UPDATE ON DISTRIBUTION SYSTEM FAULT LOCATION TECHNOLOGIES AND EFFECTIVENESS

Tom SHORT  Jinsang KIM  Chris MELHORN
EPRI - USA  EPRI – USA  EPRI - USA
tshort@epri.com  jinsangkim@epri.com  cmelhorn@epri.com

ABSTRACT
Automatic fault location is an area of significant interest and research in the industry. This paper provides an update on the work performed to date with various utilities and the fault location systems. Basic information on the techniques used to locate faults is provided as well as several examples of where these techniques have been deployed.

INTRODUCTION
As the complexity of electric distribution systems increases, so do the systems that monitor their health and performance. Permanent monitoring systems are used to track the ongoing system performance and to watch for conditions that could require attention, as well as to provide information for utility and customer personnel when there is a problem to be investigated. One particular area that has seen recent advances is the area of fault detection and location [1]. Benefits of such automated fault location are reduced fault repair time, identification of problem areas, fault cause identification and reliability improvement. The Electric Power Research Institute (EPRI) has a project that is a multi-year effort to evaluate different approaches, identify limitations, and develop recommendations as a function of the types of fault location systems [12]. In addition, a number of utilities have implemented fault location functionality to their existing substation power quality monitoring systems.

This paper provides an update on the work performed to date with various utilities, the fault location systems, the performance of the system for actual fault conditions.

OVERVIEW OF FAULT LOCATION APPROACHES
Distribution faults are normally located manually without the use of any measurements. Location is made primarily through field line inspections. Automated fault location algorithms have not been widely used due to of lack of monitoring equipment and the complexity of the problem. The literature review by Diaz and Lopez [11] provides a good overview of 89 papers and other citations. Most distribution fault-location approaches concentrate on impedance-based fault location techniques where fundamental-frequency parameters are used to estimate fault locations.

Another category of fault location algorithms is various learning systems. These can include expert systems, fuzzy logic, neural networks, and other trainable algorithms. These can be used in conjunction with other methods or as standalone algorithms. A key issue is obtaining a suitable training data set. Examples of learning systems include Jarventausta et al. [9] and Glinkowski et al. [10]. Practical fault-location methods based on the use of current and voltage phasors have recently been implemented in feeder protection devices.

Fault Location Based on Fault Currents
Progress Carolina has an advanced monitoring system that is used to locate faults. For further reference, see Lampley [2] and Peele [3,4] and analysis performed at NC State based on their data by Kim et al. [5]. Progress Carolina records steady-state trend data and fault events on all of their feeders using a remote-terminal unit (RTU) that can sample at a rate of 16 samples per cycle. Their fault-location “system” started as a spreadsheet that assumed a constant conductor size for a given circuit. When the fault current and type of fault was entered, the spreadsheet would estimate a distance. Success with that system led to development of more automated systems to locate faults, including:

- Fault Distance Tool—This is a web-based tool available to all that provides distance to the fault assuming a constant wire size for each feeder.
- Cyme software—This provides several possible fault locations. Progress has found this to be the most accurate. It uses actual wire sizes from their GIS. This requires more manual processing.
- OMS—This interface provides locations to operators. It uses actual wire sizes from GIS, and the OMS is updated the most frequently to reflect the system connectivity in the field. It has the ability to locate automatically for feeder lockouts. Other outages must be initiated manually.

The web interface allows personnel to select the company region, substation, and circuit. From there, a list of fault events is given with the type of fault event and estimated distance. From there, the operator can go to a map view shown in Figure 1.

Progress Energy uses the fault-current method of fault locating. They use the fault current from the measurement and use a fault-current profile from the given circuit to
select possible fault locations. They assume a bolted fault (i.e., no fault resistance).

**Con Edison’s Fault Location Experience**

There are more than two thousand distribution feeders in the Con Edison distribution system and most of those feeders are underground. In the past, locating faults on the system has been a painstaking process. The process used to repair a faulted feeder consists of the following steps:

- Disconnect load and isolate
- De-energize the faulted feeder
- Establish the condition of the feeder
- Locate the fault
- Identify cable, splice, or equipment that is faulted
- Make the necessary repair
- Prepare the feeder for service
- Energize the feeder
- Re-connect the load

In an effort to reduce the fault locating time and cost, direct crews more efficiently, and maintain network reliability, Con Edison has implemented a fault location system in the New York City area. To gather the information required for fault location, Con Edison employs the use of power quality monitors that are monitoring voltages and currents on a substation transformer. With the recent advancements in the fault location detection algorithms, Con Edison has been able to successfully use the power quality monitors as part of the fault location system.

The Con Edison fault location system uses the reactance to fault (RTF) method, a modified impedance-based fault location algorithm, to determine the location of a fault on their underground distribution system in Manhattan, New York. The basic principal for the RTF method is to use a computer model to calculate the reactance of each feeder in the system from the substation to the end of the feeder, store those values in a database, and compare the simulated reactance values with values calculated from measurements during a fault.

In Con Edison’s case, they use a load flow program known as Poly Voltage Load-Flow (PVL) as their prime distribution system model to obtain the calculated reactance of each feeder on their distribution system. Once these values are known they are stored in a database to be compared against measured values during fault conditions. The database is continually updated as the distribution system configuration changes. Using data from the power quality monitors on their system, the reactance to the fault (from the substation to the fault) is calculated during a fault condition. This calculated value is compared to the simulated value, which provides a very accurate starting point for locating the fault on the system.

The database contains reactance values for each feeder as measured from the substation to the each man-hole. It should be noted that more than one location could be identified as the suspect location as most feeders on the

---

Figure 1: Progress Energy’s Fault Mapping System. (Source: Lampley, G. C., "Feeder Monitoring System Overview," internal Progress Energy Carolina presentation, 2006.)

The results of their program have been very good:

- **Accuracy**—Lampley [2] reported that their locations were accurate to within 0.5 miles 75% of the time; and in most of the remaining cases, the fault was usually no more than one to two miles from the estimate.
- **Restoration improvement**—Progress Carolina as reduced their CAIDI (average restoration time) from about 80 minutes to 60 minutes since 1998 when they started using their system for fault location.

**IMPEDANCE-BASED FAULT LOCATION**

The distance from the monitoring location and the faulted section of circuit can be estimated by using the voltages and currents during a fault. The equation is very simple, just Ohms Law:

\[
d = \frac{V}{I \cdot Z_l}
\]

where,

- \(V\) = voltage during the fault, V
- \(I\) = current during the fault, A
- \(Z_l\) = line impedance, ohms per length unit
- \(d\) = distance to the fault, length unit such as miles

With complex values entered for the voltages, impedances, and currents, the distance estimate should come out as a complex number. A simplification of this approach is to use the reactance(\(X\)) to the fault as:

\[
d = \frac{\text{Im}\left(\frac{V}{I}\right)}{\text{Im}(Z_l)}
\]

Using the reactance has the advantage of avoiding the arc impedance which is mainly resistive.
system contain branches and taps. Several of these branches and taps could have the same reactance value from the substation to their respective locations.

Using Con Edison’s GIS system, this location information is presented graphically as illustrated in Figure 2. The graphical representation shows the line crew the expected location of the fault.

Stergio [6] reported that in an examination of 27 events at one location, the accuracy of the events was as follows:

- 10 (37%) were within 0 or 1 manholes (direct hits)
- 9 (33%) were within 1 – 3 manholes
- 4 (15%) were within 3 – 5 manholes
- 3 (11%) were within 5 – 10 manholes
- 1 (4%) was more than 10 manholes

70% were within three manholes.

San Diego Gas & Electric’s Fault Location Experience
San Diego Gas & Electric’s (SDG&E) distribution system is comprised of more than 100 substations utilizing distribution voltage levels of 12 kV and 4 kV, with about 60% of those underground.

SDG&E has also implemented the automatic fault location function as part of their substation monitoring system. The reactance-to-fault information calculated from the monitoring data is correlated with information from the distribution system electrical models to identify possible fault locations.

SDG&E has many of their substations monitored by power quality monitors. The power quality monitors are installed on secondary side of transformer at their area substations. Most of the power quality monitors record three-phase bus voltage, three-phase transformer current, and neutral current using existing voltage and current transducers. The monitoring data is downloaded from substation power quality monitor periodically.

The performance of the system has been tested with historical data from their power quality monitoring system and has shown to give quite accurate results.

The operator interface is the focal point of the system. The interface displays recent fault events. As much as possible, the selection of fault events and location of faults is automatic. The web-based prototype shown in Figure 3 shows a listing of events by substation. This view can be sorted. The operator would need to use this view in conjunction with SCADA or the outage management system to indicate the circuit or circuit section that is locked out. The two systems need to have common naming schemes for substations and feeder identification.

From this view, the user can plot a map of the faulted circuit or see a view of the recorded waveforms.

For a given fault location, the prototype interface can display the fault and circuit graphically as shown in Figure 4. The user can zoom in on the view, and pole numbers (or other location identifier) can be displayed.

The default mapping software is not expected to ever be very sophisticated. Utilities will likely want to interface their normal mapping software to the PQView database and query it for fault-location results. This could be the mapping capability in GIS or in the outage management system. Most database software should be able to query the PQView database on the fly to read map locations of fault location estimates.
Hydro Quebec’s Fault Location with Distributed Monitors

Hydro Quebec implemented a fault location system based on a technique known as Voltage Drop-based Fault Location or VDFL [7]. The VDFL fault location technique is based on the voltage sag waveforms recorded by remote sensors on the distribution system. This technique is similar to fault location techniques described in IEEE guide [8], which is based on the line’s apparent impedance but it introduces significant innovations.

Key points of the Hydro Quebec system are:
- Most feeders require about four measurement sites (normally three phase). The number of monitors depends on the amount of branching on the circuit.
- Meters are on the low-voltage side as only voltage is used.
- GPS time synchronization is not required.
- Waveshape synchronization is done through software.
- Calibration is not needed. Relative values of voltage sags are used. The VDFL technique automatically compensates for lack of monitoring accuracy.

Normally, one meter is placed just outside the substation and one at the end of the three-phase section farthest from the substation. Another meter is placed somewhere in the middle, and they may add a fourth if they need more meters. After synchronizing, they see if they have a measurement on each side of the fault. They cannot process events if all three are on one side of the fault (all upline or all downline).

DISCUSSION

This paper provided an update on the work performed to date with various utilities and the fault location systems. Several different systems were evaluated. The Hydro Quebec system results indicate that the voltage-only fault location is also possible. To develop better conclusions about preferred monitoring options, EPRI has been working for a comparative technical evaluation of the fault location approaches: substation based monitoring vs. distributed monitoring, fault location using both voltage and current vs. voltage-only approach, et al.

REFERENCES