# Protection coordination considerations for a highly meshed urban microgrid

Mobolaji Bello[1], Arindam Maitra[1], Roger Dugan[1], Matt McGrail[2], Andrew Reid[3] and Roe Rodrigo[3]
[1]Electric Power Research Institute (EPRI), Palo Alto, USA
[2]DIgSILENT Americas LLC, Texas, USA.
[3]Consolidated Edison Co. of New York, Inc. (ConEd), New York, USA.

**Abstract— In microgrid distribution systems, irregular system fault characteristics (with respect to grid-connected mode) and the variability of power flow direction, present challenges to developing a robust and reliable protection scheme that will have effective response in both grid-connected and grid-isolated mode. The following investigation captures a meshed network from a larger urban low-voltage (LV) network system in the service area of Consolidated Edison Company of New York (ConEdison), a United States (US) utility that has sufficient customer supplied generation to act as a standalone microgrid. The investigation assesses the viability of differential protection schemes. Protection response has been reviewed with respect to real world application; including, benefits and limitations of selectivity, sensitivity and reliability.**

*Index Terms*— **Microgrid, Inverter based generation, differential protection, islanded operating mode.**

## I. BACKGROUND AND INTRODUCTION

Microgrids are not new. However, the use of Distributed Energy Resources (DER) as microgrid generation sources is increasing. The objectives and value propositions of using DER for microgrids provides access to environmentally friendly renewable resources for energy generation. Microgrids offers a more resilient electricity supply amidst storms, as well as optimized energy use; to mention a few. Individually, these objectives are already being served in various applications using different types of DER. A prominent example is roof-top photovoltaic (PV) systems. Also common are battery energy storage and standby generators that protect critical processes in applications like hospitals and computer centers. Commercial combined heat and power (CHP) are usually designed to meet local thermal requirements while feeding power to the public grid. This is not new, but putting all the energy sources all together with a grid connection and controlling their output enables the possibility for forming a microgrid [1] [2].

Even though today's electric grid is highly reliable, in the United States, it is vulnerable to disruptions caused by natural disasters, particularly severe weather. Aging of the grid infrastructure only exacerbates this problem, creating new concerns over energy reliability and grid resiliency [3]. A more resilient grid is one that is better able to sustain and recover from adverse events like severe weather—a more reliable grid is one with fewer and shorter power interruptions felt by the customer. A microgrid is a group of interconnected loads and DER within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and that connects and disconnects from such grid to enable it to operate in both grid-connected or "island" mode [4] [5].

A microgrid presents several interconnection issues [6]. While these issues are critical to evaluating the feasibility of microgrids as a resiliency solution, it is important for communities and customers to consider the broader scope of their resiliency goals and objectives, their unique energy needs, and the economic constraints that they must work within [7] [8]. It is the goal of the grid owner/operator to investigate the most appropriate solution that can be implemented to provide effective power system protection performance in line with legislative requirements, industry standards and internal policies across all operating scenarios. It is the challenge of the protection system engineer to meet these goals in an economical way with considerations of real world restrictions.

Creating a microgrid from an existing underground meshed network poses a few challenges. This specific network is basically a secondary, or low-voltage (LV) network condensed to a point. Several transformers have multiple primary-side supplies and their secondaries are bussed together [9].

The main objective of this paper is to conceptualize and describe a high- and low-selective protection philosophy of a meshed microgrid. This paper highlights the protection coordination issues when an existing meshed LV network is converted into a microgrid; based on generation sources with low fault contribution. It further explains the strategy to coordinate protection devices during grid connected and islanded microgrid operating regime. These analyses are conducted on one of the service areas of the ConEdison LV network. This paper has the following structure: Section II describes the utility network studied, the microgrid operating regimes and highlights the protection coordination issues with the existing LV network. Section III explains the suggested protection philosophy for the studied microgrid. Section IV illustrates the analysis and results of the protection coordination settings of the studied network. Section V summarizes and concludes the paper.

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## II. MICROGRID CONFIGURATION OF THE STUDIED NETWORK

### A. Network description and operating philosophy

The main utility grid is designed so that each (LV) service load receives its power from several transformers that are simultaneously supplied from several medium-voltage (MV) (13.2, 26.4, or 33 kV) primary feeders. The LV grid system is formed from the interconnection of the secondary windings of the network transformers, via network protectors, in a parallel configuration. The standard electric service in the utility service territory is from the 208/120-V network system or "grid". The loads are then served from this grid [10]. All the primary distribution feeder system is 100% underground as shown in Figure 1.

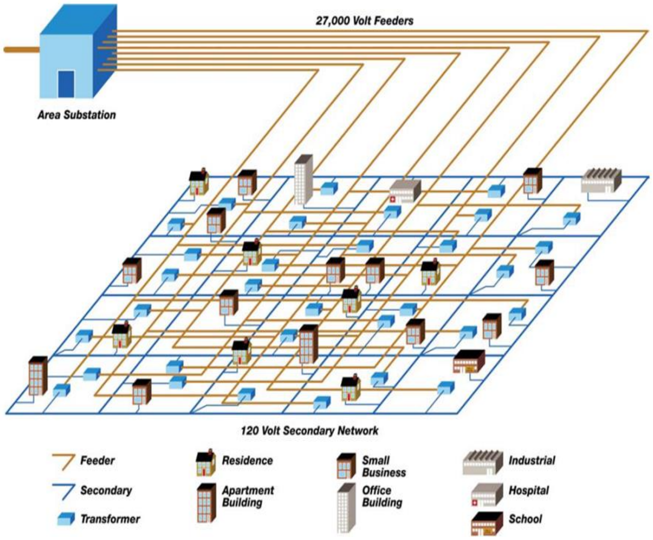

Figure 1 – Meshed Secondary Urban network [10]

Figure 2 shows the schematic layout of the studied microgrid. The studied microgrid is a smaller section of the larger low voltage system (shown in figure 1). The microgrid is a 3-phase 4-wire 208/120-V network serving a total commercial load of 1170 kVA. DER are planned for installation in the microgrid, to enable operation in both grid-connected and islanded modes. These energy sources may either be connected through a synchronous machine or an inverter, but the plan is to install these energy sources at the customer premises. There are multiple branch segments (sections between common nodes BC3998, M1048 and 10385) with multiple parallel cables. Grouping these parallel cables together into "branches" simplifies the grid layout as shown in Figure 2.

Consideration of single or multiple circuit breaker installation is needed to consider the selectivity of faults on branches with parallel cable segments. In Figure 2, the red 'Xs' identify the line-segments to be opened during island mode and are regarded as the boundary of the microgrid. There are potentially five Points of Common Coupling (PCCs) simultaneously connected to the external utility network. Three of them are connected to MV/LV transformers that supply power to the microgrid, the other two PCCs connect to other lines of the LV network.

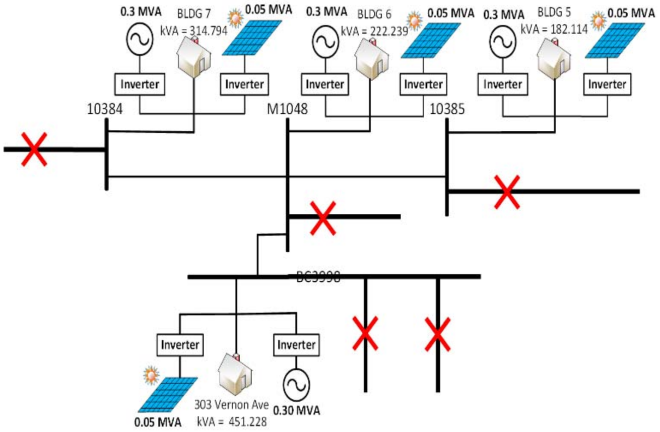

Figure 2 – Studied microgrid

The microgrid operating scenario considered in this study involves small-scale distributed CHP units (a small synchronous machine behind an inverter) and small-scale PV systems. During the grid-connected mode, the utility allows the synchronous generator to be connected behind an inverter. However, during islanded mode, the generator can operate as a synchronous generator [10] [11]. The microgrid can have multiple, different configurations and operating states, dependent on customer demand and the availability and mix of generation. The main configurations are:

- Grid-connected mode: in this mode, the microgrid is supplied by the distribution network. This configuration is heavily meshed to allow for continuity of supply following an N-1 or N-2 contingency.
- Islanded mode: in this mode, the microgrid is disconnected from the wider distribution network and supply is via local generation only.

The LV system is solidly grounded via a dedicated ground link at the distribution supply transformer (transformers are delta-wye, directly connected to ground on the secondary side). Each LV generator is assumed to be 3-phase wye-connected with the neutral solidly grounded. It is assumed that the inverter internal ground link can provide zero-sequence current. This may be accomplished by the inverter design itself, or via a separate transformer such as a delta-wye interconnection transformer in series with the inverter-connected generation. This study assumes all generation is inverter-connected. This assumption provides the worst case (minimum) fault contribution from the generation sources. All the system analysis was conducted using DIgSILENT PowerFactory [12]. The tool affords the user the capability to specify the required fault contribution for each generation type. The DER inverters are assumed to provide up to 1.8 pu fault current [13] [14]; and can sustainably provide fault current, including earth fault current until the fault is cleared or isolated.

### B. Protection overview

Generally, in a protection coordination study, the maximum fault level is used to size the protection equipment and the minimum fault current is used for relay sensitivity or pick up current selection [15]. This same philosophy should be applied for a microgrid system. To determine these operating states, we considered:

- maximum and minimum grid supply fault levels
- maximum and minimum load states for each load
- maximum and minimum generation states, for each generation source
- other asynchronous or synchronous machines (load or generation sources) within the system.
- the impact on the system from sequential protection tripping (impact to the system when partial loads are lost)

Steady-state studies were conducted on the microgrid and the load flow and short circuit current results were compared for the grid connected and islanded mode. The change in fault currents compared to the grid connected mode for different fault types recorded at various locations of the microgrid are summarized in Table I.

For three-phase faults, the fault currents decreased by at least 89%. For the single-phase-to-ground faults, the fault currents decreased by at least 85%.

TABLE I: Change in fault currents compared to the grid connected mode

| Fault Location | 3-Phase Fault (%) | 1-Phase Fault (%) | Phase-Phase Fault (%) | Phase-Phase-Ground Fault (%) |
|---|---|---|---|---|
| M1048 | -93% | -91% | -93% | -89% |
| 10384 | -89% | -85% | -89% | -81% |
| 10385 | -90% | -86% | -91% | -82% |
| BC3998 | -93% | -91% | -93% | -90% |

Load flow and short circuit studies results have indicated that from a protection perspective, there are: substantial differences in fault current level, differences in fault current direction, reduced fault current duration and potential further reduced unbalanced fault current. The existing protection installed in the carved-out microgrid consists of network protectors and fuses. Fuses and circuit breakers are installed at each customer site. Network protectors and network protector fuses are installed on the LV side of the grid supply transformers. Generally, the LV grids are protected only by network protector fuses and current-limiting fuses or "limiters" in the cable-to-cable connections (e.g. "fusible crabs"). In grid-connected mode the fault currents are very high. When a cable is faulted, the limiters blow to isolate the faulted LV cable section. Some utilities do not use limiters for smaller cables because it is assumed that the cables are small enough to "burn clear". Faults are simply left alone to "burn away clear", either by the action of limiters/fuses, or the burning away of the cable itself. Thus, the problem of fault clearing and locating arise only when the microgrid is in islanded mode because of the lack of available fault current. It is assumed that the existing network protectors and fuses located within the microgrid will continue to provide sufficient protection in grid connected mode, however may not operate reliably in islanded mode. Hence, it can be concluded that the existing protection is not sufficient for fault detection when operating microgrid in islanded mode.

### C. General Microgrid Protection.

The requirements of an appropriate microgrid protection system cannot be over-emphasized. A lot of research has been done on various protection schemes for microgrid applications. Several authors in [16] – [22] have suggested various microgrid protection schemes.

## III. SUGGESTED PROTECTION PHILOSOPHY FOR MICROGRIDS

This section discusses a general protection philosophy for microgrids, and suggests a differential protection scheme for the studied microgrid. In addition, two protection philosophies are suggested, which include high selectivity and low selectivity protection schemes [23].

### *A.* High selectivity protection philosophy:

The main aim of a high selectivity protection philosophy is that in an event of a fault condition, part of the microgrid stays connected; the unaffected areas is dependent on fault location. Considering the topology of a microgrid, the protection philosophy is described as follows:

- Determine the required level of selectivity for different fault scenarios. Generally, this can be determined by considering the impact to the customers for different grid faults.
- Group parallel cables connecting common LV nodes together into single "branches".
- Split the microgrid into separate regions/zones (two zones are identified for the studied microgrid as is illustrated in Figure 3) which with appropriate protection grading will achieve the desired selectivity.
- Ensure LV grid relays protecting branches directly connected to customers' trip first to remove the fault from the remaining healthy grid as quickly as possible.
- Ensure some time delay between tripping of customer branches and any interconnector circuits connecting main LV nodes together. There should be coordination to keep as many customers connected to the network in the event of a fault.
- Ensure customer relays trip last to ensure healthy generation remains in service post fault.

For the studied microgrid, Figure 3 shows the determination of zones (light green) and major LV nodes (light brown) to achieve a highly selective protection installation. It can be observed that any fault that leads to isolation of a zone will cause at most one customer disconnection from the microgrid whilst remaining customers may continue to share generation. To achieve a high selectivity scheme, the protection scheme would need to trip circuit breakers located at each generation connection point as well as at each outgoing branch from the major LV nodes. For the high selectivity option, it is clear from looking at the LV layout that there are two critical nodes which feed the individual customer circuits, these are M1048 and BC3998. A fault at either of these two nodes would result in loss of LV network for multiple customers.

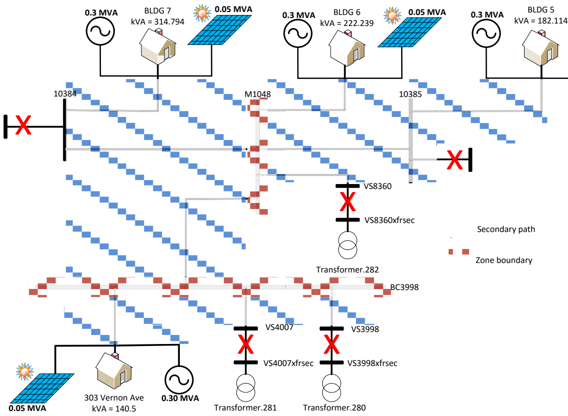

Figure 3: High selectivity protection zones [23]

## *B.* Low selectivity protection philosophy:

Determination of the system will consider the entire LV grid as a single zone, meaning that any LV grid fault will be cleared only by operating customer circuit breakers or may be split into many smaller zones. The main aim of a low selectivity protection philosophy is that, in an event of a fault condition, all the customers are isolated from the rest of the grid. For the studied microgrid, Figure 4 shows a single protection zone (light green) within the microgrid. The response of this scheme is to trip the circuit breakers located at each customer point of connection (See blue blocks in Figure 4) for a fault anywhere inside the outlined protection zone.

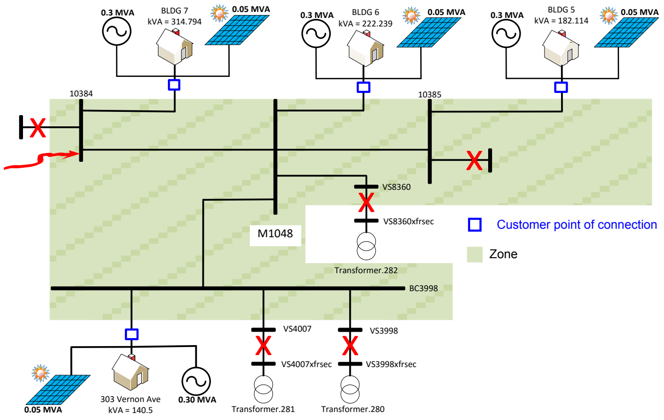

Figure 4: Low selectivity protection zone [23]

For a fault at 10384 or any location in the microgrid, the low selectivity protection philosophy results in isolation of customers from the grid that interconnects them. While customers may be able to sustain supply through local, on site generation, they will not have the support of the wider grid. It should be noted that the details and analysis of the low selectivity protection philosophy is not included in this paper.

## IV. HIGH SELECTIVITY SCHEME AND SETTINGS USING DIFFERENTIAL PROTECTION: ANALYSIS AND RESULTS

A differential protection scheme compares the difference between current entering and leaving a zone and trips if the difference is above a tripping threshold [15]. Various inaccuracies found in the field that affect the setting of differential relays, such as CT accuracy etc.; were not considered in this study.

A high selectivity differential protection scheme is proposed as follows:

- Identify branches which supply customers from a single common LV node
- Install CTs on all generation points
- Install CTs on all grid connection points
- Install differential relays for each identified zone with CT inputs from each zone entry/exit
- Differential relays trip all circuit breakers connecting the zone to LV nodes/generation sources
- Setting methodology (for each zone):
    - Set differential tripping with suitable margin above normal load conditions as calculated from system load flow or known values.
    - Delay = 0 millisecond (ms)

Figure 5 illustrates the response of the highly-selective scheme response for a fault at bus 10384 in grid isolated mode.

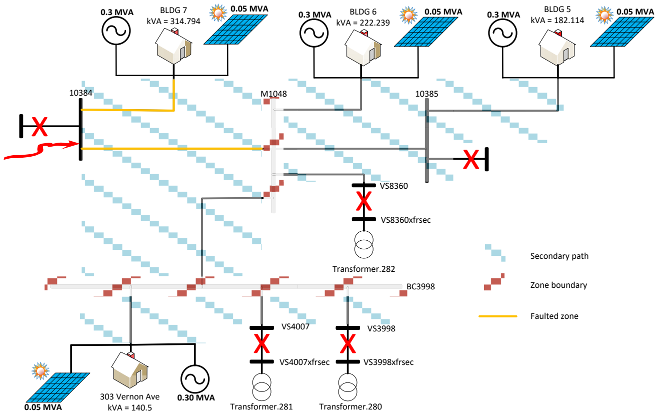

Figure 5: Fault at bus 10384-Islanded mode [23]

The orange section of the microgrid is isolated, while the rest of the microgrid remain energized. In the case of this fault, the faulted section of this grid is isolated.

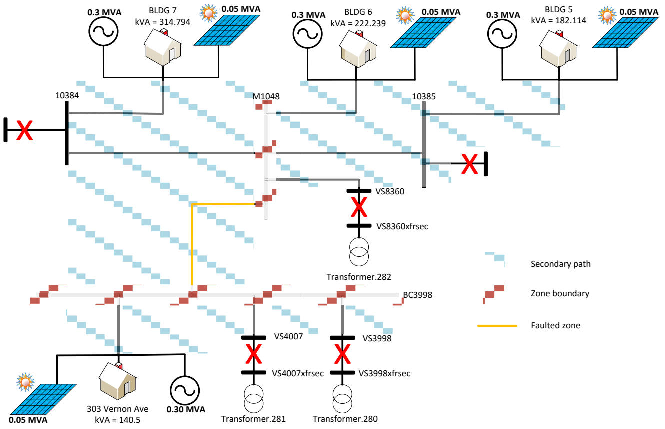

Figure 6: Fault at bus BC3998-Islanded mode [23]

Figure 6 illustrates the response of the high-selective scheme response for a fault on bus BC3998 in grid isolated mode. The orange section of the microgrid is isolated, while the rest of the microgrid remain energized. The response of the microgrid in this case, is to isolate the faulted bus from fault current sources. In this case, BC3998_Loads can provide generation for local load but operate independently and off the main grid.

is assumed that a Master Microgrid Controller (if available) can be configured to select and activate the protection settings for islanded mode or grid-connected mode, depending on the operating status of the microgrid [10] [11]. In other words, if relays with different setting groups are required, then selection of the appropriate groups can be automated by the Master microgrid controller (MMC).

## V. SUMMARY AND CONCLUSION

Generally, for the high-selectivity protection scheme, the protection scheme would trip circuit breakers located at each customer connection point as well as at each outgoing branch from the major LV nodes. It is very robust and effective because all the protection schemes met normal protection performance requirements. It also showed compliance to protection performance metrics and had acceptable fault clearance times, relay trip times etc. It demonstrated adequate system reliability. In general, high-selectivity protection schemes allow the grouping all common LV nodes into various zones. Hence have two protection zones due to a common bus. i.e. M1048 and BC 3998. The key point is that in an event of a fault condition, part of the microgrid stays connected; the unaffected areas is dependent on fault location. Low-selectivity protection scheme treats the entire LV grid as one single zone. The key point is that, in the event of a fault condition, the protection should isolate the customers from the rest of the microgrid.

Cost is a function of the desired level of selectivity and adaptability. High selectivity requires more hardware to be installed at more locations. In the case of the presented example, a high-speed communication network (with redundancy) will be required to interconnect devices. Selectivity and adaptability are functions of real world considerations where the probability of faults occurrence within the microgrid are analyzed with respect to the restoration times and the consequence of loss of supply to the customers. The cost of the system is dependent on the number of measurements, availability of appropriately-rated circuit breakers required to isolate faults, the potential change in existing infrastructure to accommodate the suggested protection scheme/system. In most instances, communication schemes might be required to either alter protection settings based on different system configurations, and/or provide communication between devices to adequately detect faults. In conclusion, two protection philosophies are proposed and shown to provide adequate protection while operating the microgrid in islanded mode. However, there are tradeoffs between selectivity, cost and reliability. It is important to consider when splitting a system into multiple zones what the overall benefit to the customer is for having a higher level of selectivity. For a microgrid system that operates only for limited durations, the added expense of enabling higher levels of selectivity may not be justified.

## ACKNOWLEDGEMENT

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