PROTECTION COORDINATION OF AN INVERTER GENERATION BASED MICROGRID FOR AN UNBALANCED DISTRIBUTION SYSTEM

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ABSTRACT

In this paper we examine the protection issues that must be dealt with, to successfully operate a microgrid when the utility experiences a grid outage. Changes in fault current levels within microgrids under grid-tied and islanded conditions present challenges to developing robust and reliable protection schemes. These schemes must provide an effective response in both grid-connected and islanded mode and the transition between these modes. In this study, a section of an actual residential community located in the western part of the United States (U.S.) was considered as part of the microgrid evaluation. A sizing analysis was conducted to select the appropriate sizes of DER; simulated using DER-CAM analysis. The two DERs considered for the study included solar PV and Battery Energy Storage System (BESS). This paper highlights the protection coordination issues when an existing unbalanced distribution system encompassing a residential subdivision is converted into a microgrid with generation sources with low fault contribution. It further explains the strategy to coordinate protection devices during grid connected and islanded microgrid operating regimes.

INTRODUCTION

A microgrid is a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid [1]. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island-mode. A microgrid presents several protection coordination issues. It is important for utilities to identify and understand various microgrid design requirements in order to utilize the opportunities and benefits of microgrids; such as system reliability and resilience. As part of the design goal, it is necessary to evaluate how to provide segments of the microgrids with sufficient coordinated fault protection while operating in an islanded separate from the utility [2-4].

This paper presents potential strategies of implementing protection schemes for inverter-based microgrids. The goal is to create an "islandable microgrid" on a sub-section of an existing highly unbalanced distribution circuit. This paper is structured as follows: the first section describes the studied system. The selection and sizing of the community microgrid is explained in section two, while the protection study analysis and strategy is described in section three. Section four highlights some observations as well as concludes the paper.

STUDIED SYSTEM

The distribution system considered for this study comprises of a suburban feeder predominantly serving residential customers. The aggregated loading of the feeder is 11.6 MVA. The feeder's aggregated line length is 54.1 km with 30.1 km of three phase lines, 10 km of two phase lines, and 14 km of single phase lines. The carved out microgrid is shown in Figure 1.

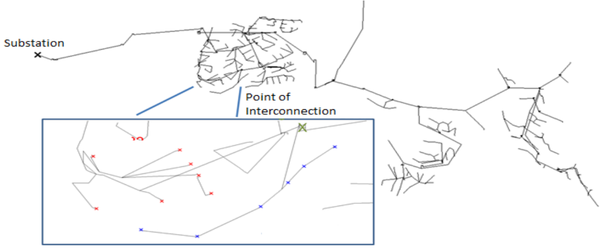

Figure 1. Feeder showing the carved out microgrid [5]

A summary of the microgrid is shown in Table 1.

Table 1: Summary of studied microgrid parameters [5]

Parameters		**Values**
Conductors	Length of three-phase lines	1.3 km
	Length of two-phase lines	0.9 km
	Length of single-phase lines	1.2 km
Loads	Peak Demand	557 kVA
Existing PV	Existing PV system	85kW

Split-phase distribution transformers (12 kV – 120/240 V) were added to each load bus. These transformers are used to step down the voltage from the medium-voltage level on the primary side to the low-voltage level on the customer side. No individual customer fuses were included in the modelled microgrid.

SIZING THE MICROGRID

To establish the feasibility of the microgrid, a detailed Distributed Energy Resource (DER) sizing analysis was performed using the Distributed Energy Resource Customer Adoption Model (DER-CAM) tool [6]. The observed maximum load was 280 kW, occurring in October, while the annual average was 104 kW. A variety of tested sensitivity options and variables includes [5]:

- Islanding Duration (hours) – This parameter defines the duration (hours) under which the microgrid will be subject to islanding conditions (i.e. islanding loading scenario defined above). For example, under a 3-hour islanding duration scenario, the outage is modelled as occurring starting at hour 0 on Monday and lasting until hour 3 of the same day.
- Additional PV Investment – As a baseline, 85 kW of distributed solar PV (currently existing on the feeder) is used as the minimum PV size in all cases. This parameter defines if additional PV investment (beyond 85 kW) is being considered for build out of the microgrid.
- Battery kW-to-kWh Ratio: This parameter defines what the fixed kw-to-kWh ratio of the energy storage system is being considered. This ratio is sometimes referred to as the C-ratio. For example, a 1:4 ratio signifies a four-hour battery configuration is being considered.
- Load Shifting – This parameter defines whether load shifting is being considered during microgrid islanding operations. Load shifting is sometimes referred to as load rescheduling or load deferral. If enabled, the parameter also defines what percentage of the daily load can be shifted. Note: load shifting can only occur within a single day and cannot occur across multiple days.
- Load Curtailment – This parameter defines whether the curtailment of load is being considered during microgrid islanding operations. This differs from load shifting in that load can be direct curtailment and does not need to be served at some other time. If enabled, the parameter also defines what percentage of the daily load can be curtailed.

Table 2 summarizes some of the results from the sensitivity analysis.

Table 2: Capacity and Energy requirements of storage as a function of islanding duration and PV irradiance [5]

		Battery kWh				
		PV Irradiance (%)				
		0%	25%	50%	75%	100%
Outage (Hours)	1	336	324	312	300	288
	2	669	642	615	588	561
	3	984	940	896	852	808
	6	1,894	1,806	1,717	1,629	1,541
	12	3,415	3,318	3,220	3,123	3,025
	24	6,121	6,009	5,898	5,787	5,676
	48	11,696	11,474	11,251	11,029	10,806
	72	16,908	16,574	16,240	15,906	15,573

Based on the results from the feasibility study and consultation with the utility, the energy storage size of 535 kW (i.e. 1.605 MWh) was selected for the protection analysis. The assumption was that this storage system can provide islanding capabilities for up to 3 hours under peak conditions. No additional PV investments were considered.

MICROGRID STUDY SCENARIOS

The studied microgrid was modelled in DIgSILENT PowerFactory [7]; which was considered to have two different operating topologies:

- Grid connected mode: in this mode, the microgrid is supplied by the distribution network; and
- Islanded mode: in this mode, the microgrid is disconnected from the wider distribution network and supply is via local generation and storage only.

In the islanded mode of operation, it is necessary to compensate for the loss of power supplied by the main distribution grid. Hence it is important for the Battery Energy Storage System (BESS) placed at the feeder head to supply the active and reactive power demand of the network based on the network load.

Two separate case studies have been performed with regards to separate BESS configurations and parameters:

- Case 1: Connection of a single three-phase BESS system at the reference bus with fault current contribution of 1.2 pu. [4], [8]
- Case 2: Connection of three (3x) single-phase BESS systems at the reference bus with fault current contribution of 1.8 pu. [8], [9].

A study conducted by [9] indicated that the three-phase inverter provides less fault current than the three single-phase inverters.

PROTECTION STUDY AND ANALYSIS

In order to analyse the appropriate protection philosophy and scheme for the studied microgrid, it is important to go through the following steps;

1. Check the adequacy of the existing protection schemes on both microgrid operating scenarios
2. If this is not sufficient, a new protection scheme will be required taking into account, the preferred protection philosophy as well as the location and operation of the protection devices (relays, circuit breakers etc.)

Existing protection analysis

The primary protection within the grid is provided by fuses installed at the primary side of each split-phase distribution transformer. It is assumed that the existing fuses located within the microgrid will continue to provide sufficient protection in grid connected mode and are sufficiently coordinated.

Load flow results have been recorded at various points throughout the system in different operational modes to establish minimum pickup thresholds for protection devices. The resulting load flows represent the true highest loading of the network to be considered for minimum fault current pickup settings. Figure 2 indicates each point where the load current is recorded. Given that load flow results vary depending upon operational topology and loading conditions, the following scenarios were taken into consideration:

- Grid connected mode – without PV
- Islanded mode connected with 1x 3 phase BESS – without PV [case 1]
- Islanded mode connected with 1x 3 phase BESS – with PV [case 2]
- Islanded mode connected with 3x 1 phase BESS – without PV [case1]
- Islanded mode connected with 3x 1 phase BESS – with PV [case 2]

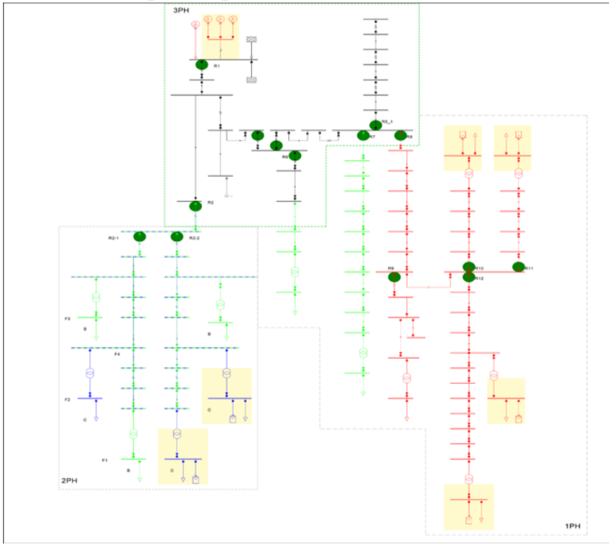

Figure 2. Microgrid with indicated monitoring points [5]

Fault current within the microgrid greatly varies depending on the mode of operation. Fault current levels reduced considerably when grid connected by 90% when in microgrid mode. Fault current provided by inverter interfaced sources in the non-grid connected mode was close to the maximum load current.

The consequence of the decreased fault current levels in the non-grid connected mode is the inability for standard overcurrent schemes to differentiate a fault from normal loading or transient conditions. For analysis, phase to ground faults were simulated and recorded at each monitoring point (shown in Figure 2). Fault current have been recorded at these locations for Grid connected without PV & BESS; Grid connected with PV source; Islanded mode with 1x 3 phase BESS; and Islanded mode with 3x 1 phase BESS. Fault level results also indicate a low level of diversity among the monitored MV locations for any one given operating mode – the fault current magnitude does not vary greatly with fault location. This can be attributed to the low level of system impedance between each point. The existing fuse based protection scheme was found to be insufficient in an islanded operation mode. This was due to the fault current being below the minimum melt current in all cases.

New protection analysis

Cost is an important factor in any microgrid design. Each circuit breaker, current transformer, voltage transformer, and communication link increases capital investment and operational and maintenance costs. As such, the cost of the system is dependent on the protection philosophy, the number of measurements, the number of circuit breakers, the potential change in existing infrastructure to accommodate the suggested protection scheme/system; and communication schemes required to either alter protection settings based on different system configurations, and/or provide communication between devices to adequately detect faults.

Suggested protection philosophy

A crucial component that determines the cost of an adopted protection scheme/s, is the protection philosophy to be used. In this particular microgrid, the suggested protection philosophy is as follows.

- Determine the required level of selectivity for different fault scenarios; by considering the impact to the customers for different grid faults.
- Split the microgrid into separate zones which with appropriate protection grading will achieve the desired selectivity.
- Ensure grid relays protecting branches directly connected to customers trip first to remove the fault from the remaining healthy grid as quickly as possible.
- Ensure that for customers with generation, the customer relays trip last; to ensure healthy generation remains in service, post fault

Three protection selectivity levels have been assessed within this study:

- Zero Selectivity: Protection system consists of a single protection zone where all faults cause loss of supply to the entire microgrid.
- Medium Selectivity: Providing some level of fault selectivity by splitting the microgrid into 11 zones (based on number of monitoring points in Figure 3).
- High Selectivity: Where each customer/distribution transformer is protected individually by splitting the microgrid into 13 zones (based on a combination of the monitoring points and shaded areas in Figure 4).

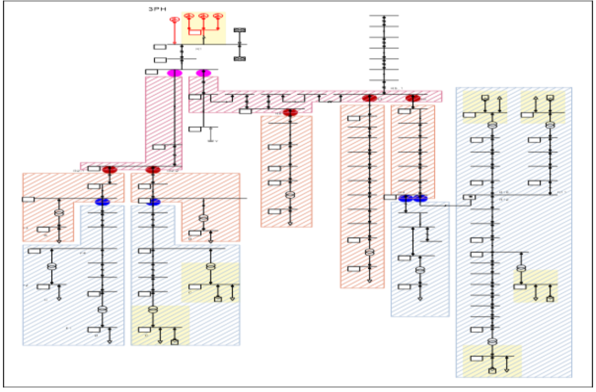

Figure 3. medium selectivity philosophy [5]

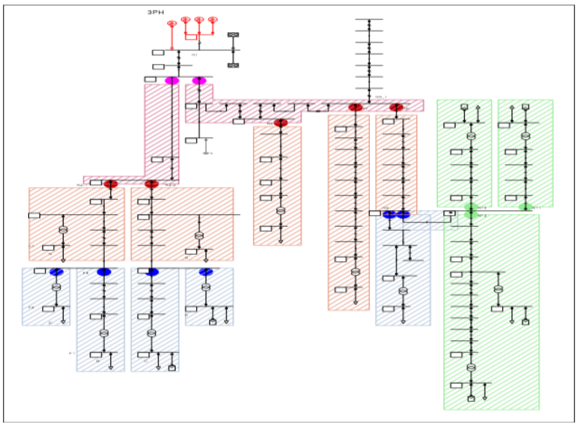

Figure 4. high selectivity philosophy [5]

Tested Protection schemes

These three selectivity levels were tested using various protection schemes; to check the effectiveness. It should be noted that auto-reclosing was not considered in the study.

Directional Overcurrent scheme: The configuration of the microgrid having a single main source of power at the point of interconnection, and multiple low power PV sources connected throughout the system via a step-down transformer, does not attribute itself well to the use of directional protection for selectivity. Each of the distributed PV generators on the network does not deliver sufficient fault current to overcome the impedance of its step-down transformer and thus, it transposes little to no fault current on the MV network in an upstream fault condition. If the system were to have larger distributed generation/storage, the validity of a directional scheme could be reconsidered.

Overcurrent scheme: A normal overcurrent was subsequently tested. Although there are marginal differences between fault current and load current, low system impedance and effective grading margins limit the capability of a highly selective protection scheme. discrete current pick-up based protection. To achieve this functionality an overcurrent protection relay utilizing a definite time curve with configurable time delay worked on both the medium and high selectivity philosophy. This scheme does not distinguish between transformer inrush and faults. No communication system was considered.

Voltage-restrained/controlled overcurrent scheme: When tested on the medium and high selectivity, it was realized that the voltage restrained overcurrent protection was also possible since the scheme is only activated whenever the voltage falls below a certain level. This enables the protection to distinguish between normal load and fault current. No communication system was considered for this scheme.

Differential scheme: A combination of line and bus differential with multiple zones worked but it was not practical. When fewer zones were created, some network nodes were left unprotected. To be effective, the scheme would require reliable communication systems.

DISCUSSION AND CONCLUSION

Overcurrent scheme would be the cheapest option since only current transformers, relays and breakers are needed. For the voltage-based overcurrent, in addition to the relays, a potential transformer will be necessary to enable voltage measurement. The differential scheme is quite expensive; hence not practical in this case.

In conclusion, there are numerous differences from a protection perspective when it comes to the two different microgrid configurations. These includes substantial differences in fault current level (especially with inverter connected generation), differences in fault current direction, remote current infeed, reduced fault current duration; and potential further reduced unbalanced fault current.

The cost of protection systems is a practical consideration in the decision to implement one scheme over another. It is the objective of this study to consider minimizing the additional hardware required to be installed to provide adequate system protection. It is important to consider when splitting a microgrid into multiple zones, what the overall benefit to the customer is for having a higher level of selectivity. Consideration is also given to the period of time in which the system is likely to be operated in islanded mode in comparison with grid connected mode.

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