Design, Integration, and Testing of a Passive Adaptive Protection System for Microgrid Applications

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SUMMARY

The advent of new technologies and the rise of Distributed Energy Resources (DERs) connected to electric distribution systems are expediting the development of microgrids. Some of the main drivers behind the deployment of microgrids include improved system reliability, superior power quality, enhanced energy efficiency, and reduced energy cost. However, despite their advantages, microgrids also challenge the conventional protection and control practices in distribution systems. More specifically, the operation of the system as a microgrid will affect the selectivity and sensitivity of overcurrent protection schemes that are commonly utilized in distribution systems. This is mainly caused by dynamic changes in the microgrid operating mode, configuration, load, generation, and short-circuit characteristics.

One of the proposed solutions to alleviate the protection issues associated with microgrid operation is to develop adaptive protection schemes that can adjust to the changes in the microgrid configuration and/or operating conditions. This paper will first present an overview of protection issues and potential solutions for protecting microgrid systems. It will then discuss the design, implementation considerations, and testing of an Adaptive Protection System (APS) for practical microgrids with high penetration of renewable resources. A typical utility microgrid is simulated using the Real-Time Digital Simulator (RTDS), and the adaptive protection scheme is implemented in the microgrid control system that interfaces with the RTDS. A comprehensive set of Hardware-In-the-Loop (HIL) tests is conducted to verify the effectiveness of the adaptive protection scheme. The experiences and lessons learned in implementing and testing the APS will benefit protection and automation engineers as well as utilities that are currently deploying or planning to deploy microgrid systems in their electric distribution grids.

KEYWORDS

Adaptive Protection, Distributed Energy Resource, HIL Testing, Microgrid

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1. Introduction

For the past decades, the penetration of renewable energy resources has been on a steady rise in the world. As an example, the renewable generation is serving about one-third of the loads in California, with solar systems taking a major portion of this generation [1]. Microgrids have the capability to integrate these energy resources and offer energy and reliability services to remote areas and/or (critical) customer loads connected to the utilities' distribution systems. In addition, due to the decentralized architecture, microgrids can reduce the transmission and distribution losses and provide enhanced control flexibility to critical sectors. Further, microgrids help the transition from expensive fossil-fuel-based generation to clean and sustainable energy resources such as solar Photovoltaic (PV) systems and energy storage systems.

Protection of electric distribution networks is primarily achieved using non-directional overcurrent protective devices such as relays, reclosers, sectionalizers, and fuses. The main assumption in the design of distribution protection systems is the unidirectional flow of power, which enables straightforward coordination of protective devices via proper selection of time-current protection curves and settings. In addition, protection systems are typically designed for worst-case scenarios and validated under minimum and maximum fault currents in the protection zone to manage the impacts of expected changes in the system. However, this conservative approach will not be effective for microgrid systems with constant changes in operating conditions such as operating mode, topology, DER status (off-line vs on-line), DER power output, DER control mode, etc. These changes cause the fault current magnitude, direction, and characteristics of a microgrid to vary constantly.

A microgrid usually connects to a central grid at the Point of Interconnection (POI) and operate in the grid-connected mode. In case of expected/unexpected power outages caused by faults or extreme weather conditions, the microgrid can isolate from the main grid (either automatically or manually) and operate in the islanded mode. Operation as an island causes the short-circuit current level of the microgrid to drop significantly compared to the grid-connected mode. The main protection challenges associated with microgrids are listed below:

- Bidirectional fault current, leading to mis-operation of non-directional overcurrent relays;
- Varying fault current level;
- Protection coordination under various system topology and load/generation levels (e.g., change in protection zone due to circuit reconfiguration);
- Protection of the POI to enable seamless transition to the islanded, if needed (islanding); and
- Seamless transition from the islanded mode to the grid-connected mode (resynchronization)

To address the challenges associated with microgrid protection, either partially or in whole, several solutions have been proposed/implemented [2], which can be of two types: (i) customized logic-based solutions and (ii) communication-based solutions. Adaptive protection is one of the elegant methods proposed for microgrid protection. The protective relays in the power industry have evolved from single-function electro-mechanical relays to modern digital relays that offer multiple protective functions, self-diagnosis, data recording, and communication capabilities. In particular, the advanced communication technologies have enabled high performance peer-to-peer communications amongst protection relays as well as communications to a central controller. This paper demonstrates how these features can be utilized to design an effective protection scheme for a microgrid with high penetration of renewable resources and various operating modes/conditions.

2. Adaptive Protection Systems: Design and Implementation

2.1. Definition

An Adaptive Protection System (APS) is defined as a near-real-time activity that modifies the protection system response to a (expected) change in system configuration and/or operating condition in a timely manner by means of externally generated signals [3]. While the protection response modification can include protection setting group(s), setting value(s), and/or protection functions, this study will focus on switching to the appropriate protection setting groups and switching sequence.

2.2. Design and Implementation

The proposed protection solution consists of two stages, namely, enhanced protection coordination and centralized protection setting adjustment.

2.2.1. Enhanced Protection Coordination – Communication-Based Blocking Scheme

To enhance protection coordination for microgrid overcurrent (OC) devices, a blocking scheme can be implemented using peer-to-peer communications (in this case, IEC61850 GOOSE messages) amongst relays. The scheme adjusts the OC operating time of an upstream relay (by adding 0.3-sec delay) when the relay receives a blocking signal from its downstream relay (see Figure 1). This enables several OC devices to be coordinated with smaller coordination time interval (e.g., 0.1sec); this is because the upstream relay will operate with (0.3-sec) delay when a fault is seen by the downstream relay. Figure 2 shows the logic diagram for 51-2 device in Figure 1.

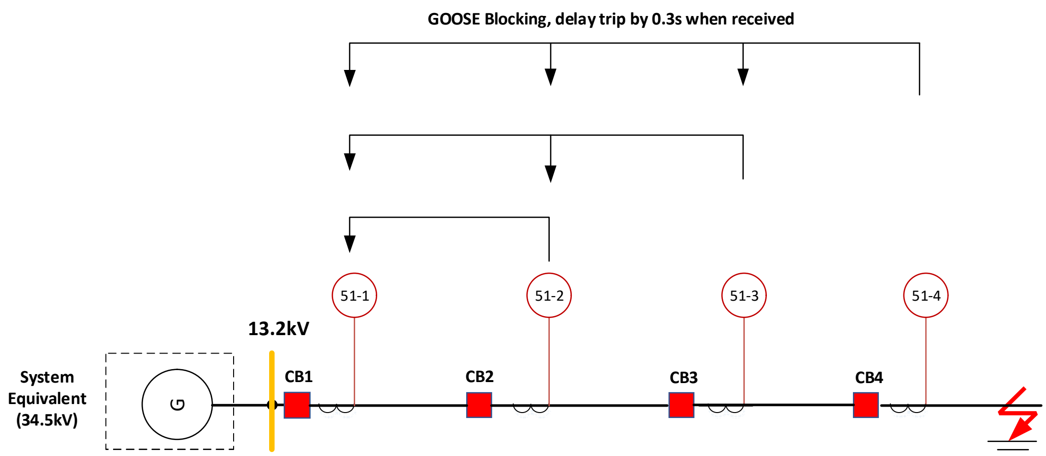


Figure 1 Enhanced protection coordination – blocking scheme

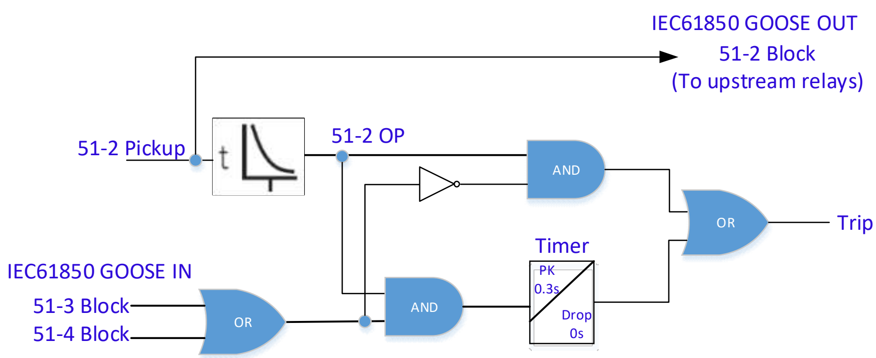


Figure 2 Blocking scheme logic diagram using GOOSE messages

2.2.2. Substation-Centric Protection Setting Adjustment

In general, there are two different methods to implement protection setting changes in an APS: (i) offline setting calculations (pre-calculated/passive method) and (ii) online setting calculations (active method) [4], [5]. This study focuses on the first method, which is based on pre-calculated protection setting groups (passive) and real-time system monitoring and matching. The processes, sequence of actions, and data flow to implement this solution for microgrids will be described in this section.

The microgrid control system continuously monitors the microgrid topology and updates the system operating mode/configuration status by analysing real-time system information such as switch/breaker status (ON/OFF) and DER status (online/offline); the microgrid controller is also monitoring and supervising active protection setting groups of various Intelligent Electronic Devices (IEDs). As such, when a change in the operating mode or system configuration is detected/expected, the microgrid controller evaluates whether the existing protection is adequate. If it is not, the IEDs that require protection setting change will be identified, and proper setting group setpoints are issued to them. Further, the proper sequencing order is determined. Figure 3 shows the sequence diagram for an APS (offline/passive setting calculation). It should be noted that complete protection coordination may not be achieved for all system conditions; thus, it is important to specify 'adequate protection' for a microgrid project in line with the project requirements and/or operating strategy.

Based on the above discussions, a passive adaptive relaying scheme consists of three major stages:

1) *Offline Analysis*: Meaningful microgrid configurations are identified, and protection studies are performed to calculate relay settings for those configurations/topologies. The microgrid configurations and corresponding protection settings are arranged in a lookup table.
2) *Online Matching*: The microgrid configuration is continuously monitored via the state of switching devices. Once a change is detected, proper relay settings for new topology are selected from the lookup table along with assigned sequencing order. If the new topology is not defined as a meaningful configuration, the relay settings will remain intact.
3) *Activate Setting Group*: Setting group change commands are transmitted to corresponding IEDs through a reliable communication medium, and the change confirmation is received.

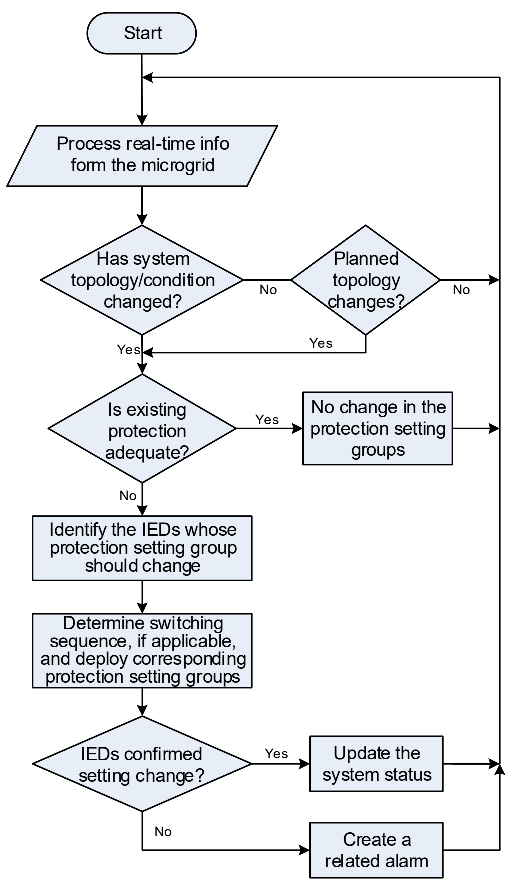


Figure 3 High-level flowchart of an APS (passive/pre-calculated protection settings)

2.3. Design and Implementation Considerations

Some of the main considerations in the design and implementation of an APS are as follows:

- The effectiveness of the APS can be impacted by fuses, electromechanical relays, and solid-state relays that do not provide flexible protection settings/characteristics.
- The use of a reliable communication medium (PLC, fiber, etc.) and a standard communication protocol (DNP3, IEC6185, etc.) is essential for the development of an APS.
- Dependency on the communication system and central processor may necessitate redundancy.
- Due to bidirectional power flows in microgrids, using directional elements is essential. Thus, protection coordination should be done for forward and reverse directions, with relays supporting different settings for both directions.
- The lookup table should be updated when a new system configuration is allowed; it is important to conduct protection studies for all the permitted configurations.
- The APS function should coordinate with other distribution automation functions in place (e.g., service restoration and/or load transfer applications).

3. Case Studies

Figure 4 shows a simplified single-line diagram of a utility microgrid. As can be seen in this figure, the microgrid consists of two 12kV feeders that are tied to each other through a Normally Open (NO) tie breaker. The microgrid is also interconnected with the main utility grid at a POI via a 69kV/12kV transformer bank. When the utility grid is lost, e.g., due to an external fault, the microgrid can operate in the islanded mode and supply the load on both feeders (POI breaker is open). The microgrid controller, as the brain of the system, will monitor the system condition including loss of utility and reconfigure the network as needed.

3.1. Short Circuit Analysis

Short-circuit and protection studies were performed for possible microgrid configurations, using the ASPEN OneLiner **Error! Reference source not found.**. Table 1 lists the allowable configurations for the microgrid of Figure 4, which are defined based on the status of major switching devices. Table 2 provides microgrid three-phase-to-ground (3LG) and single-line-to-ground (SLG) short-circuit currents in various operating modes. As can be observed in this table, the fault current levels change significantly under different operating modes. It should be noted that, except baseline configuration, the microgrid experiences bi-directional power flow in other modes. Thus, protection coordination should be done for both forward and reverse directions and augmented by the blocking scheme.

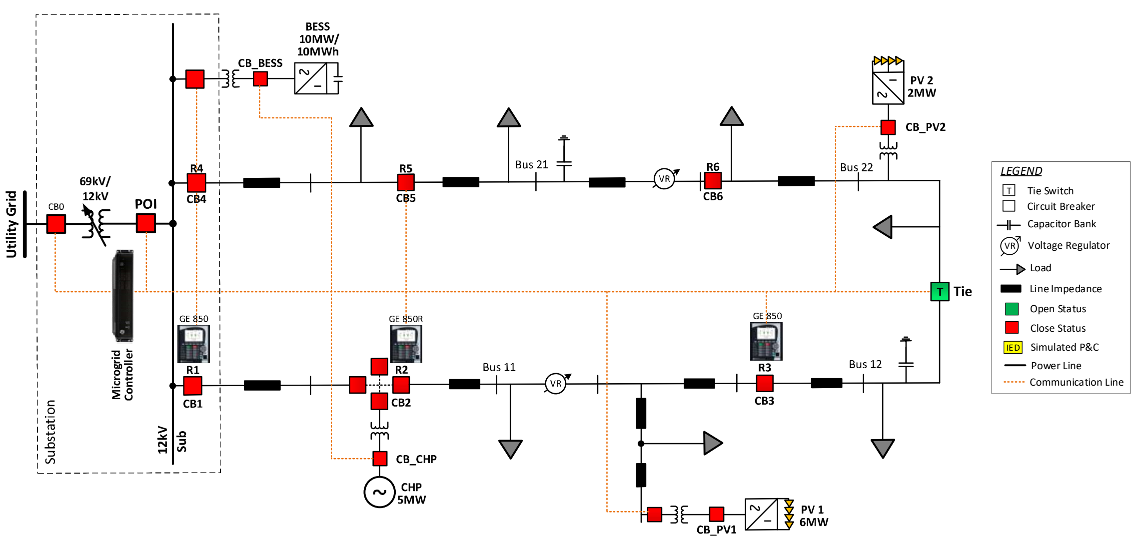


Figure 4 Simplified single-line diagram of the microgrid

Table 1 Microgrid operating mode/configuration (based on status of major switching devices)

Operating Mode/Configuration	POI	CB1/CB2	CB4	CB_CHP	CB_BESS	Tie
Baseline (no DER)	ON	ON	ON	OFF	OFF	OFF
Grid-connected (Tie Open – Normal)	ON	ON	ON	ON	ON	OFF
Grid-connected (Tie Close – Looped)	ON	ON	ON	ON	ON	ON
Transfer	ON	OFF	ON	ON	ON	ON
Islanded (Tie Open)	OFF	ON/OFF	OFF/ON	ON	ON	OFF

Table 2 Microgrid 3LG fault current level in different operating modes (A)

Operating Mode/Configuration	Sub	Bus 11	Bus 12	Bus 21	Bus 22
3LG Faults					
Baseline (no DER)	6884.6	3471.5	3266.2	4778.8	3908.8
Grid-connected (Tie Open – Normal)	9197.5	4364.4	4046.2	5835.6	5835.6
Grid-connected (Tie Close – Looped)	9222.7	6175.9	6213.8	6643	6214.5
Transfer	8813.4	5410.2	5688.8	6547.8	5691.8
Islanded (Tie Open)	2555	2196.1	2105.6	2207.5	2007.9
SLG Faults					
Baseline (no DER)	6949	2927.3	2715.6	4303.7	3350.7
Grid-connected (Tie Open – Normal)	9195.8	3676.6	3355.1	5094.5	3855
Grid-connected (Tie Close – Looped)	9225	5467.7	5557.3	5991.8	5557.8
Transfer	8698.9	4755.2	5067.7	5912.5	5069.7
Islanded (Tie Open)	2492.1	2058.1	1946.1	2074.9	1838.6

3.2. Feeder Over-Current Protection Coordination

The coordination study aims at calculating relay protection settings to ensure they are coordinated under different operating conditions. An automated process, using scripts, can be adopted in the protection software tool to perform coordination studies. Based on the allowable configuration, each IED may use several setting groups for different directions. For this study, a total number of 3 protection setting groups were identified to be needed. A matrix table was setup in the microgrid controller such that the correct setting group will be selected for each operating mode; this will further be discussed in Section 4.2.

4. Integration and Testing

4.1. Test Setup and Data Flow

HIL testing with Protection and Control (P&C) hardware equipment were performed to verify the performance of the developed APS. The microgrid of Figure 4 was simulated in the RTDS and P&C devices were interfaced with the RTDS (physical P&C devices are indicated in Figure 4). Figure 5 shows the HIL testbed developed in the GE Digital Integration Laboratory. Low-energy inputs of some relays were utilized to minimize the number of amplifiers required for testing. The proposed testing approach ensures that the test results are the best representation of the field environment.

4.2. Test Cases and Results

This section outlines the test cases and results of the study. In preparation of the test plan, various operating scenarios that can affect system protection were considered. Operating mode of the microgrid is dynamically monitored and evaluated by the microgrid controller. The controller collects relevant data to identify any topology change in the system. The controller also reacts to microgrid's configuration changes by issuing proper setting group change command to corresponding IEDs.

The APS algorithm, monitoring and supervisory HMI are developed in real-time microgrid controller [7]. Figure 6 shows the HMI representation of the microgrid configuration developed for this study. Status of the major breakers, switches, and DERs are monitored by the controller to determine the protection setting group and sequencing order. When the mode of operation changes, the actual setting group of the protective relays are compared with the setting group required for that operation mode. If the setting group is different, then a command is sent to that relay to change the setting group.

For a fault between R2 and R3 in Figure 4, Relay R2 blocks its upstream relay (R1) and isolates the fault. The microgrid controller will then reconfigure the system by closing the tie switch. Once the tie is closed, the operating mode changes to 'Transfer' followed by protection setting changes. Figure 6 (microgrid controller HMI) shows "Transfer" mode when the microgrid is connected to the grid through Feeder 2 (CB1 open, Tie closed and CB2 closed). The real-time setting group of the IEDs matches the setting groups defined in the table under "Transfer" mode.

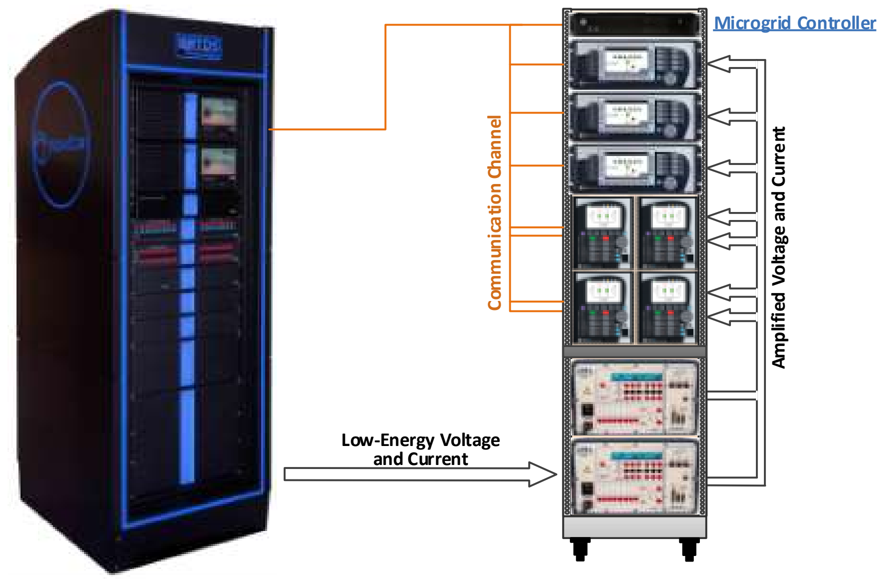
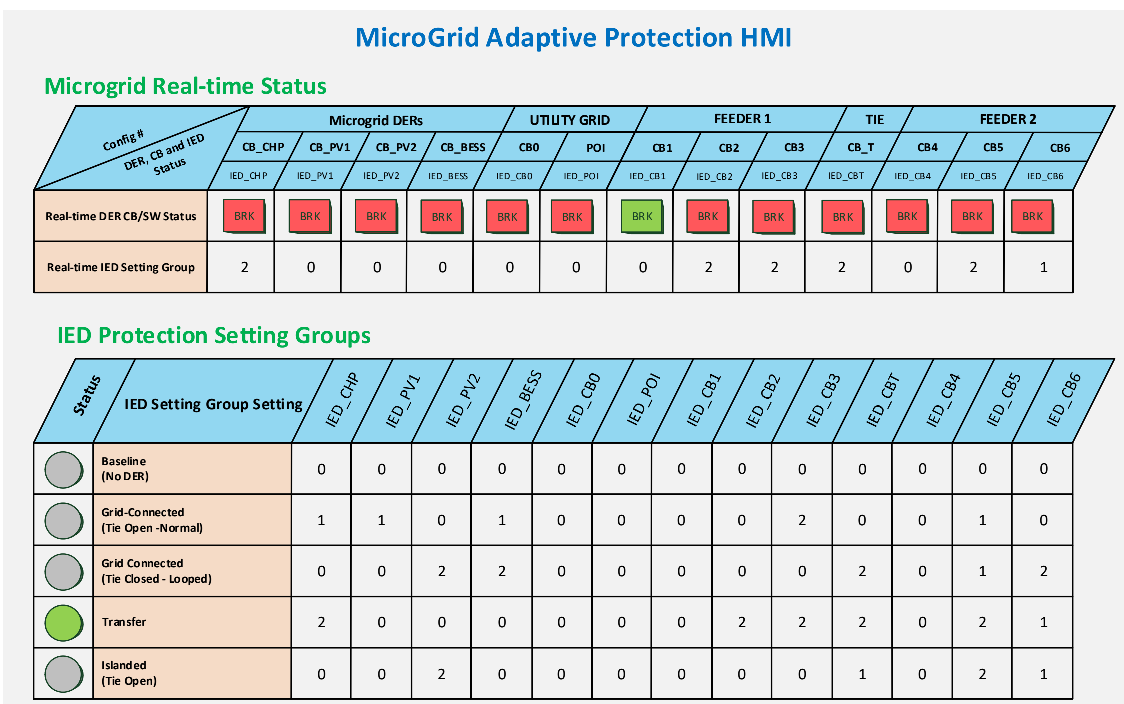


Figure 5 Hardware-in-the-loop test setup



Config # / DER, CB and IED Status	Microgrid DERs				UTILITY GRID		FEEDER 1			TIE	FEEDER 2		
	CB_CHP	CB_PV1	CB_PV2	CB_BESS	CB0	POI	CB1	CB2	CB3	CB_T	CB4	CB5	CB6
	IED_CHP	IED_PV1	IED_PV2	IED_BESS	IED_CB0	IED_POI	IED_CB1	IED_CB2	IED_CB3	IED_CBT	IED_CB4	IED_CB5	IED_CB6
Real-time DER CB/SW Status	BRK	BRK	BRK	BRK	BRK	BRK	BRK	BRK	BRK	BRK	BRK	BRK	BRK
Real-time IED Setting Group	2	0	0	0	0	0	0	2	2	2	0	2	1

Status	IED Setting Group Setting	IED_CHP	IED_PV1	IED_PV2	IED_BESS	IED_CB0	IED_POI	IED_CB1	IED_CB2	IED_CB3	IED_CBT	IED_CB4	IED_CB5	IED_CB6
	Baseline (No DER)	0	0	0	0	0	0	0	0	0	0	0	0	0
	Grid-Connected (Tie Open -Normal)	1	1	0	1	0	0	0	0	2	0	0	1	0
	Grid Connected (Tie Closed - Looped)	0	0	2	2	0	0	0	0	0	2	0	1	2
	Transfer	2	0	0	0	0	0	0	2	2	2	0	2	1
	Islanded (Tie Open)	0	0	2	0	0	0	0	0	0	1	0	2	1

Figure 6 HMI for Adaptive Protection Setup

5. Summary and Conclusions

This paper presented an overview of overcurrent protection issues and solutions for the microgrid systems. It then focused on the design and testing of passive adaptive protection systems for microgrids. In addition, implementation considerations were discussed to provide the utility engineers/managers with some guidelines on APS requirements. The proposed solution consists of enhanced protection coordination using an IEC61850 GOOSE blocking scheme and a centralized protection setting adjustment via real-time microgrid monitoring. A comprehensive set of Hardware-in-the-Loop tests were conducted to verify the effectiveness of the adaptive scheme. The testing results indicate that APS can elegantly resolve the protection coordination challenges for a microgrid system. More specifically, for typical microgrid sizes, a passive scheme provides an effective and manageable solutions.

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