# ADVANCED AND ADAPTIVE PROTECTION FOR ACTIVE DISTRIBUTION GRID

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## ABSTRACT

*Classic protection schemes for existing distribution systems designed for passive and radial networks have been shown to be inadequate for emerging distribution grids. A new protection paradigm, architecture and philosophy are required in response to changes in behaviour of fault currents. These changes are due to the introduction of distributed generation and flexible network topologies, microgrids and islanded schemes. This paper introduces the concept of the advanced and adaptive protection for emerging distribution grids. Viable solutions using intelligent electronic devices and appropriate communication systems are presented. Preliminary results as applied a specific distribution system operated by Duke Energy are also shown. The proposed concept will pave the way for the optimal protection of future smart grids.*

## INTRODUCTION

Rapid and dramatic changes have been occurring in the electrical distribution systems in the U.S. and worldwide during the past two decades. There are many drivers that have been providing the impetus for these changes. These developments also have been creating challenging needs and opportunities for new models, tools, and technologies to design, plan and operate the emerging systems. There is a clear need for leveraging the intelligence and information provided by sensors, energy boxes, and smart meters to integrate Distributed Energy Sources (DERs) with Distribution Management Systems (DMS) to enhance performance of the emerging distribution grid. This need builds on the U.S. DOE Vision towards an Intelligent North American Grid by 2030. The results when implemented, will improve load factor, efficiency, and reliability to meet the 2020 DOE Smart Grid R&D Cost and Performance Targets. The preliminary investigation indicates that conventional overcurrent relays will be inadequate for active distribution networks. Computer-based digital relays integrated with proper communication systems may be more suitable to accommodate varying fault current ranges as network topology changes.

The primary focus of this paper is to introduce the concept of advanced and adaptive protection for emerging distribution grids. This entails presenting some of the initial results obtained to date as applied to a specific distribution system operating in grid, autonomous microgrid, and islanded modes. The following points will also be discussed in the paper:

- The use of remote interrupters and line sensors for fast fault interruption (coordination implemented through communication)
- The use of PMUs and line sensors for fault location
- The use of all measurement-capable devices for zone protection, including high impedance fault detection.

## ADVANCED AND ADPATIVE PROTECTION

Conventional protection designed for passive radial networks is insufficient for the increasingly complex and active networks. These may have radial and looped topology integrated with diverse distributed generation sources, storage, and controllable loads [1]-[6]. The design of such protection systems for emerging distribution systems needs a totally new protection paradigm, architecture, and philosophy making use of new protective devices and sensors such as digital relays, Phasor Measurement Units (PMUs), intelligent reclosers, and line sensors. The new paradigm leverages advanced communication infrastructure for fast fault interruption and service restoration as well. It is also able to adaptively respond to changing operation conditions (such as variations of DG outputs) and varying network topologies. Thus the technical approach adopted for developing the advanced and adaptive protection system includes the selection of computer-based protective devices. These will facilitate flexible coordination which will be more likely to be global at the substation level unlike the local coordination philosophy that has been adopted in the past.

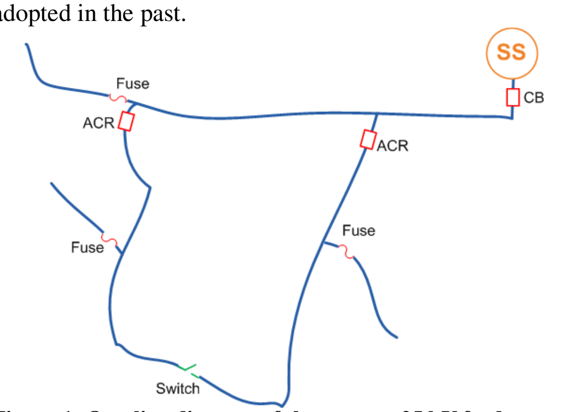


**Figure 1: One-line diagram of the current 25 kV feeder**

The main problems with the protection of distribution systems brought out by emerging changes are summarized as: a) under/over reach and false trip of protective devices, b) loss of coordination among protective devices, and c) islanding issues. To illustrate these issues, one feeder of an existing 25 kV substation within the Duke Energy grid is used. A section of the one-line diagram of the current system is shown in Figure 1.

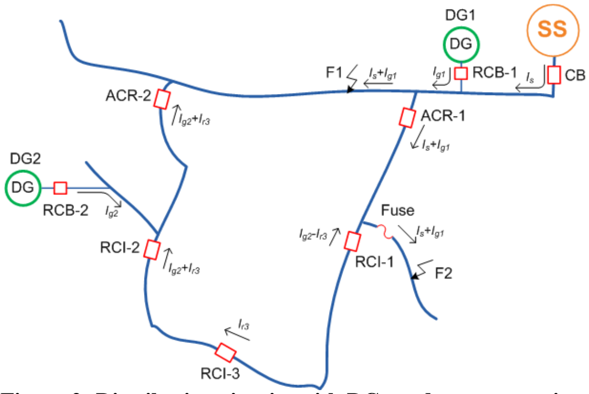


**Figure 2: Distribution circuits with DGs and new protection devices**

The original system as shown in Figure 1 is passive and radial. Automatic Circuit Reclosers (ACRs) and fuses are used to protect the system. A fuse-saving scheme is also used for overhead lines.

New devices can be added to augment the system to accommodate Distributed Generators (DGs) and improve reliability. However, problems can arise if the devices use only local signals for protection. In order to minimize the number of customers affected by a circuit fault, three Remote Controlled Interrupters (RCIs) were installed as depicted in Figure 2 to isolate the faulted section. Looped circuit operation is allowed by RCI-3 to enhance the system reliability. Two Distributed Generators (DGs) are installed in this feeder and Remote Controlled Breakers (RCBs) are used to isolate them from the rest of the circuits for safety purposes to conform with the original IEEE 1547 Standard. With these proposed changes, conventional protection schemes are no longer adequate. Several examples are provided here to justify the aforementioned issues.

(i) For a fault designated as F1 identified on the top of Figure 2, occurring in a line segment which is designed to be protected by relay and circuit breaker at the substation, the fault current contributed by DG1 changes the range of fault currents seen by the relay. This will cause a prolonged trip or a reluctant trip, which is also known as protection of blinding. The fault current contributed by DG2 and the substation in loop operation will make ACR-2 reclose on an energized line.

(ii) For a temporary fault designated as F2 in line segment identified again in Figure 2, which is designed to be cleared by ACR-1 through a reclosing process (fuse-saving scheme), the fault current contributed by DG1 increases the maximum coordination current. In this case, the fuse will blow before ACR-1 attempts to reclose and the fault current from other direction supplied by DG2 and the substation will cause unnecessary tripping of RCI-1.

(iii) For either fault F1 or F2, the recloser and the digital relay with reclosing function will close on circuits energized by the two DGs, therefore, causing unsynchronized reclosing. The DGs have to be disconnected to ensure the safety of personnel.

To resolve above issues, an advanced protection scheme is needed, which is able to adaptively accommodate varying generation patterns and network topologies, and isolate faulted circuits in a fast and reliable fashion.

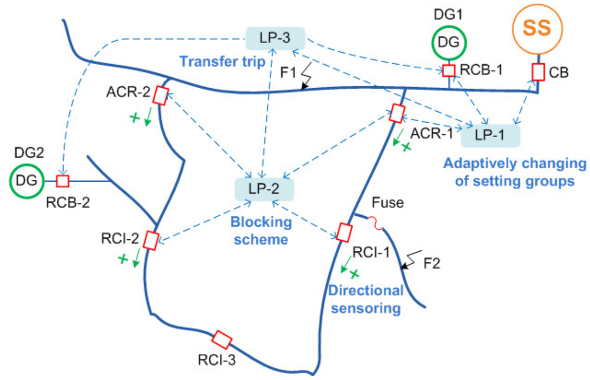


**Figure 3: Advanced and adaptive protection schemes**

Figure 3 shows the modifications required to the system of Figure 2 to describe the advanced and adaptive protection scheme. The automation and coordination of the protection scheme can be implemented using a Logic Processor (LP) through communication [7]. The protection logic changes required are summarized below:

- Settings groups for the digital relay and ACR-1 are changed adaptively according to the operation states of DG1.
- A blocking scheme is used to enable fast trip for downstream relays.
- A transfer trip scheme is used to coordinate breakers at DGs with reclosers and disconnect DGs from the grid when necessary.

The intelligent fault current interrupter with directional sensitivity is used for protection in the loop operational mode. In radial operation (RCI-3 is normally open); the pulse reclosing feature of the intelligent reclosers allows fast service restoration and reduced number of affected customers [8].

## FAULT LOCATION USING SYNCHRONIZED PHASOR MEASUREMENTS

The capability of accurately locating a fault in distribution systems can help the repair process, expedite system restoration, and thus reduce outage duration. Distribution networks have a large number of branches. The growing penetration of distributed energy resources and implementation of flexible network configurations (such as looped and meshed fashion) in emerging grids have been changing the traditional current flow pattern. These characteristics make it difficult to accurately locate a line fault. Current practices, such as line investigation by repair crew and fault analysis based methods are either time consuming and/or less accurate. Using fault indicators can narrow the faulted area; however, the range of the estimated area depends on the deployment of these devices. Also, the fault indicators may fail in tracing the fault location under bidirectional current flow conditions.

Due to the highly branched structure of distribution networks, the apparent impedance based fault searching algorithms could yield multiple locations when measurements are available only at one terminal, such as with the substation [9], [10]. Therefore, an additional procedure is needed to find the actual fault location. A new fault location approach leverages synchrophasors with high accuracy and time synchronization. These measurements are often provided by PMUs and PMU-capable devices which have been widely used in power systems for the purpose of monitoring and control [11].

The method uses voltage and current phasor measurements from different locations, such as substations and remote terminals of feeders. The procedure involves estimating all possible fault locations first, and then eliminating the non-faulted cases. The candidate locations are found by iterating every possible line segment, which is partitioned segment with the same parameter. In the presence of laterals (tapped on lines, distribution transformers etc.), the Thevenin equivalent circuit is estimated to calculate the branch currents. For lines with single end measurements, the resistive fault is handled using an iterative algorithm. For lines with remote current infeed, the fault impedance has zero impact on result accuracy. This method works for both active and passive systems, and it is not constrained to device locations.

A modern 25kV/120MVA distribution substation located in Duke Energy territory is used to demonstrate the efficacy of this proposed fault location method. This system consists of six feeders supplying over seventeen thousands customers. The deployment of synchrophasor devices at the substation and the far end of each feeder are proposed, as shown in Figure 4. Several case studies have been simulated to test the performance of the proposed scheme. Figure 5 shows the results for a case of a phase-to-ground fault with a fault resistance of 100 Ω occurring in the middle of a lateral line (ID#37768062) of the feeder which has 609 lines, 419 distribution transformers and two distributed generators with capacity of 3-MVA and 1-MVA. Six possible lines were found and the faulted line was pinpointed within 1% of the line length.

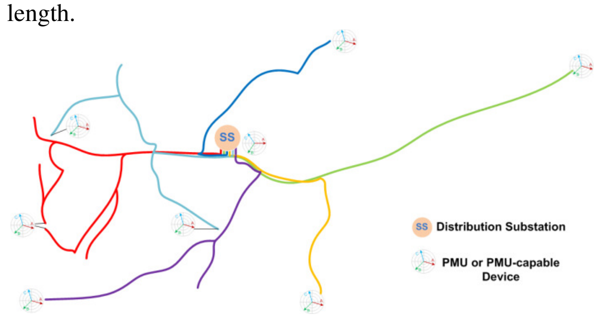


**Figure 4: Main circuits of feeders and locations of PMUs**

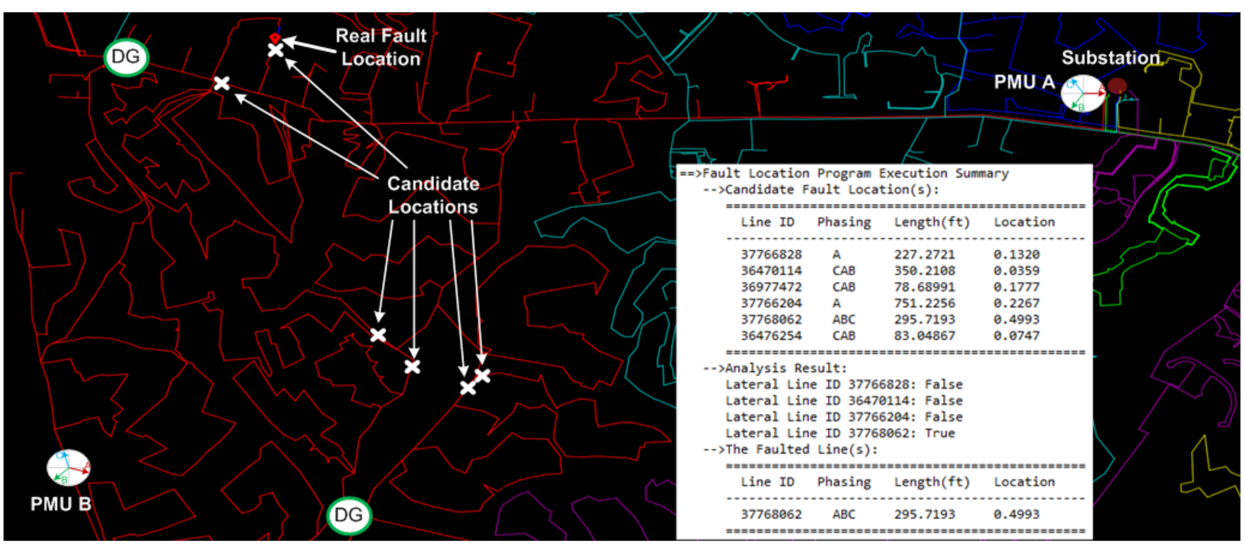


**Figure 5: Illustrations of a fault location result**

## DIFFERENTIAL ZONE PROTECTION FOR MICROGRIDS

Current differential based protection algorithms have been widely used for the protection of electric power apparatus because of their simplicity, high sensitivity, and capability of handling high impedance faults. Differential protection applied to lines requires a communications system [12]. The principle of current differential relaying can be extended to multiple line segments to form zone protection schemes.

In terms of the communication infrastructure, the zone protection schemes can be implemented in either centralized control or localized autonomous fashion by using dedicated protection controllers. Figure 6 presents an example of differential zone protection implemented using a centralized controller at the substation. The analog and digital (if applicable) measurements from each device are gathered and sent to the central controller for protective algorithm processing through aggregators.

The measurement can be provided by any digital relay, switching device and/or line sensor. The communication system is selected in terms of the requirements from the options, such as radio, 3G/4G M2M, Wi-Fi and PLC. The differential zone protection schemes are well suited to protect microgrids and easily integrated with grid protection schemes.

The differential zone protection scheme is extremely well suited for microgrids because of the nature of microgrid faults. Due to the high penetration of inverter sources in a microgrid, nearly all faults will have very low fault currents which cannot be detected by over-current devices. Differential zone protection has no problems detecting these faults. The small footprint of microgrids facilitates the communication needs of a differential zone protection scheme.

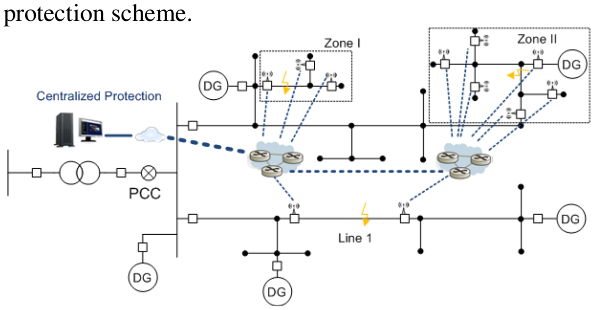


**Figure 6: Centralized differential zone protection**

## CONCLUSION

This paper introduces a novel concept of advanced and adaptive protection and designs for active distribution networks. It demonstrates the versatility of a combination of local intelligence and centralized management, applying it to a practical example in a real system. With the challenges of increasing distributed generation and the complexity of large-scale demand response and electric vehicles, there is clearly a need for such concepts to be trialled and adopted by utilities as they start to implement new technologies into their network.

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