on this microgrid were SEL 311L Line Current Differential Protection
176 and Automation System, SEL-751 Feeder Protection Relays, SEL-487B Bus Differential and

177 Breaker Failure Relays, SEL-587Z High-Impedance Differential Relays, and SEL-700G
178 Generator Protection Relays.¹⁶

179

180 **Figure 3.** University of California, San Diego, simplified microgrid diagram.¹⁵

181

182 **2.4. Consortium for Electric Reliability Technology Solutions Microgrid, Columbus** 183 **(OH) - USA**

184

185 The Consortium for Electric Reliability Technology Solutions (CERTS) microgrid testbed
186 is a 13.2/0.48 kV system operated by the American Electric Power (AEP). The CERTS
187 testbed is a microgrid with natural gas DERs. This microgrid has three feeders with 60 kW
188 inverter-based natural gas DERs that are connected to the utility grid. The inverter-based
189 natural gas DER feeders and the utility grid are connected through an interface static switch.¹⁷
190 The microgrid is protected with a symmetrical-component-based scheme. However, the
191 interface static switch is equipped with conventional protection schemes such as overvoltage
192 (59), undervoltage (27), overfrequency and underfrequency (81), and directional overcurrent
193 (67). The interface static switch is capable of islanding the microgrid¹⁸ during power quality
194 incidents, based on protection function responses shown in Table 1.^{8, 19} However, the design
195 of the CERTS microgrid has not considered a protection study against faults within the island
196 in this project. Figure 4 shows the CERTS microgrid in Ohio.⁶

197

198

199 **Table 1.** Protection settings for the interface static switch.^{8, 19}

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

200

201 **Figure 4.** Consortium for Electric Reliability Technology Solutions microgrid in Ohio.⁶

202

203 **2.5. Santa Rita Jail Microgrid, Dublin (CA) – USA**

204

205 The Santa Rita Jail Microgrid in Dublin (CA) provides energy to approximately 4,000
 206 inmates.²⁰ This microgrid is a 12.47/0.48 kV system with a PV system (1.5 MW), a molten
 207 carbonate fuel cell (1.0 MW), backup diesel generators (2×1.0 MW), storage battery system
 208 (2.0 MW/4.0 MWh) and wind turbine generators (5×2.3 kW). The microgrid interconnection
 209 is enabled with an interface static switch, which permits fast isolation of the microgrid. The
 210 interface static switch has islanding and synchronization functions without the need for
 211 external signals and is set with conventional protection functions such as overvoltage (59),
 212 undervoltage (27), and overfrequency and underfrequency (81) that are used to detect
 213 islanding situations.⁸ In addition, the directional overcurrent (67) elements are used to
 214 distinguish between external (grid) and internal (microgrid) faults. The overvoltage (59),

215 undervoltage (27), and overfrequency and underfrequency (81) elements of the interface static
216 switch and microgrid DERs are coordinated to ensure the DERs remain online during the
217 islanding situations. Figure 5 shows the one-line diagram for the Santa Rita Jail microgrid.²¹
218 The interface static switch is capable of islanding the microgrid¹⁸ during power quality
219 incidents, based on protection function responses shown in Table 1,^{8, 19} similar to the CERTS
220 microgrid, Columbus (OH) – USA. The protection scheme of the Santa Rita Jail microgrid
221 does not have selective coordination against faults within the islanded microgrid. Thus, a fault
222 within the islanded microgrid leads to a shutdown of the entire island. In addition, a backup
223 breaker is provided for the interface static switch. This backup device is a 12 kV standard
224 vacuum circuit breaker with protective relays installed upstream from the interface static
225 switch. The backup circuit breaker operates when the protection schemes of the interface
226 static switch fail.

227

228 **Figure 5.** Santa Rita Jail microgrid one-line diagram.²¹

229

230 **2.6. Illinois Institute of Technology Microgrid, Chicago (IL) – USA**

231

232 The Illinois Institute of Technology (IIT) Microgrid²² is located in Chicago. It is a
233 12.47/4.16/0.48 kV system with natural gas (8 MW) and wind (8 kW) turbines and PV (300
234 kV) and flow battery (500 kWh) systems. This microgrid is fed through two 12.47/4.16 kV
235 transformer substations to ensure seamless operation of the system if one of the feeders fails.
236 In the substations, transformers are installed with appropriate protective devices. However, the

237 IIT microgrid uses a hierarchical protection scheme. This hierarchical protection scheme is
 238 based on localized differential protection in seven loops and four coordinated protection
 239 levels, which are implemented by communication-assisted digital directional relays.²³ Table 2
 240 shows the conventional protection schemes and functions (primary, backup, and others) of the
 241 four levels for the hierarchical protection scheme in the IIT microgrid. Figure 6 shows the IIT
 242 microgrid one-line diagram.⁸

243

244 **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

245

246 **Figure 6.** Illinois Institute of Technology microgrid one-line diagram.⁸

247

248 2.7. San Diego Gas and Electric Company's Microgrid, Borrego Springs (CA) – USA

249

250 The Borrego Springs Microgrid, developed by the San Diego Gas and Electric Company,
251 provides energy to 615 customers with a peak load of 4.6 MW. This microgrid is fed by a
252 69/12 kV substation from the utility grid side and has two diesel generators (2×1.8 MW), a
253 PV (0.7 MW) system, and a substation battery (500 kW/1500 kWh) system with three
254 feeders.²⁴ In the Borrego Springs Microgrid, the magnitudes of the fault currents in the island
255 mode are so small that overcurrent relays cannot trip. As a result, a voltage-restrained
256 overcurrent protection was designed for the islanded modes of the microgrid. The voltage
257 restrained overcurrent protection provides improved sensitivity of overcurrent relaying by
258 making the set overcurrent operating value proportional to the applied input voltage. The
259 voltage restrained overcurrent protection improved the sensitivity of the overcurrent relays for
260 small fault currents, but the selectivity of the protection system along the microgrid remains
261 affected because of the small magnitude of the fault currents. Figure 7 shows the San Diego
262 Gas and Electric Company's microgrid one-line diagram.²⁵

263

264 Figure 7. Borrego Springs Microgrid one-line diagram.²⁵

265

266 2.8. Oncor Microgrid, Lancaster (TX) – USA

267

268 The ONCOR microgrid is a 12.47/0.48 kV system (1 MW) located in Lancaster, Texas.
269 This microgrid has four smaller operating zones. The “Telecom Operations” and “Meter
270 Shop” zones have diesel generators, the “Transformer Shop” zone contains the battery energy
271 storage, and the “TDEC and Environmental Lab” zone has two PV systems, battery energy
272 storage, and a microturbine. Figure 8 shows the Oncor microgrid one-line diagram.²⁶

273

274 **Figure 8.** Oncor microgrid one-line diagram.²⁶

275

276 This microgrid is fed by a 12.47 kV overhead distribution line through an automatic
277 isolation switch that provides the protection and control functions to operate as islanded or
278 grid-connected modes. An S&C IntelliRupter was installed at this interconnection point to
279 detect the voltage loss on one or more phases. The IntelliRupter quickly isolates the microgrid
280 to perform islanding. When the source is suitable for reconnection, the IntelliRupter quickly
281 reconnects to the grid.²⁶ Downstream from the IntelliRupter and serving the four microgrid
282 zones, an S&C’s SCADA-Mate Switching System was applied on the overhead lines.²⁶ This
283 system provides the isolating and sectionalizing functionality to have automatic fault isolation
284 and circuit restoration capabilities. In this microgrid, issues related to the protection scheme
285 were addressed. When the microgrid was connected to the electric grid, the fault current
286 magnitudes were detected by the protection scheme. However, when islanded, the fault
287 current magnitudes on site were substantially reduced because of limited onsite generation.
288 Hence, the microgrid required a protection scheme that would operate securely for both grid-
289 connected and islanded operations. As a solution, a dynamic protection system was

290 implemented by installing eight protective relays with assisted communication.²⁶ This
291 protection system enabled the microgrid to alter its protection scheme according to the
292 operating mode based on an adaptive protection scheme. The protective relays use the IEC
293 61850 Generic Object-Oriented Substation Events (GOOSE) messaging to perform protection
294 setting decisions to protect the microgrid regardless of whether it was grid connected or
295 islanded.²⁶

296

297 **2.9. New Energy and Industrial Technology Development Organization Microgrid,** 298 **Los Alamos (NM) - USA**

299

300 The New Energy and Industrial Technology Development Organization (NEDO)
301 Microgrid is in Los Alamos, New Mexico. This project was developed by Los Alamos County
302 Department of Public Utilities (LACU) through a collaboration with Japan. This microgrid has
303 a Japanese PV system (2×1 MW) and battery storage (1.8 MW). The project is based on the
304 integration and control of PV technology with Micro Energy Management System (EMS) on
305 an American distribution system.²⁷ The PV system and battery storage are integrated into the
306 Los Alamos power plant to work under diverse situations and to achieve a reliable power
307 supply under unstable operational conditions by charging or discharging the batteries. This
308 microgrid feeds power to approximately 1,900 customers. Figure 9 shows the NEDO
309 microgrid one-line diagram.⁶

310

311 **Figure 9.** New Energy and Industrial Technology Development Organization microgrid one-
312 line diagram.⁶

313

314 The protection and control devices are optical fiber communication lines. The S&C Vista
315 pad-mounted switchgear is used to integrate the NEDO and LACU generation sources.²⁸ The
316 Vista utilizes bidirectional SEL 451 relays to accommodate the reverse power flow conditions
317 from the battery and PV system. The fault current conditions of the electrical system change
318 depending on the microgrid source of connectivity. Therefore, the SEL relays need to be set
319 on either parallel mode (normal operation) or islanding mode (sole supply source). The Micro
320 EMS has the functionality to provide islanding connectivity to part of the LACU distribution
321 system but only after a complete feeder shutdown.²⁸

322

323 **2.10. New Energy and Industrial Technology Development Organization Microgrid,** 324 **Los Alamos (NM) - USA**

325

326 The Palmdale Water District (PWD) Microgrid Project has renewable and nonrenewable
327 DERs that feed some external loads of a water treatment plant. This microgrid is a 0.48 kV
328 system that has two backup diesel generators (1×1000 kW / 1×800 kW), a wind turbine
329 (950 kW), and hydro (250 kW) and natural gas (200 kW) generators with an ultra-capacitor
330 (450 kW). Figure 10 shows the PWD microgrid one-line diagram.⁶

331

332 **Figure 10.** Palmdale Water District microgrid one-line diagram.⁶

333 This microgrid decreased energy expenses, improved the energy system dependability,
334 and enhanced the power quality.²⁹ The ultra-capacitor (450 kW), DC/AC power conversion
335 and static switch is known as the “EnergyBridge™ EB 450,” which is the energy storage
336 system for the PWD microgrid. The EnergyBridge™ EB 450 system has static switching and
337 PowerRouter controls that are combined with Maxwell Technologies.²⁹ The system provides
338 energy for critical load demand and high-quality power to protect loads during utility
339 disturbances and seamlessly transitions to a backup generator in the event of a grid outage. It
340 can support loads up to 450 kW for 30 seconds.²⁹

341

342 **2.11. Ameren Microgrid, Champaign (IL) - USA**

343

344 The Ameren microgrid project has renewable and non-renewable DERs that feed some
345 external loads. The microgrid installation at the Ameren Illinois Technology Applications
346 Center near the University of Illinois campus in Champaign was designed, engineered, and
347 constructed by S&C Electric Company, and integrates wind, solar, natural gas, and battery
348 storage.³⁰ The Ameren microgrid project involved a nested 50 kW microgrid within a 1 MW
349 microgrid, all interconnected at 12.47 kV. S&C Electric Company constructed both a 100 kW
350 wind turbine and a 125 kW solar array, and provided the utility with two 430 kW natural gas
351 generators as additional alternative energy sources.^{31,32} Also, a 250 kW (500 kWh) energy
352 storage was provided to serve as the backbone of the microgrid, enabling it to operate on
353 100% renewable generation.³¹ The Ameren microgrid one-line diagram is shown in Figure 11.

354

355 **Figure 11.** Ameren microgrid one-line diagram.³⁰

356

357 The Ameren microgrid challenge was to test the facility in a real-world scenario that used
358 the same switchgear, sensing, and protections systems to accommodate both grid-connected
359 and islanded power sources. This is especially complicated because the main grid has a fault-
360 current potential of thousands of amperes, while the faults within an islanded microgrid could
361 be in the tens of amperes.³¹ In the Ameren microgrid, S&C Electric Company developed an
362 adaptive protection and control software to help with the transition of the multiple generation
363 sources into and out of “microgrid mode” without creating an outage.³¹ Also, following a
364 utility outage, the company also developed a way to “black start” the microgrid without the
365 need for a reference voltage from the utility source. To accomplish this, a PureWave® SMS-
366 250 Storage Management System (SMS) provides battery energy storage for the smaller of the
367 two microgrids. The PureWave® SMS-250 allows Ameren to fully integrate renewable
368 energy sources. The wind and solar generation can run in the microgrid and exceed the load
369 because the PureWave SMS-250 can be put into charging mode while still providing the
370 microgrid reference frequency and voltage.³¹ A Remote Supervisory Vista® Underground
371 Distribution Switchgear integrated the microgrid, providing also SpeedNet™ Radios to
372 support device communication. To make the various sources of generation work smoothly,
373 both in the main grid and within the islanded microgrid, a Grid Master® Microgrid Control
374 System was installed. The system has nine IPERC® cybersecure, adaptive, and distributed
375 Intelligent Power Controllers, and provides control functionality of the microgrid.³¹

376

377 **2.12. University of California Irvine Microgrid, Irvine (CA) - USA**

378

379 The University of California Irvine (UCI) microgrid is in the main campus of the
380 University of California, Irvine (CA). The UCI Microgrid is a test bed that is served by
381 Southern California Edison through the UCI Substation, which steps down voltage from 66 to
382 12.4 kV using two 15 MVA transformers. It also encompasses ten 12.4 kV circuits,
383 includes 3.7 MW of solar power, and is served by a 13.5 MW gas and a 5.6 MW steam turbine.
384 The test bed incorporates a centralized chilling plant, including a large thermal energy storage
385 tank (4.5 million gallons/60,000 ton-hours), and serves all major buildings with district
386 heating and cooling.^{33,34} The UCI microgrid also contains a set of distributed energy resources
387 that includes two-axis tracking concentrated solar photovoltaic systems, and a 2 MW/ 500
388 kW-hr Li-Ion battery deployed at the UCI substation. More than 100 advanced meters have
389 been installed to obtain high-resolution load data. Under the Zero Emission Vehicle-Network
390 Enabled Transport program, a fleet of 77 advanced vehicles are installed.³⁵ The UCI microgrid
391 one-line diagram is shown in Figure 12.³³

392

393 **Figure 12.** University of California Irvine microgrid one-line diagram.³³

394

395 The UCI microgrid protection system was based on the islanding field demonstration
396 using four SEL devices.³³ A SEL 451 protection, automation, and bay control system relay
397 detects the loss of utility power, and generates a direct transfer trip signal to a SEL 700G
398 Generator Protection Relay. Upon receipt of a transfer trip from the SEL 451, the 700G

399 Generator Protection Relay interfaces to the control inputs of the gas turbine, and adjusts the
400 turbine frequency and voltage reference set points and operation mode control. It also
401 implements resynchronization of the gas turbine to the grid.³³ In addition, a SEL 3530 real-
402 time automation controller serves as a data acquisition and interface system, and a SEL 751
403 feeder protection relay trips and closes the point of common coupling breaker.³³ In the UCI
404 microgrid protection, the standard generator protection curves for phase and ground current
405 differential, phase instantaneous overcurrent, time delay overcurrent, phase unbalance,
406 under/overvoltage, over/under frequency, and rate of change frequency identified the
407 operation scenarios that cannot achieve seamless islanding.³³ Those results allowed to
408 determinate a range for islanding capabilities. Then, protection setting groups and other
409 operating modes were applied for islanding and grid connectivity, based on adaptive
410 protection scheme.³³

411

412 **2.13. Guasimas del Metate (NAY) / Tierra Blanca del Picacho (GTO) Solar Microgrids** 413 **– MEX**

414

415 The Guasimas del Metate and Tierra Blanca del Picado microgrids are located in the states
416 of Nayarit (NAY) and Guanajuato (GTO) in Mexico. These microgrids are part of the “White
417 Flag Program” sponsored by the Electrical Federal Commission of Mexico.³⁶ The objective of
418 this program was to provide energy to isolated communities by using renewable energy
419 systems. The microgrids of Guasimas del Metate and Tierra Blanca del Picacho are identical
420 and feed a load composed of approximately 52 households. Each microgrid includes an

421 integrated protection, control, and monitoring system. The system collects and processes data
422 from the microgrid substations and sends the data to the supervisory control and data
423 acquisition (SCADA) master of two remote control centers. The PV system (45.9 kW) for
424 each microgrid has solar arrays with a DC/AC inverter and a battery with a DC/AC inverter.³⁶
425 This PV system can collect and store energy that is consumed by residential customers. The
426 PV system is connected to a 0.22/13.8 kV transformer (75 kVA) that supplies energy to the
427 community by a radial distribution network of 13.8 kV. Figure 13 shows the Guasimas del
428 Metate and Tierra Blanca del Picacho solar microgrid one-line diagram.³⁶ The microgrid
429 protection schemes have SEL protective, control and communication devices. The control
430 systems of the solar array and battery bank inverters include an undervoltage protection
431 algorithm that detects DC and AC circuit faults and automatically shuts down the inverter in
432 approximately 5 ms. The undervoltage protection algorithm for the inverter control systems
433 provides the primary protection for faults in the DC and AC circuits. The relay that performs
434 the protection scheme for the microgrid trips the breaker located at the transformer low-
435 voltage side.

436

437 **Figure 13.** Guasimas del Metate and Tierra Blanca del Picacho solar microgrid one-line
438 diagram.³⁶

439

440 In this microgrid, the behavior of the phase overcurrent (50/51), ground overcurrent (51N),
441 undervoltage (27), voltage balance (60), and volts-per-hertz (24) relay elements was studied.
442 The volts-per-hertz (24) element was evaluated for failures at the inverter control system.³⁶

443 Table 3 shows the protective relay elements response for single-line-to-ground (SLG), line-to-
 444 line (LL), line-to-line-ground (LLG), and three-line (3L) faults on the 13.8 kV network. In
 445 Table 3, elements 27 and 60 trip to all (SLG-LL-LLG-3L) and unbalanced (SLG-LL-LLG)
 446 faults, respectively. The elements 27 and 60 were enabled as a backup protection scheme, and
 447 element 24 provided redundant backup protection for the inverter control system failures.³⁶

448

449 **Table 3.** Protection element response to faults on the 13.8 kV network.³⁶

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

450

451 **2.14. Wind-Diesel Microgrid, Ramea (NLA) – CND**

452

453 The Ramea Wind-Diesel Microgrid is located at the Newfoundland and Labrador area in
 454 Canada. This microgrid system was installed to provide energy to isolated communities. The
 455 microgrid is not connected to a grid because it is located on a small island 10 km from the
 456 south shore of Newfoundland, with a population of 700 (conventional fishery neighborhood).
 457 This project is a 4.16 /0.48 kV microgrid system with three CAT 3512 diesel generators (3 ×
 458 925 kW) and six wind turbines (6 × 65 kW).³⁷ This project is a self-ruling diesel-based system

459 with a medium-scale wind plant. The energy system has a peak demand and annual energy
460 generation of 1.2 MW and 4,556 MWh, respectively. If the power generation of the diesel
461 plant decreases to 30% of its capacity, the control mechanism recovers the lost potential by
462 integrating wind turbines into the system until the diesel generator again supplies over 30% of
463 its capacity.⁶ The average and minimum load of the system are 528 kW and 202 kW,
464 respectively. Figure 14 shows the Ramea wind-diesel microgrid one-line diagram.³⁷

465

466 **Figure 14.** Ramea wind-diesel microgrid one-line diagram.³⁷

467

468 The microgrid has two dissemination 4.16 kV feeders that are controlled with
469 WOODWARD controls, and modicon PLC.³⁸ A wind-diesel integrated control system
470 (WDICS) is used to control and supervise the operation of the wind turbines and to facilitate
471 their integration into the system, which is controlled and primarily supplied by the diesel
472 generator plant. The WDICS configuration is composed of a diesel plant master controller
473 (DPMC), a wind plant master controller (WPMC), and a SCADA system with internet access
474 for monitoring and data acquisition. The DPMC is a fully integrated and digital automatic
475 controller that supervises the overall wind-diesel network operation as well as
476 synchronization, load sharing, and load following control of the diesel generators. The WPMC
477 performs automatic control and protection of the wind power plant including start-up and
478 shutdown of the wind turbines. The WPMC also has communication with the DPMC to report
479 power generation of the turbines and to update the maximum limit for wind power import.
480 The communication link between DPMC and WPMC is a 1 km wireless connection.³⁷

481

482 **2.15. British Columbia Hydro Microgrid, Boston Bar (BC) – CND**

483

484 The British Columbia Hydro Microgrid is in Boston Bar (BC), Canada. This microgrid is a
485 4.16/25/69 kV system that has two hydropower generators (2×3.5 MW) joined by a single
486 bus. The system also has a 4.16/25 kV and 69/25 kV substations that are connected to the
487 hydropower generators and utility grid, respectively. In this microgrid, if the high-voltage
488 feeder encounters any deficiency, the microgrid can work in island mode. It allows a 3MW
489 peak load and 8.6 MVA of hydroelectric generation in the islanded mode.³⁹ The hydro
490 microgrid has the capacity to include the substation level or island mode immediately utilizing
491 remote auto-synchronization without bringing on load shedding. This proving ground and
492 genuine system operation has automatic and manual synchronization, and it was tested with
493 step load and dead load with black-start competence utilizing a 55 kW diesel generator.^{40,41}
494 This microgrid can supply one or more feeders during power outages. Figure 15 shows the
495 British Columbia hydro microgrid one-line diagram.⁶

496

497 **Figure 15.** British Columbia hydro microgrid one-line diagram.⁶

498

499 The protection methods applied to this project are based on an adaptive protection
500 schemes to change the overcurrent protection settings in the islanded mode and a positive-
501 voltage field control used in the excitation system to enable high fault currents for feeder
502 faults.⁴⁰ A remote auto-synchronization is applied to reconnect the microgrid in island mode.

503 The communication is implemented by a leased telephone line³⁹ that is used to monitor the
504 substation breakers and protection settings changes for the adaptive protection scheme.

505

506 **2.16. British Columbia Institute of Technology Microgrid, Burnaby (BC) – CND**

507

508 The British Columbia Institute of Technology (BCIT) Microgrid is located on campus in
509 Burnaby (BC), Canada. This project represents a scaled-down microgrid that is used for
510 research and instructional activities. This microgrid system has two wind turbines (2×5 kW),
511 a PV system (300 kW), steam turbine (250 kW), and Li-particle battery (550 kWh).⁶ This
512 microgrid feeds four areas, the Canada-way receiving station, Goard-way receiving station,
513 residential serving area, and small load centers.⁴² Seventy percent of total campus energy is
514 consumed by the Canada-way and Goard-way receiving stations. Figure 16 shows the British
515 Columbia Institute of Technology microgrid communication network.⁶

516

517 **Figure 16.** British Columbia Institute of Technology microgrid communication network.⁶

518

519 In this microgrid, a communication-aided fault detection, isolation, and service restoration
520 (FDIR) strategy was implemented that employs a differential protection to detect and locate
521 faults within the microgrid for grid-connected and islanded modes. This differential protection
522 scheme continuously monitors the three-phase currents at both ends of each 12.47 kV feeder.
523 When a fault is detected between the feeders, the currents at the beginning and end of the
524 feeders are not identical. If this current difference is sustained for three consecutive cycles (50

525 ms), a fault is declared by the protection devices. This time delay (50 ms) does not allow
526 tripping to occur for temporary faults or short-term disturbances.⁴² Once a fault is detected, a
527 trip signal is sent to the corresponding breakers. If the fault isolation results at the island
528 mode, the distribution management system sends a signal to the DER controllers to switch the
529 control mode from the active/reactive power to voltage/frequency mode such that the service
530 for the islanded mode is guaranteed at the microgrid.⁴²

531

532 **2.17. Boralex Planned Islanding Microgrid, Senneterre (QC) – CND**

533

534 The Boralex Planned Islanding Microgrid is in Senneterre (QC), Canada. It is a privately
535 owned thermal power plant that feeds the Hydro-Quebec network through the Senneterre
536 substation. This microgrid is a 13.8/120/25 kV system that supplies energy to 3,000
537 customers.⁴³ The Senneterre substation (120/25 kV) is connected to a 31 MVA steam turbine
538 (26.35 MW), 120 kV transmission line (grid-link), and three 25 kV feeders (1×7 MVA / 2×4
539 MVA). The steam turbine demonstrates a stable operation in isochronous mode under
540 differing loads when the peak load is about 7 MW.⁴³ In this microgrid, the steam turbine is
541 used to island the Senneterre substation during a possible restoration of the 120 kV
542 transmission line. Its islanding capacity allows the continuity of energy supply to Hydro-
543 Quebec customers.⁴⁴ This microgrid operates in islanded mode only for planned maintenance.
544 In such cases, the radial topology of the system is preserved, and the protection coordination
545 at the islanded mode has shown that the protection settings of protective devices do not need
546 to change due to the large size of the steam turbine that allows the same fault current

547 magnitudes to be maintained during the islanded mode.⁴⁴ This project showed that each
548 microgrid needs to be studied individually to determine its protection schemes because not all
549 microgrids need to adapt their protection schemes to the grid-connected and islanded modes.
550 Figure 17 shows the Boralex Planned Islanding microgrid one-line diagram.⁶

551

552 **Figure 17.** Boralex Planned Islanding microgrid one-line diagram.⁶

553

554 **3. Advantages and Disadvantages of Protection Schemes**

555

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

568

569 **Table 4.** Conventional protection schemes for microgrid projects.

Functions (Device N°)	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 fuses	-Needs to be complemented with directional and/or adaptive overcurrent protections -Needs communication
Directional Overcurrent (67)	- Provides proper solution to coordinate protective devices for different microgrid circuit paths	- Needs forward and reverse coordination - Needs adaptive settings

570

571 Alternatively, the nonconventional protection schemes are protection functions that are not
572 set in the ANSI/IEEE Device Numbers Standard¹ but are applied in current microgrids. The
573 most common nonconventional protection schemes applied in microgrids are adaptive,
574 voltage-restrained, hierarchical, and symmetrical component protection schemes. The
575 nonconventional protection schemes are based on traditional protection schemes but apply
576 additional functions that protect and control the distributed energy resources, DC/AC

577 inverters, energy storages, transformers, power lines, and feeders for different operation
 578 modes and/or circuit path applications for the microgrids. Table 5 shows the advantages and
 579 disadvantages of nonconventional protection schemes based on current and ongoing projects.

580

581 **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

582

583 **4. Results**

584

585 **4.1. Operation and Capacity of Microgrids in North America**

586

587 Microgrids are classified as small or large systems, depending on their size. In small
 588 microgrids, protective relays are used for control, metering, and protection. However, large
 589 microgrids are controlled by one or more centralized controllers connected to metering and
 590 protection devices. The metering and protection devices are controlled by a central device that
 591 can be connected to more than 100 distributed protective relays. The majority of microgrid
 592 projects in Canada and Mexico have hydro and solar DERs, respectively, whereas the majority

593 of microgrid projects in the USA have solar, wind, diesel, thermal, and gas DERs. Most
594 microgrids allow islanded and grid-connected modes. The microgrid projects in the USA and
595 Mexico have inverter- and rotation-based DERs because PV systems and rotative generators
596 are used. However, most microgrid projects in Canada are focused on rotation-based DERs
597 instead of PV systems because solar energy projects are usually not technically or
598 economically feasible in Canada. The microgrid projects use PV, wind, hydro, diesel, fuel
599 cells, steam, and gas turbines. Figure 18 shows the real power in MW supply by the DERs for
600 the microgrid projects. The DERs that provide most of the power supply for these microgrid
601 projects are represented by the hydro and gas turbines. Table 6 shows the operation modes,
602 types of DERs, and power supply for the microgrid projects collected in this literature review
603 for the USA, Mexico, and Canada.

604

605 **Figure 18.** Real power (MW) supply by distributed energy resources.

606 **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						
	Duke Energy Microgrid, Mount Holly (NC)	X	X	X		0.05						
	UC Microgrid, San Diego (CA)	X	X	X	X	3.0				2.8	3.0	27.0
	Consortium for Electric Reliability Technology Solutions, Columbus (OH)	X			X							0.18
	Santa Rita Jail Microgrid, Dublin (CA)	X	X	X	X	1.5	0.011		2.0	1.0		
	Illinois Institute of Technology Microgrid, Chicago, IL	X	X	X	X	0.3	0.008					8.0
	San Diego Gas and Electric Company’s Microgrid, Borrego Springs (CA)	X	X	X	X	0.7			3.6			
	ONCOR Microgrid, Lancaster (TX)	X	X	X	X	0.2			0.4			0.4
	NEDO Microgrid, Los Alamos (NM)	X	X	X		2.0						
	Palmdale Water District Microgrid, Palmdale (CA)	X	X		X		0.95	0.25	1.8			0.2
	Ameren Microgrid, Champaign (IL)	X	X	X	X	0.13	0.1					0.86
	University of California Irvine Microgrid, Irvine (CA)	X	X	X	X	3.7					5.6	13.5
MEX	Guásimas del Metate (NAY) Solar Microgrid		X	X		0.046						
	Tierra Blanca del Picacho (GTO) Solar Microgrid		X	X		0.046						
CND	Wind-Diesel Microgrid, Ramea, Newfoundland (NLA)		X		X		0.39		2.775			
	BC Hydro Microgrid, Boston Bar (BC)	X	X		X			14.0				
	British Columbia Institute of Technology Microgrid, Burnaby (BC)	X	X	X	X	0.3	0.01				0.25	
	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

608 **4.2. Protection Schemes Used in North American Microgrids**

609

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

625 The IIT microgrid (Chicago, IL, USA) has a hierarchy protection scheme with four
626 differential protection levels (load-way, loop, feeder, and microgrid protection levels). The
627 feeder protection level has an additional adaptive protection scheme with directional
628 overcurrent relay settings to detect faults at different microgrid modes. The ONCOR
629 (Lancaster, TX, USA) microgrid performs both grid-connected and islanded operations by an

630 adaptive protection scheme with assisted communication with relays using IEC 61850
631 GOOSE messaging to perform protection setting decisions. The BC hydro microgrid (Boston
632 Bar, BC, CND) has an adaptive protection scheme to change the overcurrent protection
633 settings in the islanded mode. Communication is provided via a leased telephone line, which
634 is used to monitor the substation breakers and protection setting changes for the adaptive
635 protection scheme.

636 The Ameren microgrid (Champaign, IL, USA) has an adaptive protection and control
637 software to help with the transition of the multiple generation sources into and out of
638 “microgrid mode” without creating an outage. Also, following a utility outage, it has a way to
639 “black start” the microgrid without the need for a reference voltage from the utility source.

640 The UCI microgrid (Irvine, CA, USA) also uses an adaptive protection. In this microgrid, the
641 standard generator protection curves for phase and ground current differential, phase
642 instantaneous overcurrent, time delay overcurrent, phase unbalance, under/overvoltage,
643 over/under frequency, and rate of change frequency identified the operation scenarios that
644 cannot achieve seamless islanding. Those results allowed to determine a range for islanding
645 capabilities. Then, protection setting groups and other operating modes were applied for
646 islanding and grid connectivity, based on adaptive protection scheme.

647 The Guasimas del Metate (NAY, MEX) and Tierra Blanca del Picado (GTO, MEX)
648 microgrids have rather small fault currents that overcurrent relays cannot trip because of solar
649 arrays and battery bank inverters. The application of undervoltage protection algorithm detects
650 DC and AC circuit faults and automatically shuts down the inverter in approximately 5 ms.
651 The undervoltage (27) and voltage balance (60) elements are enabled as backup protection

652 scheme, and the volts-per-Hertz (24) element is provided as redundant backup protection for
653 the inverter control system failures. The SDGEC (Borrego Springs, CA, USA) microgrid also
654 has small fault currents that overcurrent relays cannot trip. Consequently, a voltage-restrained
655 overcurrent protection was designed for the islanded modes of the microgrid. The voltage-
656 restrained overcurrent protection provides improved sensitivity of overcurrent relaying by
657 making the set overcurrent operating value proportional to the applied input voltage, but the
658 selectivity of the protection system along the microgrid is affected because of the small
659 magnitude of the fault currents. The ONCOR (Lancaster, TX, USA) microgrid has small fault
660 currents as well when the microgrid is islanded. As a solution, a dynamic protection system
661 was implemented by installing eight protective relays with assisted communication that
662 enabled the microgrid to alter its protection scheme according to the operating mode based on
663 an adaptive protection scheme. However, at the Boralex Planned Islanding microgrid
664 (Senneterre, QC, CND), protection coordination at the islanded mode showed that the
665 protection settings of protective devices did not need to change due to the large size of the
666 steam turbine that allowed the same fault current magnitudes to be maintained during islanded
667 mode. In conclusion, each microgrid needs to be studied individually to determine its
668 protection schemes because not all microgrids need to adapt their protection schemes to the
669 grid-connected and islanded modes.

670 The conventional protection schemes applied in North American projects are shown in
671 Figure 19. The power quality is represented by the voltage and frequency ranges. The
672 overvoltage (59), undervoltage (27), and frequency (81) elements were the most common
673 conventional protection schemes related to the power quality of the microgrids. In addition,

674 the overvoltage (59), undervoltage (27), and frequency (81) elements were used to detect the
675 islanding conditions. The directional overcurrent (67) elements played an important role in
676 microgrid projects because they allowed external (grid) faults to be distinguished from
677 internal (microgrid) faults. In addition, the directional overcurrent (67) elements were set in
678 forward and reverse direction by using inverse time (51) and instantaneous (50) overcurrent
679 curves.

680

681 **Figure 19.** Conventional protection schemes for microgrids.

682

683 The nonconventional protection schemes applied in actual North American projects are
684 shown in Figure 20. The adaptive protection scheme was the most common nonconventional
685 protection scheme applied in the microgrids. The scheme could detect if the microgrid was set
686 in grid-connected or islanded mode and select the relay settings for the actual microgrid
687 conditions and avoid relay misoperations. The voltage-restrained overcurrent protection
688 scheme was also used for the islanded modes of the microgrid. The scheme provided
689 improved sensitivity of overcurrent relaying by making the set overcurrent operating value
690 proportional to the applied input voltage. The voltage-restrained overcurrent protection
691 improved the sensitivity of the overcurrent relays for small fault currents.

692

693 **Figure 20.** Nonconventional protection schemes for microgrids.

694

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

700

701

702

703 **Table 7.** Conventional and nonconventional protection schemes for North American microgrid projects^a

COUNTRY	Microgrid Projects	Conventional Protection Schemes										Nonconventional Protection Schemes		
		27	59	60	24	81	21	87	50	51	67	Adaptive protection	Voltage-restrained overcurrent	Hierarchical
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			
	Ameren Microgrid, Champaign (IL)											X		
	University of California Irvine Microgrid, Irvine (CA)	X	X		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)

705 **5. Discussion**

706

707 Microgrids with renewable energy systems, such as wind farms and solar PV installations,
708 have been considered as promising generation sources to cover the continuously increasing
709 demand of energy.⁴⁵ However, the incoming high penetration of wind and solar distributed
710 generators at microgrids is increasing the electrical utility concerns about protection schemes⁴⁶
711 and power quality.⁴⁷

712 Microgrids with IBDG based on PV arrays could present low power quality because PV
713 arrays have individual current sources with independent DC current ripple of the converter
714 ripple. Then, PV array and converter ripple currents are not in synchronism and produce
715 subharmonics in the DC circuit that increase the total harmonic distortion in the current
716 waveform.⁴⁸ In addition, the inertia of DERs limits the frequency variations in the case of
717 sudden load or generation changes. The penetration of DERs based on renewable energy can
718 reduce the inertia of the grid, and the synthetic inertia can be introduced using smart grid
719 techniques to overcome this problem.⁴⁹ In the standard operation of a power system, the
720 frequency is regulated within strict limits by adjusting the electrical supply to meet the
721 demand. If the balance between generation and demand is not reached, the system frequency
722 changes at a rate initially determined by the inertia of the total system. The total system inertia
723 comprises the combined inertia of most of the spinning generation and load connected to the
724 power system.⁵⁰ The low levels of rotational inertia in microgrids by an inverter connected to
725 DERs, such as wind turbines and PV panels, do not provide any rotational inertia and have
726 some effect on the microgrid's frequency dynamics.⁴⁹ The loss of rotational inertia, and its

727 increasing time variance, leads to frequency instability phenomena in microgrids.⁵¹ The wind
728 turbines are asynchronous machines that do not have inherent inertia. However, several wind
729 turbine suppliers enabled the rotating mass of the blades to be used to create synthetic inertia
730 and feed additional power into the microgrid to support loss of generation.⁴⁹ In addition, wind
731 turbines are variable in nature and may not be able to provide energy for frequency support
732 during times of low production. Therefore, energy storage systems based on providing
733 primary and long-term support energy can also provide the synthetic inertia or dynamic
734 support for microgrids. Although many microgrids with storage systems installed do not have
735 a means of communication between all devices in the network,⁴⁹ the interconnection and
736 communication between all microgrid protection and control devices is a feature that will
737 allow effective use of distributed energy storage systems to provide frequency support.⁵²

738 Another major area of concern is how the islanded and grid-connected operation of wind
739 turbine and PV penetration will impact the effectiveness of utility protection equipment,^{53, 54}
740 and how Inverter-Based Distributed Generations (IBDG) can impact the fault current seen by
741 protective relays,⁵⁵ that can adversely affect the protection zones as well as the time-
742 dependent coordination between primary and backup protective devices.⁵⁶ As indicated in the
743 IEEE Std. 1547,¹⁸ islanded microgrids with IBDG cannot provide enough fault current
744 magnitude for the operation of conventional protective devices. This is due to the low fault
745 current levels injected by IBDG, which are normally limited to 120% of the inverter rated
746 current.⁵⁷ Then, actual distribution protective devices (fuses and overcurrent relays) based on
747 conventional protection schemes cannot reliably protect microgrids due to the limited shorth
748 circuit capacity,⁴⁶ and nonconventional protection schemes are implemented to improve

749 microgrid systems. Based on Tables 6 and 7, the operation and protection schemes for North
750 American microgrids are shown in Figure 21. The majority of microgrids were operated at
751 grid-connected mode. For nonconventional protection schemes, the adaptive protection
752 function was applied for more than 60 % of microgrids, while, for conventional protection
753 schemes, the voltage (27, 59), and current (51, 67, 50) protection functions were applied for
754 more than 60 % of microgrids too.

755

756 **Figure 21.** Operation and protection schemes in North American microgrids.

757 The overvoltage (59), undervoltage (27), frequency (81), volts-per-hertz (24), and voltage-
758 restrained overcurrent protection schemes were applied to the islanded modes with DERs that
759 had small fault current magnitudes. These protection schemes improved the sensitivity for
760 small fault currents, but the selectivity of the protection system along the microgrid was
761 affected because of the small magnitude of the fault currents. In addition, the directional
762 overcurrent (67) elements played an important role in microgrid projects because the
763 directional overcurrent (67) elements could distinguish between external (grid) and internal
764 (microgrid) faults, and the directional overcurrent (67) elements were set in forward and
765 reverse direction by using inverse time (51) and/or instantaneous (50) overcurrent curves. The
766 interface static switch had also an important function because it islanded the microgrid after
767 having power quality incidents,¹⁸ based on protection functions, setting ranges, and clearing
768 times provided by Table 1.^{8, 19} Of the nonconventional protection schemes, using adaptive
769 protection to change the overcurrent protection settings in the islanded and grid-connected
770 modes was the most common practice for the majority of the microgrid projects. Adaptive

771 protection also needs to implement a communication system to monitor the substation breaker
772 states and set the protection settings changes for the microgrid operation modes.

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

780

781 **6. Conclusions**

782

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

791 The main goal of this study was to examine each microgrid individually based on its
792 operational modes and types of DERs, the results of which are critical to designing the best

793 technical and economical solutions for the protection and control system of microgrid
794 projects. The protection scheme results and discussions of North American microgrid projects
795 presented in this paper provide crucial information that can be used to guide protection and
796 control engineers and/or researchers in defining protection schemes for microgrids based on
797 the types of DERs and microgrid operational modes.

798 The majority of North American microgrids are relatively new, and they were not
799 exposed to a great number of fault situations in-the-field. Therefore, microgrid protection
800 schemes' behaviours at fault situations are not available. In the future, a research study based
801 on collecting fault record events from electrical utilities in microgrids can be performed, to
802 analyse the effectiveness of fault identification and clearance with conventional and
803 nonconventional protection schemes.

804

805 **Acknowledgments**

806

807 This work was supported by the Transmission Reliability Program, Project 3CETE004 at
808 Oak Ridge National Laboratory.

809

810 **Conflict of interest**

811

812 The authors declare that there is no conflict of interest that could be perceived as prejudicing
813 the impartiality of the research reported.

814

815 **References**

816

- 817 1. IEEE Standard C37.2-2008. IEEE Standard Electrical Power System Device Function
818 Numbers, Acronyms, and Contact Designations. 2008:1-56. Available:
819 <https://ieeexplore.ieee.org/document/4639522>. Accessed: 2020-3-14.
- 820 2. Hirsch A, Parag Y, Guerrero J. Microgrids: A review of technologies key drivers and
821 outstanding issues. Renewable and Sustainable Energy Reviews. 2018;(90):420–411.
822 Available: <https://www.sciencedirect.com/science/article/pii/S136403211830128X>.
823 Accessed: 2020-3-14.
- 824 3. Oudalov A, Fidigatti A, Degner T, et al. Advanced Architectures and Control Concepts for
825 MORE MICROGRIDS. Contract No: SES6-019864, WORK PACKAGE C, Alternative
826 Designs for Microgrids, DC2: Novel protection systems for microgrids. 2009:1-168.
827 Available: <http://www.microgrids.eu/documents/668.pdf>. Accessed: 2020-3-14.
- 828 4. Buigues G, Dysko A, Valverde V, et al. Microgrid Protection: Technical challenges and
829 existing techniques. Proc. Int. Conf. on Renewable Energies and Power Quality, Bilbao,
830 Spain. 2013:1-6. Available: <http://icrepq.com/icrepq'13/262-buigues.pdf>. Accessed: 2020-3-
831 14.
- 832 5. Jiang W, He Z, Bo Z. The Overview of Research on Microgrid Protection Development.
833 Proc. Int. Conf. on Intelligent System Design and Engineering Application, Changsha,
834 Hunan, China. 2010: 693-697. Available: <https://ieeexplore.ieee.org/document/5743505>.
835 Accessed: 2020-3-14.

- 836 6. Bayindir E, Hossain E, Kabalaci E, et al. Investigation on North American Microgrid
837 Facility. International Journal of Renewable Energy Research. 2015;5(2):558-574.
838 Available:[https://pdfs.semanticscholar.org/f182/86f9313f8db8377444edd9b0f9b79ba35f22.p](https://pdfs.semanticscholar.org/f182/86f9313f8db8377444edd9b0f9b79ba35f22.pdf)
839 [df](https://pdfs.semanticscholar.org/f182/86f9313f8db8377444edd9b0f9b79ba35f22.pdf). Accessed: 2020-3-14.
- 840 7. Haron AR, Mohamed A, Shareef H. A Review on Protection Schemes and Coordination
841 Techniques in Microgrids. Journal of Applied Sciences. 2012;12(2):101-11. Available:
842 <https://scialert.net/abstract/?doi=jas.2012.101.112>. Accessed: 2020-3-14.
- 843 8. Shiles J, Wong E, Rao S, et al. Microgrid Protection: An Overview of Protection Strategies
844 in North American Microgrid Projects. IEEE Power & Energy Society General Meeting,
845 Chicago, Illinois, USA; 2017:1-5. Available: <https://ieeexplore.ieee.org/document/8274519>.
846 Accessed: 2020-3-14.
- 847 9. Edwards W and Manson S. Using Protective Relays for Microgrid Controls. 71st Annual
848 Conference for Protective Relay Engineers. College Station, Texas, USA; 2018:1-7.
849 Available: <https://ieeexplore.ieee.org/document/8349834>. Accessed: 2020-3-14.
- 850 10. Laaksonen H J. Protection Principles for Future Microgrids. IEEE Transactions on Power
851 Electronics.2010;25(12):2910-2918.Available:<https://ieeexplore.ieee.org/document/5549919>
852 . Accessed: 2020-3-14.
- 853 11. Electric Power Board, Chattanooga, Tennessee. Department of Energy Next Generation
854 Components Research & Development Program Planning Workshop. 2016:1-15. Available:
855 [https://www.energy.gov/sites/prod/files/2017/09/f36/%5B5%5D%20EPB%20Presentation%](https://www.energy.gov/sites/prod/files/2017/09/f36/%5B5%5D%20EPB%20Presentation%20-%20Lilian%20Bruce.pdf)
856 [20-%20Lilian%20Bruce.pdf](https://www.energy.gov/sites/prod/files/2017/09/f36/%5B5%5D%20EPB%20Presentation%20-%20Lilian%20Bruce.pdf). Accessed: 2020-3-14.

- 857 12. Case Study: Municipal Utility's Grid Improves by 50% with Self-Healing Technology.
858 S&C Electric Company. 2017:1-2. Available: [https://www.sandc.com/globalassets/sac-
859 electric/documents/sharepoint/documents---all-documents/case-study-766-1001.pdf](https://www.sandc.com/globalassets/sac-
859 electric/documents/sharepoint/documents---all-documents/case-study-766-1001.pdf).
860 Accessed: 2020-3-14.
- 861 13. Case Study Duke Energy Builds Microgrid Control System with Standard Power System
862 Components. Schweitzer Engineering Laboratories. Date Code: 20170111. 2017:1-4.
863 Available: <https://selinc.com/literature/case-studies/?title=duke%20energy>. Accessed: 2020-
864 3-14.
- 865 14. Central Utility Plant at University of California, San Diego, EcoMotion. Available:
866 <http://ecomotion.us/the-u-c-san-diego-microgrid/>. Accessed: 2020-3-14.
- 867 15. Use of Stationary Fuel Cells as the Backbone of the Modern Microgrid. 2017:1-16.
868 Available:[http://www.microgridresources.com/search?s=tag:%22FuelCell%20Energy%22&
869 executesearch=true](http://www.microgridresources.com/search?s=tag:%22FuelCell%20Energy%22&executesearch=true). Accessed: 2020-3-14.
- 870 16. UC San Diego Optimizes Microgrid System with SEL POWERMAX® and Protection
871 Relays. Schweitzer Engineering Laboratories. Date Code: 20170111. 2016:1-6. Available:
872 <https://selinc.com/solutions/success-stories/UCSD-microgrid/>. Accessed: 2020-3-14.
- 873 17. Eto J. Overview of the CERTS Microgrid Laboratory Test Bed. Proc. Int. Conf. IEEE
874 Power & Energy Society General Meeting, Calgary, Alberta, Canada. 2009:1-7. Available:
875 <https://ieeexplore.ieee.org/document/5211205>. Accessed: 2020-3-14.
- 876 18. IEEE Standard 1547.2-2008: IEEE Application Guide for IEEE Standard for
877 Interconnecting Distributed Resources with Electric Power Systems. 2008:1-219. Available:
878 <https://ieeexplore.ieee.org/document/4816078>. Accessed: 2020-3-14.

- 879 19. Alegria E, Brown T, Minear T, et al. CERTS microgrid demonstration with large-scale
880 storage and renewable generation. IEEE Transactions on Smart Grids. 2014;5(2):937-943.
881 Available: <https://ieeexplore.ieee.org/document/6670071>. Accessed: 2020-3-14.
- 882 20. Santa Rita Jail. Available: <https://building-microgrid.lbl.gov/santa-rita-jail>. Accessed: 2020-
883 3-14.
- 884 21. Santa Rita Jail Microgrid. Available: [http://www.powersurety.com/portfolio-](http://www.powersurety.com/portfolio-items/microgrid-modeling/)
885 [items/microgrid-modeling/](http://www.powersurety.com/portfolio-items/microgrid-modeling/). Accessed: 2020-3-14.
- 886 22. Microgrid Project at IIT. Available: <http://www.iitmicrogrid.net/microgrid.aspx>. Accessed:
887 2020-3-14.
- 888 23. Che L, Khodayar M, Shahidehpour M. Adaptive Protection System for Microgrids:
889 Protection practices of a functional microgrid system. IEEE Electrification Magazine.
890 2014;2(1): 66–80. Available: <https://ieeexplore.ieee.org/document/6774516>. Accessed:
891 2020-3-14.
- 892 24. California Energy Commission. Borrego Springs Microgrid Demonstration Project. Final
893 Project Report. San Diego Gas & Electric. CEC-500-2014-067. 2013:1-84. Available:
894 <https://ww2.energy.ca.gov/2014publications/CEC-500-2014-067/CEC-500-2014-067.pdf>.
895 Accessed: 2020-3-14.
- 896 25. Bialek T. Borrego Springs Microgrid 2.0, 2014-2018. San Diego Gas & Electric Company.
897 2018:1-15. Available: [https://ww2.energy.ca.gov/research/notices/2019-04-](https://ww2.energy.ca.gov/research/notices/2019-04-26_workshop/presentations/Tom%20Bialek_Boreggo%20Springs%20Microgrid.pdf)
898 [26_workshop/presentations/Tom%20Bialek_Boreggo%20Springs%20Microgrid.pdf](https://ww2.energy.ca.gov/research/notices/2019-04-26_workshop/presentations/Tom%20Bialek_Boreggo%20Springs%20Microgrid.pdf).
899 Accessed: 2020-3-14.

- 900 26. S&C engineers overcome real-world challenges constructing a groundbreaking microgrid. S
901 & C Electric Company. 2016:1-4. Available: [https://www.sandc.com/globalassets/sac-
902 electric/documents/sharepoint/documents---all-documents/case-study-180-1073.pdf](https://www.sandc.com/globalassets/sac-
902 electric/documents/sharepoint/documents---all-documents/case-study-180-1073.pdf).
903 Accessed: 2020-3-14.
- 904 27. Hayashi H. Smart Grid Demonstration in Los Alamos Presentation. 4th International
905 Conference on Integration of Renewable and Distributed Energy Resources. Albuquerque,
906 New Mexico, USA. 2010:1-17. Available:
907 [https://smartgrid.epri.com/doc/14_SG%20Post%20Workshop_LosAlamos%20uGrid_Hayas
908 hi.PDF](https://smartgrid.epri.com/doc/14_SG%20Post%20Workshop_LosAlamos%20uGrid_Hayas
908 hi.PDF). Accessed: 2020-3-14.
- 909 28. De La Torre R. 2014 Electric Reliability Plan. Los Alamos County Department of Public
910 Utilities. County of Los Alamos, New Mexico, USA. 2014: 1-33. Available:
911 <https://www.energy.gov/sites/prod/files/2019/03/f61/LA%20County%202014.pdf>. Accessed:
912 2020-3-14.
- 913 29. Ultra-capacitor Energy Bridge UPS for Palmdale Water District. Presentation of Northern
914 Power Systems, Inc. 2006:1-20. Available: [https://www.sandia.gov/ess-
915 ssl/docs/pr_conferences/2006/mckay.pdf](https://www.sandia.gov/ess-
915 ssl/docs/pr_conferences/2006/mckay.pdf). Accessed: 2020-3-14.
- 916 30. Kennedy M. Ameren's TAC Microgrid Seamlessly Integrates Distributed Energy
917 Resources, POWER, 2017:1-2. Available: [https://www.powermag.com/amerens-tac-
918 microgrid-seamlessly-integrates-distributed-energy-resources/](https://www.powermag.com/amerens-tac-
918 microgrid-seamlessly-integrates-distributed-energy-resources/). Accessed: 2020-3-14.
- 919 31. S&C Builds Ameren a Microgrid To Study Distribution Use Cases. S&C Electric Company.
920 2018:1-2. Available: <https://www.sandc.com/globalassets/sac->

- 921 [electric/documents/sharepoint/documents---all-documents/case-study-180-](#)
922 [1076.pdf?dt=637195547667161293](#). Accessed: 2020-3-14.
- 923 32. Fact Sheet: Ameren's Champaign Microgrid. Ameren. 2017:1-2. Available:
924 <http://ameren.mediaroom.com/download/microgrid-facts.pdf>. Accessed: 2020-3-14.
- 925 33. Samuelsen S. Generic Microgrid Controller, University of California, Irvine. Final
926 Technical Report, U.S. Department of Energy, Award No. DE-OE0000730, 2018:1-246.
927 Available: <https://www.osti.gov/servlets/purl/1501818>. Accessed: 2020-3-14.
- 928 34. UCI microgrid. Available: http://www.apep.uci.edu/UCI_Micro_Grid.html. Accessed:
929 2020-3-14.
- 930 35. Feng W, Jin M, Liu X et al. A review of microgrid development in the United States - A
931 decade of progress on policies, demonstrations, controls, and software tools. Applied
932 Energy.2018; 228(10):1656-1668. Available: <https://doi.org/10.1016/j.apenergy.2018.06.096>
933 . Accessed: 2020-3-14.
- 934 36. Ortiz CE, Alvarez Rada JF, Hernandez E, et al. Protection, Control, Automation, and
935 Integration for Off-Grid Solar-Powered Microgrids in Mexico. 40th Annual Western
936 Protective Relay Conference, Spokane, Washington, USA. 2013:1-11. Available:
937 [https://cdn.selinc.com/assets/Literature/Publications/Technical%20Papers/6627_ProtectionC](https://cdn.selinc.com/assets/Literature/Publications/Technical%20Papers/6627_ProtectionControl_HA_20131015_Web3.pdf?v=20190325-150349)
938 [ontrol_HA_20131015_Web3.pdf?v=20190325-150349](https://cdn.selinc.com/assets/Literature/Publications/Technical%20Papers/6627_ProtectionControl_HA_20131015_Web3.pdf?v=20190325-150349). Accessed: 2020-3-14.
- 939 37. Katiraei F and Abbey C. Diesel Plant Sizing and Performance Analysis of a Remote Wind-
940 Diesel Microgrid. Proc. Conf. IEEE Power & Energy Society General Meeting, Tampa,
941 Florida, USA. 2007:1-5. Available: <https://ieeexplore.ieee.org/document/4276041>.
942 Accessed: 2020-3-14.

- 943 38. Hatziargyriou N, Asano H, Iravani R, et al. Microgrids. IEEE Power and Energy Magazine.
944 2007;5(4):78-94. Available: <https://ieeexplore.ieee.org/document/4263070>. Accessed: 2020-
945 3-14.
- 946 39. Su W and Wang J. Energy Management Systems in Microgrid Operations. The Electricity
947 Journal. 2012;25(8):45-60. Available: <https://doi.org/10.1016/j.tej.2012.09.010>. Accessed:
948 2020-3-14.
- 949 40. Katiraei F, Abbey C, Tang S et al. Planned Islanding on Rural Feeders - Utility Perspective.
950 Proc. IEEE Power & Energy Society General Meeting - Conversion and Delivery of
951 Electrical Energy in the 21st Century. Pittsburgh, Philadelphia, USA. 2008:1-6. Available:
952 <https://ieeexplore.ieee.org/document/4596774>. Accessed: 2020-3-14.
- 953 41. Lasseter RH, Eto JH, Schenkman B, et al. CERTS Microgrid Laboratory Test Bed. IEEE
954 Transactions on Power Delivery. 2011;26(1):325-332. Available:
955 <https://ieeexplore.ieee.org/document/5673682>. Accessed: 2020-3-14.
- 956 42. Kamh MZ, Iravani R, EL-Fouly THM. Realizing a smart microgrid-pioneer Canadian
957 experience. Proc. IEEE Power & Energy General Meeting. San Diego, California, USA.
958 2012:1-8. Available: <https://ieeexplore.ieee.org/document/6345629>. Accessed: 2020-3-14.
- 959 43. Lidula NWA and Rajapakse AD. Microgrids research: A review of experimental microgrids
960 and test systems. Renewable and Sustainable Energy Reviews. 2011;15(1):186-202.
961 Available: <https://www.sciencedirect.com/science/article/abs/pii/S136403211000328X>.
962 Accessed: 2020-3-14.
- 963 44. Gauthier M, Abbey C, Katiraei F, et al. Planned islanding as a distribution system
964 operation tool for reliability enhancement. 19th CIRED, Vienna, Austria. 2007:1-4.

- 965 Available: http://www.cired.net/publications/cired2007/pdfs/CIRED2007_0270_paper.pdf.
- 966 Accessed: 2020-3-14.
- 967 45. García-Gracia M, El Halabi N, Alonso A, et al. Harmonic Distortion in Renewable Energy
968 Systems: Capacitive Couplings. IntechOpen: Power Quality Harmonics Analysis and Real
969 Measurements Data. 2011:261-278. Available: [https://www.intechopen.com/books/power-](https://www.intechopen.com/books/power-quality-harmonics-analysis-and-real-measurements-data/harmonic-distortion-in-renewable-energy-systems-capacitive-couplings)
970 [quality-harmonics-analysis-and-real-measurements-data/harmonic-distortion-in-renewable-](https://www.intechopen.com/books/power-quality-harmonics-analysis-and-real-measurements-data/harmonic-distortion-in-renewable-energy-systems-capacitive-couplings)
971 [energy-systems-capacitive-couplings](https://www.intechopen.com/books/power-quality-harmonics-analysis-and-real-measurements-data/harmonic-distortion-in-renewable-energy-systems-capacitive-couplings). Accessed: 2020-3-14.
- 972 46. Hooshyar A and Iravani R. Microgrid Protection, IEEE Proc., 2017;105(7):1332-1353.
- 973 Available: <https://ieeexplore.ieee.org/document/7885003>. Accessed: 2020-3-14.
- 974 47. Hong S and Zuercher-Martinson M. Harmonics and Noise in Photovoltaic (PV) Inverter and
975 the Mitigation Strategies. Solectria Renewables. 1-7. Available:
976 [https://www.solectria.com/site/assets/files/1482/solectria_harmonics_noise_pv_inverters_wh](https://www.solectria.com/site/assets/files/1482/solectria_harmonics_noise_pv_inverters_whte_paper.pdf)
977 [ite_paper.pdf](https://www.solectria.com/site/assets/files/1482/solectria_harmonics_noise_pv_inverters_whte_paper.pdf). Accessed: 2020-3-14.
- 978 48. Halpin SM. Revisions to IEEE Standard 519-1992. 2005-2006 IEEE/PES Transmission and
979 Distribution Conference and Exhibition, Dallas, Texas. 2006:1-3. Available:
980 <https://ieeexplore.ieee.org/document/1668665>. Accessed: 2020-3-14.
- 981 49. Synthetic Inertia in Grids with a High Renewable Energy Content. Energize. Available:
982 <http://www.ee.co.za/article/synthetic-inertia-grids-high-renewable-energy-content.html>
983 . Accessed: 2020-3-14.
- 984 50. Gonzalez-Longatt FM. Effects of the Synthetic Inertia from Wind Power on the Total
985 System Inertia after a Frequency Disturbance. Second International Symposium on

- 986 Environment-Friendly Energies and Applications. Newcastle, England. 2012:389-395.
- 987 Available: <https://ieeexplore.ieee.org/document/6294049> . Accessed: 2020-3-14.
- 988 51. Energy Storage, Keeping Smart Grids in Balance. Brochure. ABB. 2012:1-12. Available:
- 989 [https://library.e.abb.com/public/59a2be960fdb777a48257a680045c04a/ABB%20Energy%20S](https://library.e.abb.com/public/59a2be960fdb777a48257a680045c04a/ABB%20Energy%20Storage_Nov2012.pdf)
- 990 [torage_Nov2012.pdf](https://library.e.abb.com/public/59a2be960fdb777a48257a680045c04a/ABB%20Energy%20Storage_Nov2012.pdf). Accessed: 2020-3-14.
- 991 52. Schmutz J. Primary Frequency Control Provided by Battery. Semester Thesis. EEH – Power
- 992 Systems Laboratory, ETH Zürich. 2013:1-50. Available:
- 993 [http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=D0AB8D13F4B32EE9A95D60B5](http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=D0AB8D13F4B32EE9A95D60B5A0426184?doi=10.1.1.699.9945&rep=rep1&type=pdf)
- 994 [A0426184?doi=10.1.1.699.9945&rep=rep1&type=pdf](http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=D0AB8D13F4B32EE9A95D60B5A0426184?doi=10.1.1.699.9945&rep=rep1&type=pdf). Accessed: 2020-3-14.
- 995 53. Sena SS, Quiroz JE, Broderick RJ. Analysis of 100 Utility SGIP PV Interconnection
- 996 Studies. 2014 IEEE 40th Photovoltaic Specialist Conference. Denver, Colorado, USA.
- 997 2014:1005-1010. Available: <https://ieeexplore.ieee.org/document/6925084>. Accessed: 2020-
- 998 3-14.
- 999 54. Kabouris J. and Kanellos FD. Impacts of Large Scale Wind Penetration on Energy Supply
- 1000 Industry. Energies. 2009;2:1031-1041. Available: [https://www.mdpi.com/1996-](https://www.mdpi.com/1996-1073/2/4/1031/pdf)
- 1001 [1073/2/4/1031/pdf](https://www.mdpi.com/1996-1073/2/4/1031/pdf). Accessed: 2020-3-14.
- 1002 55. Baran ME, Hooshyar H, Shen Z, et al. Accommodating High PV Penetration on
- 1003 Distribution Feeders. IEEE Transactions Smart Grid. 2012;3(2):1039-1046. Available:
- 1004 <https://ieeexplore.ieee.org/document/6204237>. Accessed: 2020-3-14.
- 1005 56. Hooshyar H, Baran ME, Vanfretti L. Coordination Assessment of Overcurrent Relays in
- 1006 Distribution Feeders with High Penetration of PV Systems. 2013 IEEE Grenoble

1007 Conference, France. 2013:1-6. Available: <https://ieeexplore.ieee.org/document/6652117>.

1008 Accessed: 2020-3-14.

1009 57. Soleimanisardoo A, Karegar HK, Zeineldin HH. Differential Frequency Protection Scheme

1010 Based on Off-Nominal Frequency Injections for Inverter-Based Islanded Microgrids. IEEE

1011 Transactions on Smart Grid. 2019;10(2):2107-2114. Available:

1012 <https://ieeexplore.ieee.org/document/8244308>. Accessed: 2020-3-14.

1013

1014 **List of Abbreviations:** 3L, Three-Line; AEP, American Electric Power; ANSI, American

1015 National Standards Institute; BC, British Columbia; BCIT, British Columbia Institute of

1016 Technology; CA, California; CERTS, Consortium for Electric Reliability Technology

1017 Solutions; CND, Canada; DC/AC, Direct Current / Alternating Current; DERs, Distributed

1018 Energy Resources; DPMC, Diesel Plant Master Controller; EMS, Energy Management

1019 System; EPB, Electric Power Board; FDISR, Fault Detection, Isolation, and Service

1020 Restoration; FP, Feeder Protection; GOOSE, Generic Object-Oriented Substation Events;

1021 GTO, Guanajuato; IBDG, Inverter-Based Distributed Generations; IEC, International

1022 Electrotechnical Commission; IEEE, Institute of Electrical and Electronics Engineers; IIT,

1023 Illinois Institute of Technology; IL, Illinois; LACU, Los Alamos County Department of

1024 Public Utilities; LL, Line-to-Line; LLG, Line-to-Line-Ground; LP, Loop Protection; LWP,

1025 Load-Way Protection; MEX, Mexico; MP, Microgrid Protection; NAY, Nayarit; NC, North

1026 Carolina; NEDO, New Energy and Industrial Technology Development Organization; NLA,

1027 Newfoundland and Labrador; NM, New Mexico; OH, Ohio; PV, Photovoltaic; PWD,

1028 Palmdale Water District; QC, Quebec; SCADA, Supervisory Control and Data Acquisition;

- 1029 SEL, Schweitzer Engineering Laboratories; SLG, Single-Line-to-Ground; SMS, Storage
1030 Management System; TN, Tennessee; TX, Texas; UCI, University of California Irvine; USA,
1031 United States of America; WDICS, Wind-Diesel Integrated Control System; WPMC, Wind
1032 Plant Master Controller.

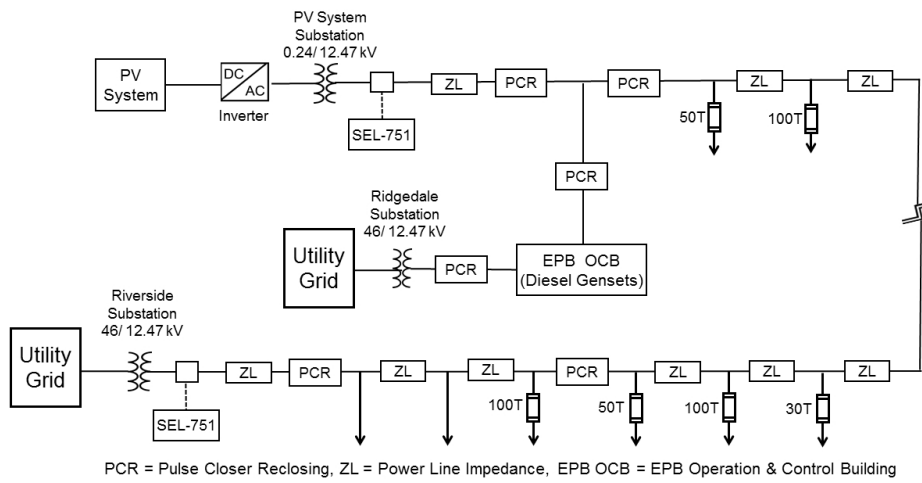


Figure 1. Electric Power Board microgrid simplified one-line diagram.

Figure 1. Electric Power Board microgrid simplified one-line diagram

338x190mm (96 x 96 DPI)

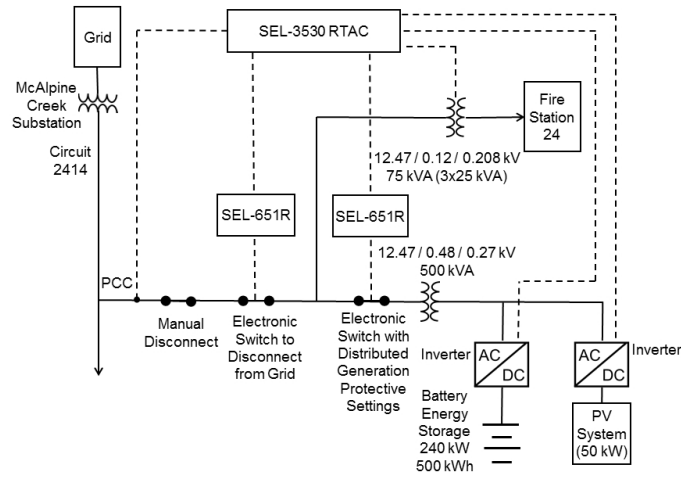


Figure 2. Duke Energy microgrid one-line diagram.

Figure 2. Duke Energy microgrid one-line diagram.

338x190mm (96 x 96 DPI)

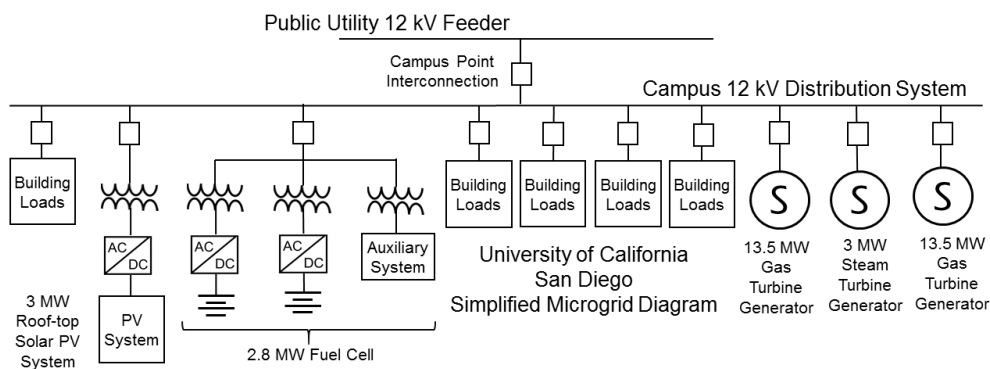


Figure 3. University of California, San Diego, simplified microgrid diagram.

Figure 3. University of California, San Diego, simplified microgrid diagram.

338x190mm (96 x 96 DPI)

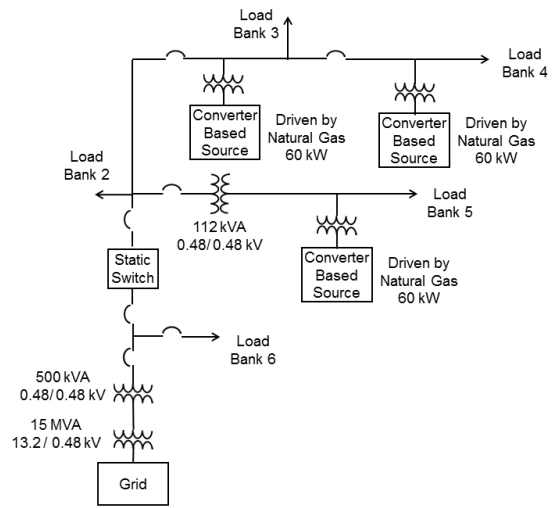


Figure 4. Consortium for Electric Reliability Technology Solutions microgrid in Ohio.

Figure 4. Consortium for Electric Reliability Technology Solutions microgrid in Ohio.

338x190mm (96 x 96 DPI)

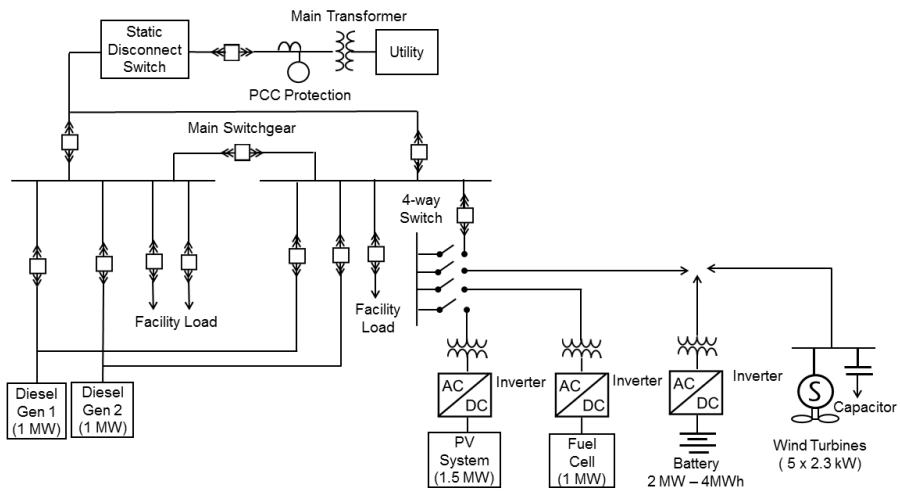


Figure 5. Santa Rita Jail microgrid one-line diagram.

Figure 5. Santa Rita Jail microgrid one-line diagram.

338x190mm (96 x 96 DPI)

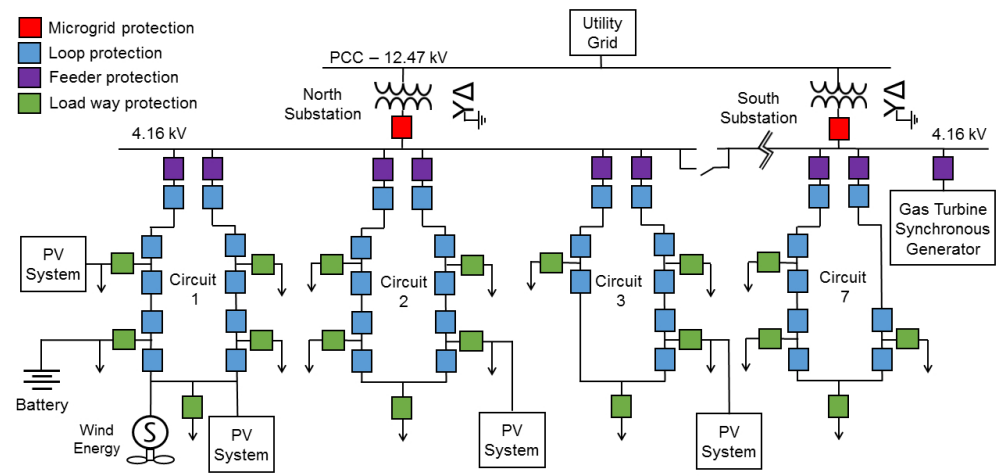


Figure 6. Illinois Institute of Technology microgrid one-line diagram.

Figure 6. Illinois Institute of Technology microgrid one-line diagram.

338x190mm (96 x 96 DPI)

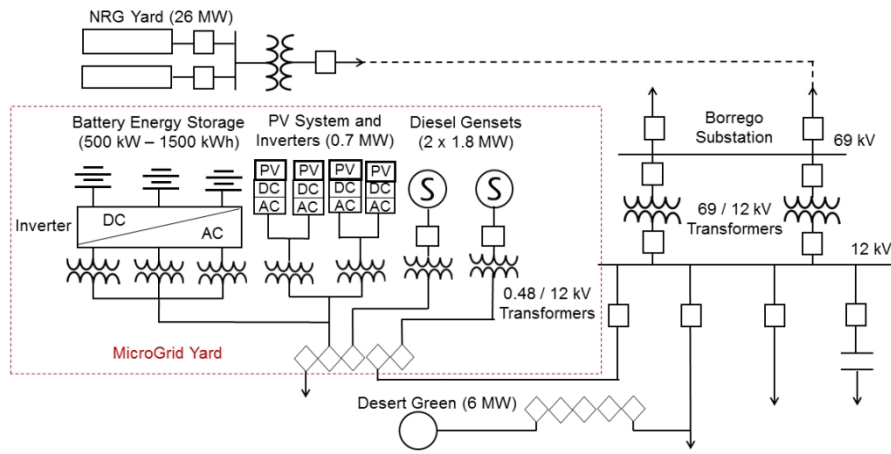


Figure 7. Borrego Springs Microgrid one-line diagram.

Figure 7. Borrego Springs Microgrid one-line diagram.

338x190mm (96 x 96 DPI)

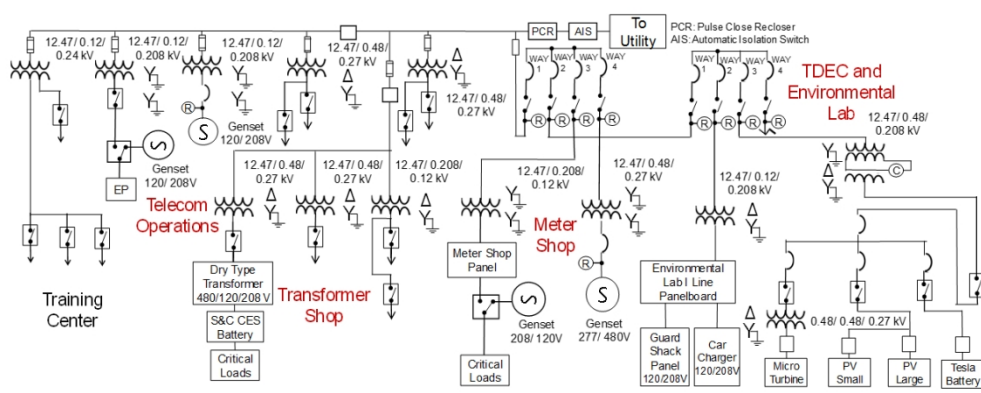


Figure 8. Oncor microgrid one-line diagram.

Figure 8. Oncor microgrid one-line diagram.

338x190mm (96 x 96 DPI)

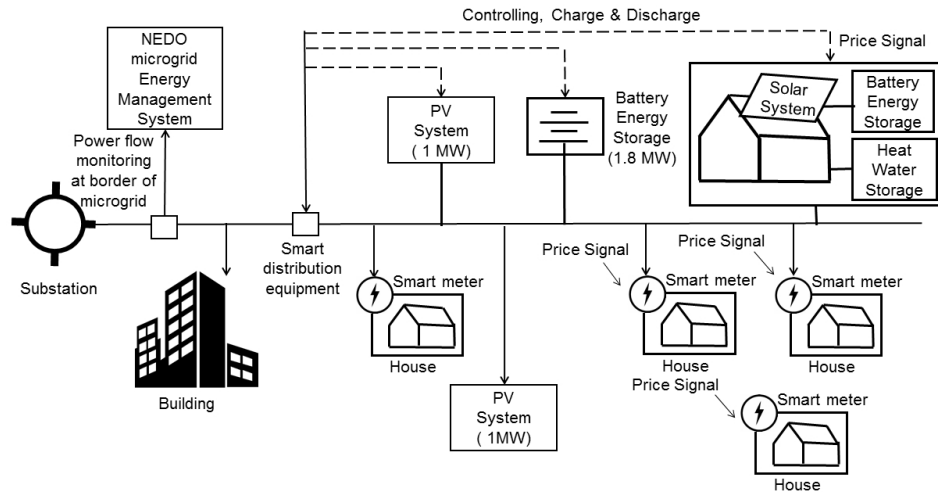


Figure 9. New Energy and Industrial Technology Development Organization microgrid one-line diagram.

Figure 9. New Energy and Industrial Technology Development Organization microgrid one-line diagram.

338x190mm (96 x 96 DPI)

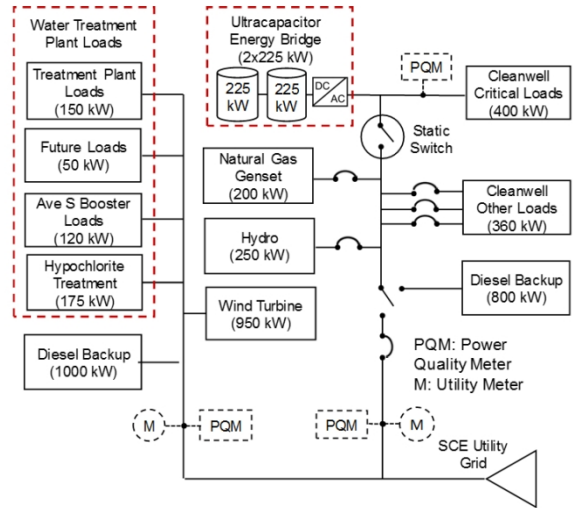


Figure 10. Palmdale Water District microgrid one-line diagram.

Figure 10. Palmdale Water District microgrid one-line diagram.

338x190mm (96 x 96 DPI)

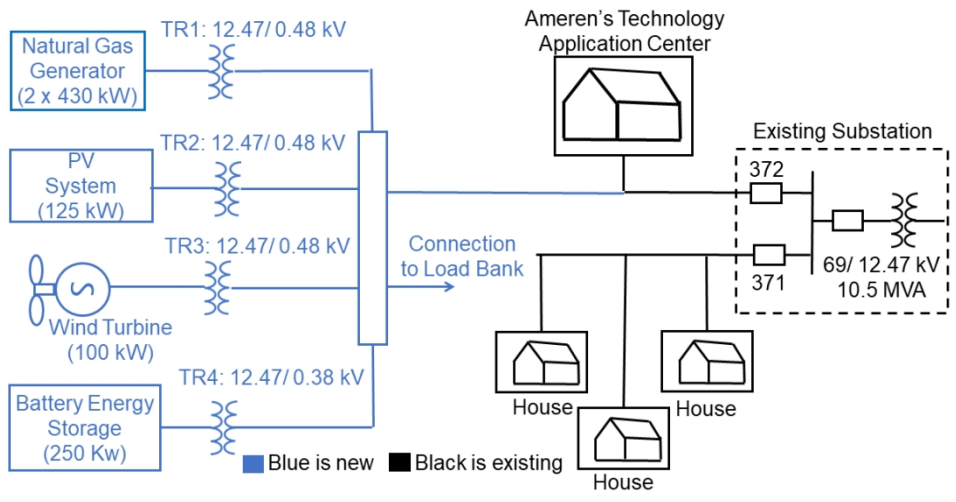


Figure 11. Ameren microgrid one-line diagram.

Figure 11. Ameren microgrid one-line diagram.

338x190mm (96 x 96 DPI)

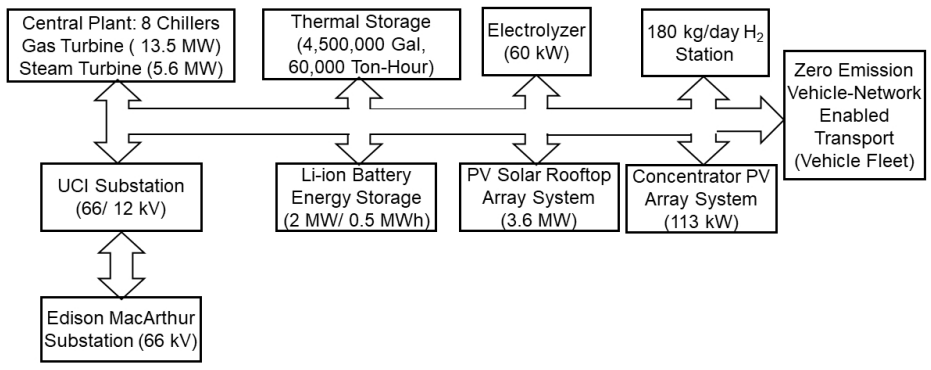


Figure 12. University of California Irvine microgrid one-line diagram.

Figure 12. University of California Irvine microgrid one-line diagram.

338x190mm (96 x 96 DPI)

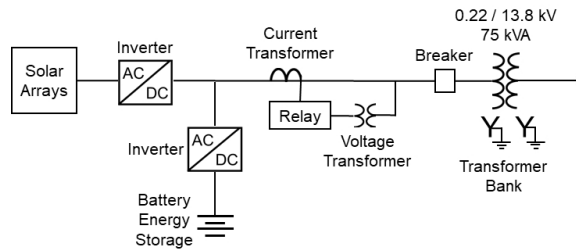


Figure 13. Guasimas del Metate and Tierra Blanca del Picacho solar microgrid one-line diagram.

Figure 13. Guasimas del Metate and Tierra Blanca del Picacho solar microgrid one-line diagram.

338x190mm (96 x 96 DPI)

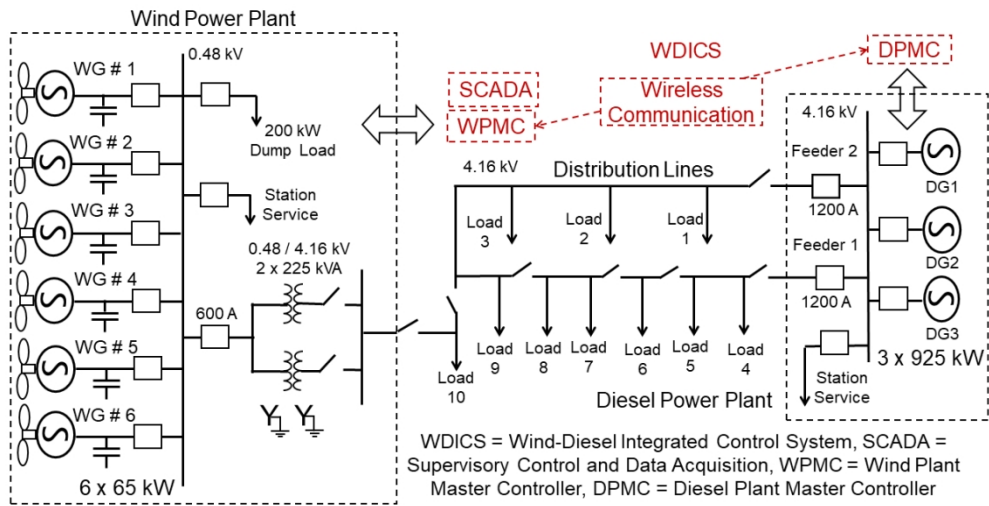


Figure 14. Ramea wind-diesel microgrid one-line diagram.

Figure 14. Ramea wind-diesel microgrid one-line diagram.

338x190mm (96 x 96 DPI)

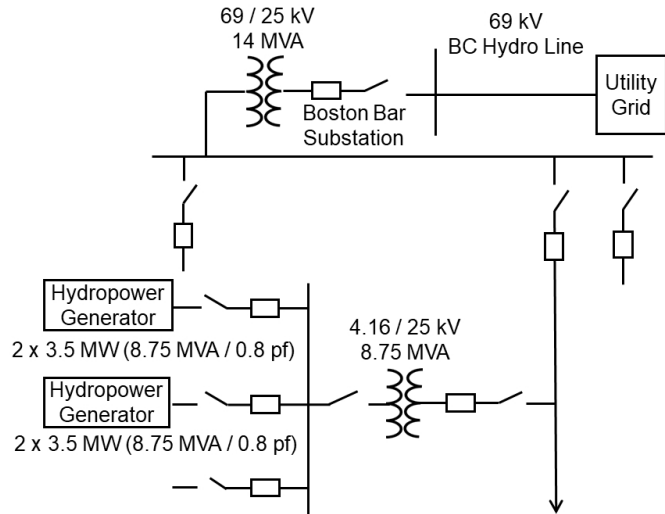


Figure 15. British Columbia hydro microgrid one-line diagram.

Figure 15. British Columbia hydro microgrid one-line diagram.

338x190mm (96 x 96 DPI)

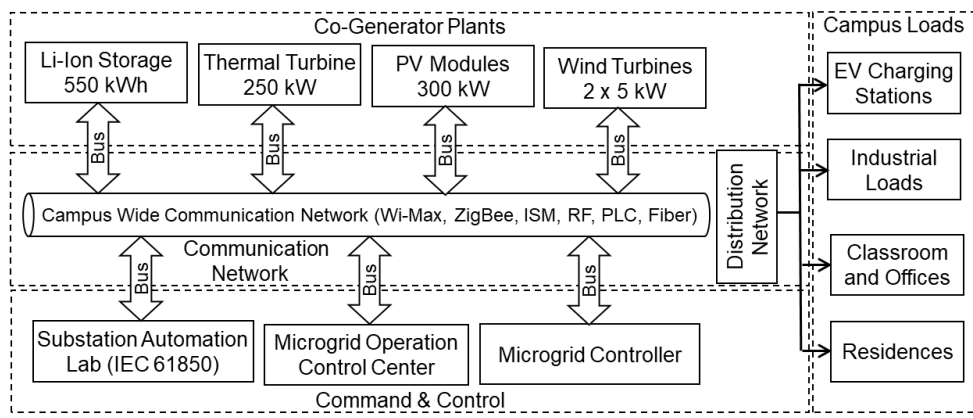


Figure 16. British Columbia Institute of Technology microgrid communication network.

Figure 16. British Columbia Institute of Technology microgrid communication network.

338x190mm (96 x 96 DPI)

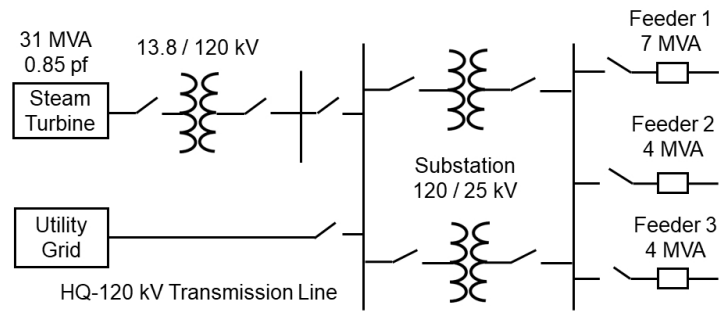


Figure 17. Boralex Planned Islanding microgrid one-line diagram.

Figure 17. Boralex Planned Islanding microgrid one-line diagram.

338x190mm (96 x 96 DPI)

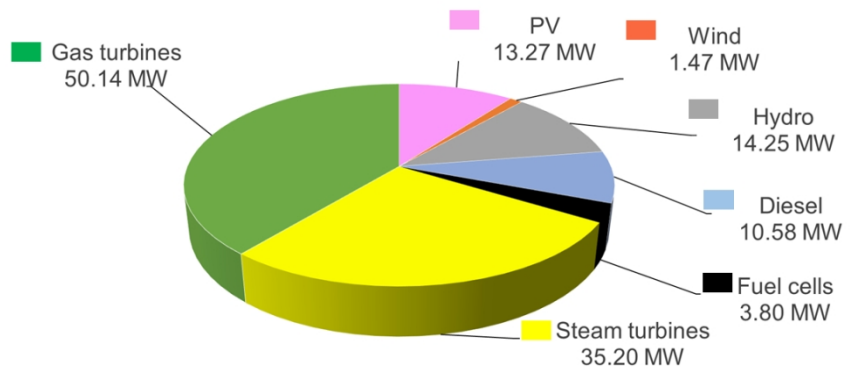


Figure 18. Real power (MW) supply by distributed energy resources.

Figure 18. Real power (MW) supply by distributed energy resources.

338x190mm (96 x 96 DPI)

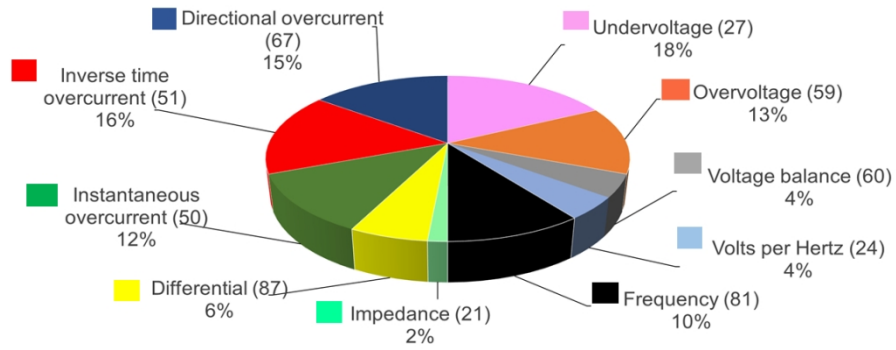


Figure 19. Conventional protection schemes for microgrids.

Figure 19. Conventional protection schemes for microgrids.

338x190mm (96 x 96 DPI)

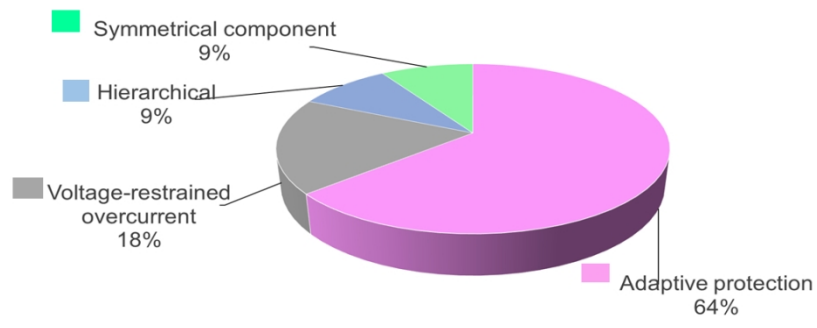


Figure 20. Nonconventional protection schemes for microgrids.

Figure 20. Nonconventional protection schemes for microgrids.

338x190mm (96 x 96 DPI)

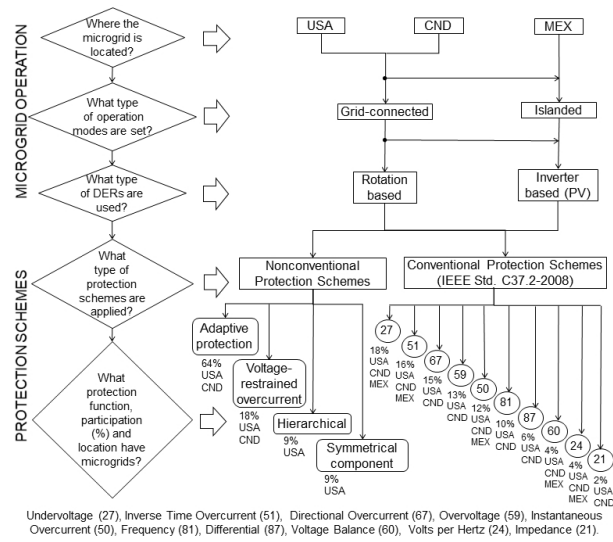


Figure 21. Operation and protection schemes in North American microgrids.

Figure 21. Operation and protection schemes in North American microgrids.

338x190mm (96 x 96 DPI)