FAULT LOCATION ON DISTRIBUTION SYSTEMS: AN UPDATE ON EPRI AND DOE RESEARCH

Tom Short, tshort@epri.com
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Introduction

EPRI is currently performing a study to evaluate fault location approaches and systems as part of project P128.003, Distribution Fault Location. 2006 was the first year of a three-year project designed to develop practical system(s) for locating distribution faults. The initial approach is based on impedance-based methods for locating faults using data from digital relays and other monitoring sources. Figure 1 shows an example of what we are trying to do based on measurements at the substation.

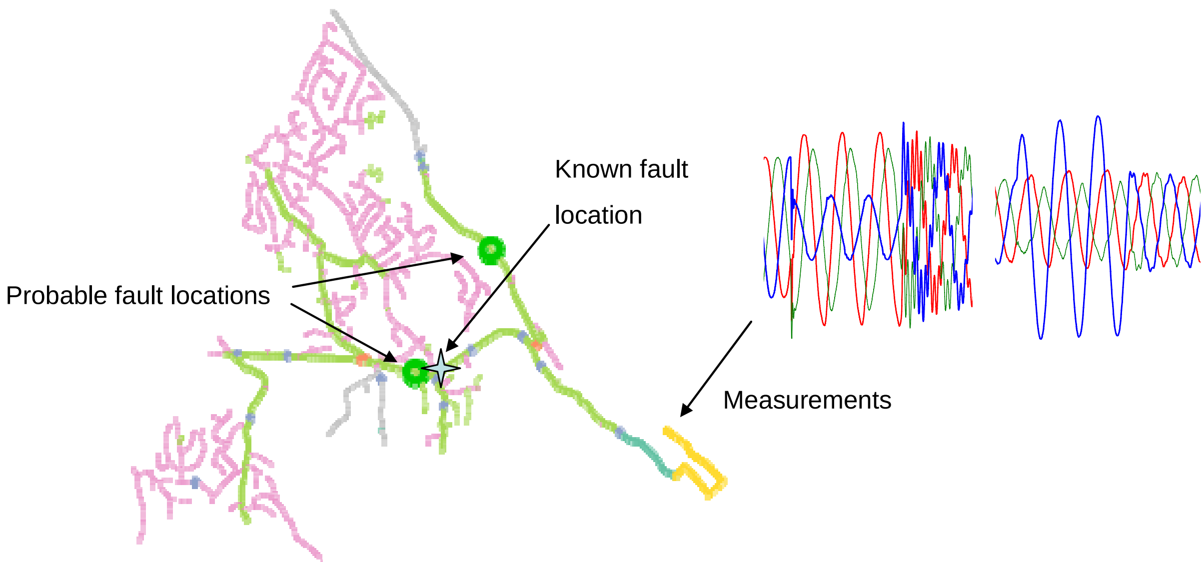


Figure 1. Fault location example.

Two utilities already have large-scale systems in place that can do this:

- *Progress Carolina* – Measure at the feeder level. They use the current to locate faults. They have half-mile accuracy 75% of the time; most of the rest are usually within one to two miles [Lampley, 2002]. They have reduced CAIDI from 80 minutes to 60 minutes.
- *Con Edison* – Faults are located based on voltage and current at the substation bus measured with power quality recorders. They use the reactance portion of the impedance to the fault (thus limiting arc resistance effects). For single line-to-ground faults, they

have found 37% within 1 manhole, 52% within 5 manholes, and 62% within 10 manholes [Stergiou, 2005].

The EPRI project is taking the lessons learned from Progress Carolina and Con Edison to further advance fault location approaches. To do this, fault data was collected from many sources, and various fault-location approaches were evaluated.

Ohms-Law Algorithms

If we know the voltages and currents during a fault, we can use these to estimate the distance to the fault. The equation is simple, just Ohms Law (see Figure 2):

$$d = \frac{V}{I \cdot Z_l}$$

where,

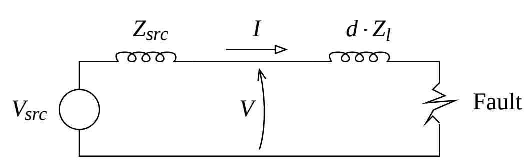
V = voltage during the fault, V

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 and impedances and currents, the distance estimate should come out as a complex number. The real component should be a realistic estimate of the distance to the fault; the imaginary component should be close to zero. If not, then something is wrong.



$$d = \frac{V}{I \cdot Z_l}$$

Figure 2. Fault location calculations.

While the idea is simple, a useful implementation is more difficult. Different fault types are possible (phase-to-phase, phase-to-ground, etc.), and each type of fault sees a different impedance. Fault currents may have offsets. The fault may add impedance. There are uncertainties in the impedances, especially the ground return path. Conductor size changes also make location more difficult.

Many relays or power quality recorders or other instruments record fault waveforms. Some relays have fault-locating algorithms built in.

The Ohms Law equation is actually overdetermined—we have more information than we really need. The distance is a real quantity, but the voltages, currents, and impedances are complex, so the real part of the result is the distance, and the reactive part is zero. Most fault-locating algorithms use this extra information and allow the fault resistance to vary and find the distance that provides the optimal fit [Girgis et al., 1993; Santoso et al., 2000]. The problem with that approach is that the fault resistance soaks up the error in other parts of the data—it does not necessarily mean a better distance estimation. Most fault arcs have a resistance that is very close to zero. In most cases, we're better off assuming zero fault resistance.

The most critical input to a fault impedance algorithm is the impedance data. Be sure to use the impedances and voltages and currents appropriate for the type of fault. For line-to-ground faults, use line-to-ground quantities; and for others, use phase-to-phase quantities:

Line-to-ground fault

$$V=V_a,\ I=I_a,\ Z=Z_S=(2Z_1+Z_0)/3$$

Line-to-line, line-to-line-to-ground, or three-phase faults

$$V=V_{ab},\ I=I_a-I_b,\ Z=Z_1$$

Remember that these are all complex quantities. It helps to have software that automatically calculates vector quantities from a waveform. Several methods are available to calculate the rms values from a waveform; a Fourier transform is most common. Some currents have significant offset that can add error to the result. Try to find the magnitudes and angles after the offset has decayed (this is not possible on some faults cleared quickly by fuses).

Although the voltages and currents are complex, we can also estimate the distance just using the absolute values. Although we lose some information on how accurate our solution is because we lose the phase angle information, in many cases, it is as good as using the complex quantities. So, the simple fault location solution with absolute values is:

$$d=\frac{V}{I\cdot Z_l}$$

where,

V = absolute value of the rms voltage during the fault, V

I = absolute value of the rms current during the fault, A

Z_l = absolute value of the line impedance, ohms per length unit

d = distance to the fault, length unit such as miles

With this simple equation, we can estimate answers with voltage and current magnitudes. For a ground fault, $Z_l = Z_S$ is about one ohm per mile. If the line-to-ground voltage, V=5000 V, and the fault current, I=1500 A, the fault is at about 3.3 miles (5000/1500). Remember to use the phase-to-phase voltage and $|I_a - I_b|$ (and not $|I_a| - |I_b|$) for faults involving more than one phase.

We can calculate the distance to the fault using only the magnitude of the current and the line and source impedances involved. In this case, we're doing the same thing as taking a fault current profile and interpolating the distance. In fact, it is often much easier to use a fault current profile developed from a computer output rather than this messy set of equations. If the prefault voltage is missing, assume that it is equal to the nominal voltage. If we have the prefault voltage, divide the current by the per-unit prefault voltage before interpolating on the fault current profile. Using a fault current profile also allows changes in line impedances along the length of the line. Carolina Power & Light used this approach, and Lampley [2002] 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.

Fault locations of line-to-line and three-phase faults are most accurate because the ground path is not included. The ground return path has the most uncertainties. The ground return path depends on the number of ground rods, the earth resistivity, and the presence of other objects in the return path (cable TV, buried water pipes, etc.). The ground return path is also nonuniform with length.

This type of fault location is useful for approximate locations. For permanent faults, a location estimate helps shorten the lengths of circuit patrolled. Distance estimates can also help find those irksome recurring temporary faults that cause repeated momentary interruptions. Fault locations are most accurate when the fault is within five miles of the measurement; beyond that, the voltage profile and fault current profiles flatten out considerably, which increases error. Fault location is difficult if a circuit has many branches. If a fault is two miles from the source on phase B, but there are twelve separate circuits that meet that criteria, the location information is not as useful. Fault location is also difficult on circuits with many wire-size changes; it works best on circuits with uniform mainline impedances with relatively short taps. Impedance-based location methods produce close but not pinpoint results.

Fault Location System

Fault-location algorithms are only one component of an integrated system to locate faults. In fact, the algorithms may be the easiest part. A fault location system must be integrated with the monitoring event database and the system circuit information (see Figure 3). This must be brought together and presented to the operator. The event data must be made available within minutes to be most useful to dispatchers.

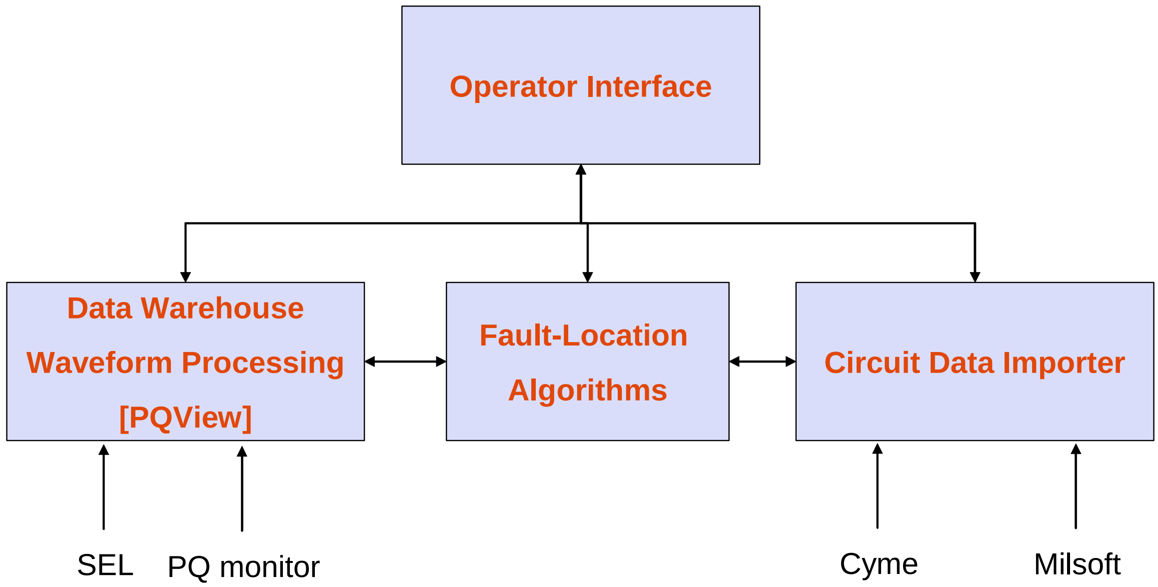


Figure 3. Integrated fault location system.

Arc Voltage Estimation

One of the important results of the EPRI research is that with monitoring data, we've found that it is possible to estimate the voltage in an arc. This has a number of ramifications:

- *Fault location* – The arc in a fault can impact fault location as it adds resistance to the short-circuit impedance. If we directly account for this, location accuracy will improve.
- *Estimating arc power and energy* – If we know the arc voltage, we can estimate the arc power and energy. We can use this for equipment failure forensics, investigation of manhole explosions, and arc flash estimation.
- *Fault type estimation* – Preliminary results suggest that it is possible to develop probabilities to differentiate between splice failures and cable failures on underground systems (splice failures have more arc voltage). Taking it farther, it might be possible to differentiate between tree faults and lightning for example.

Figure 4 shows various arcs recorded during the EPRI Distribution Power Quality (DPQ) study. Arcs are generally resistive (the short-circuit current is in phase with the arc voltage), but it is a nonlinear resistance. Arcs tend to be a square wave because the voltage tends to be constant regardless of current.

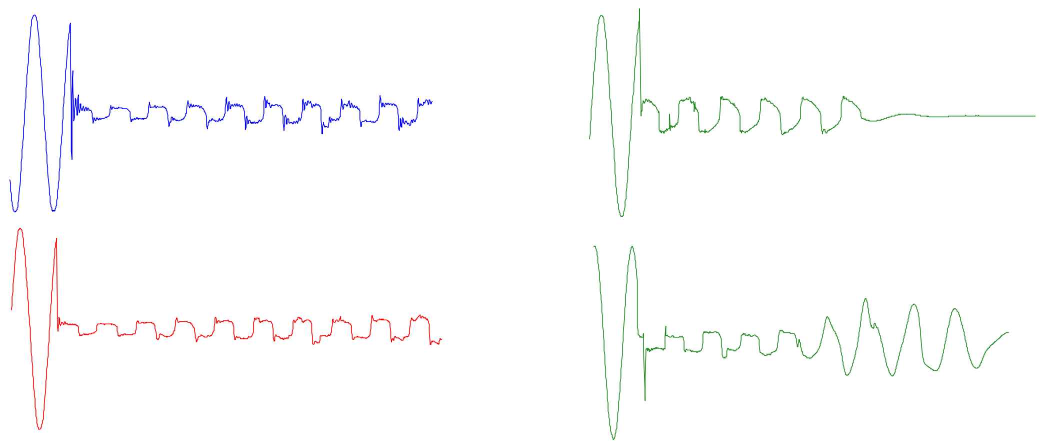


Figure 4. Various arc voltages measured by feeder monitors in the EPRI DPQ study.

It is generally more convenient to talk about arc voltage rather than arc resistance. In air, arcs have about 400 V per foot of arc length.

Estimating arc voltage relies on the fact that the arc voltage is nearly a square wave. Once the square-wave assumption is made, we can estimate arc voltage as follows:

$$V = R * I + L * dI/dt + V_{arc} * \text{sign}(I)$$

This is an overdetermined system. If we use 128 points over one cycle, that gives us 128 equations and three unknowns (R, L, and V_{arc}). It assumes that the arc voltage is a square wave in phase with the line current. This approach follows that developed by Radojevic et al. [2000, 2004, 2005]. They developed their methodology for transmission lines, but it applies well to distribution circuits.

Two enhancements were needed to make this work more consistently with monitoring data:

1. The derivative of current (dI/dt) was estimated with smoothing splines. Just using trapezoidal approximation $(i_{k+1} - i_{k-1})/2\Delta t$ resulted in far too much noise that dominated the result.

2. A constrained minimization approach was used to solve the overdetermined system. The error squared was minimized as suggested by Radojevic et al., but the solution parameters (R, L, and V_{arc}) were constrained to be positive using a quadratic programming solution.

The EPRI DPQ study monitored many distribution feeders with three monitors on each circuit. We verified the arc voltage estimation by estimating the arc voltage at the substation monitor with that of a downstream monitor that more directly estimated the voltage across the arc. The following graphs compare the estimated arc voltage to the measured arc voltage.

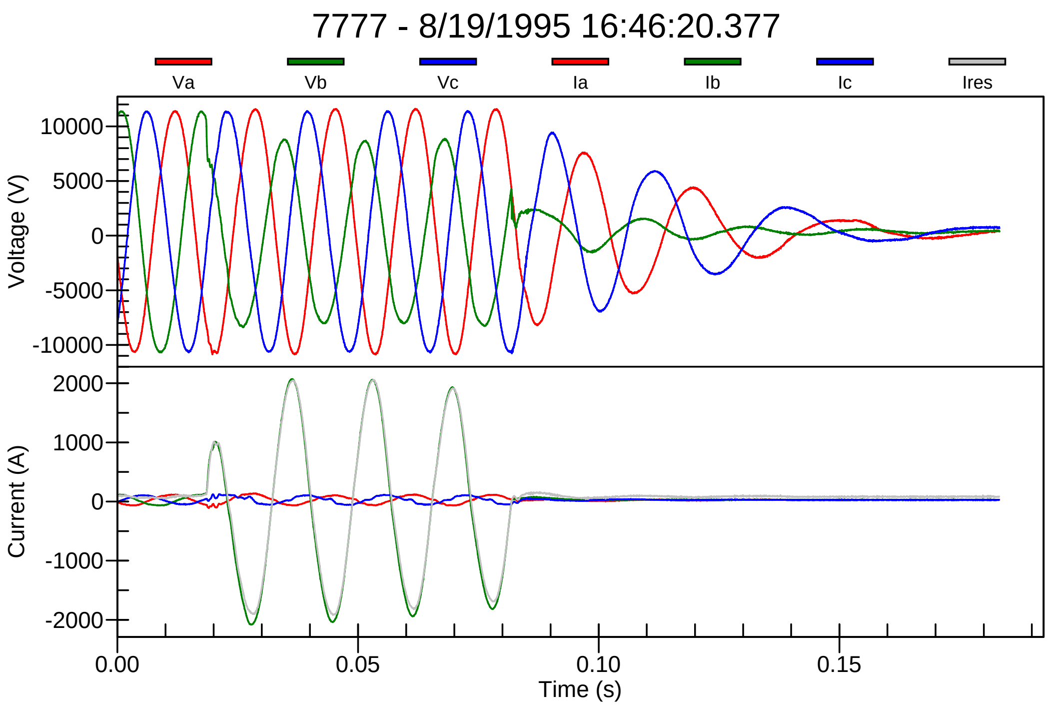


Figure 5. Substation monitoring of an event from the EPRI DPQ database.

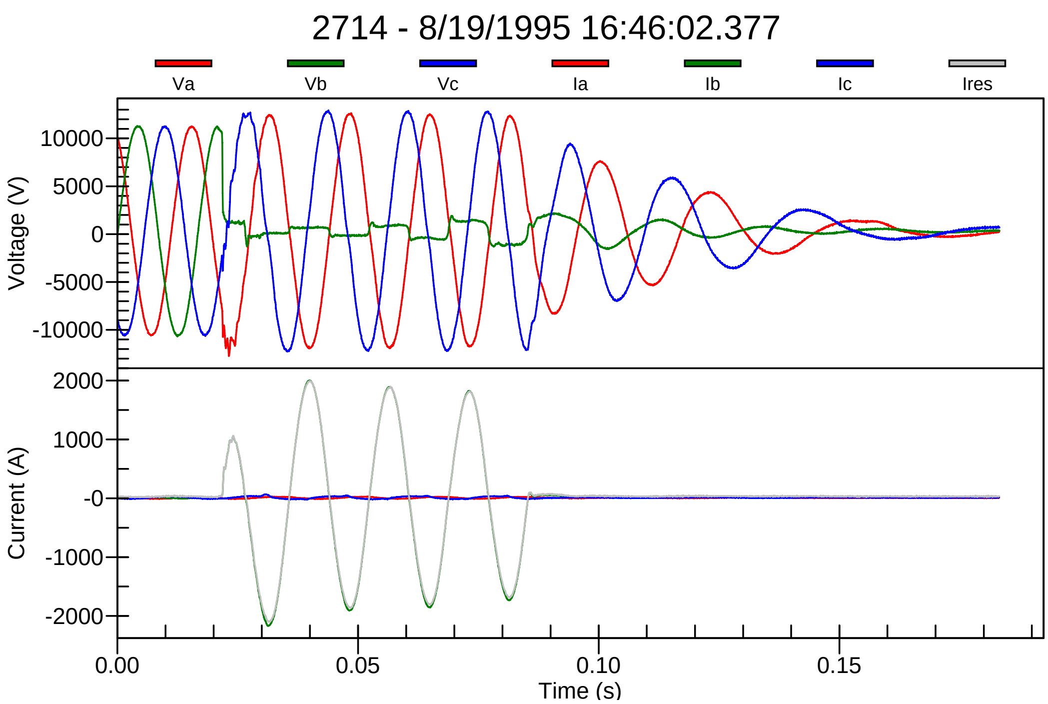


Figure 6. Downstream feeder monitor results for the same event.

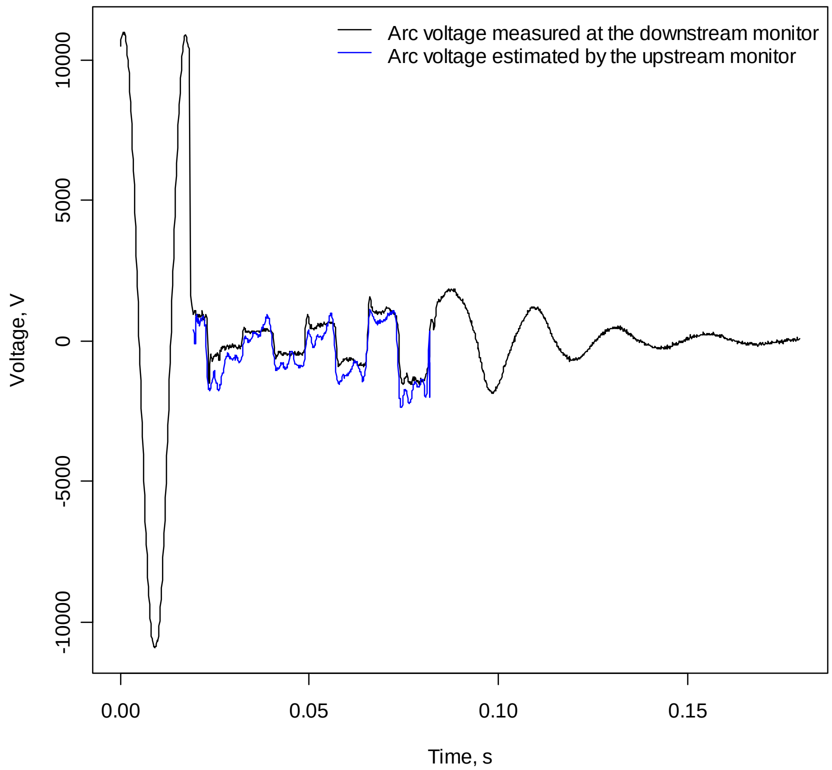


Figure 7. Comparing the arc voltage estimate from the substation data with the measured arc voltage.

Figure 8 shows a typical line-to-ground fault with high arc voltage that was recorded at the substation. The indicators of high arc voltage are that the voltage bulges to the left, and the current looks tipped to the right.

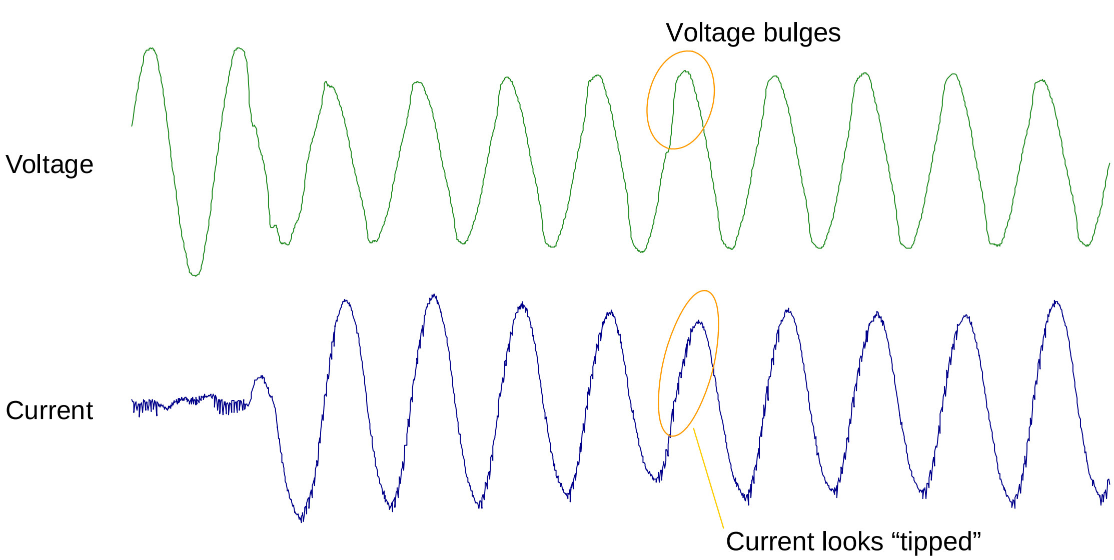


Figure 8. Typical event with high arc voltage.

DOE Event Disturbance Library

The US Department of Energy is currently sponsoring a project to develop a disturbance library that will be a repository for waveforms and other monitoring data along with event-specific information that is needed for analysis. The library will be a resource for the entire industry that will facilitate development and testing of advanced algorithms and approaches to identify, characterize, and locate faults and incipient faults. The most significant need of researchers in this area is data that can be used to train expert systems and test new algorithms. See http://www.expertmonitoring.com/doe_ams/ for more information.

There are numerous utilities across the country that can contribute to the proposed disturbance library but there is a need to design the system for integration of data from a wide variety of monitoring systems that are in use around the country. In addition, the library will support information describing the systems involved and also the specific events. Without this additional information, the waveforms themselves have limited value because they are not correlated with specific conditions or systems. As illustrated in the figure below, the disturbance library must be able to integrate data from a wide variety of monitoring platforms and provide additional information related to the system and the events that can be used for analysis.

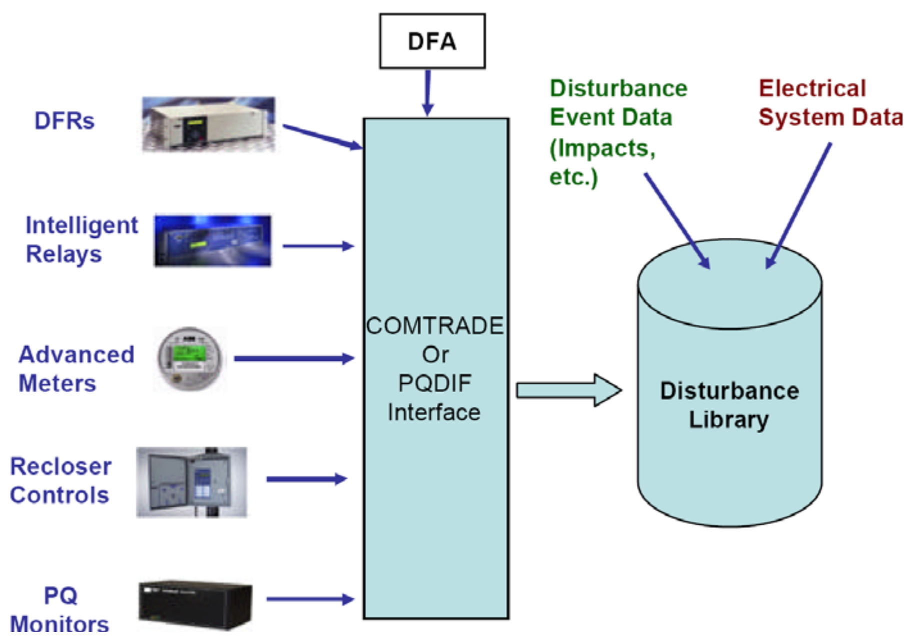


Figure 9. Disturbance library overview.

The following is a summary of the types of monitoring data to be included in the database:

1) Monitoring data (from relays, PQ monitors, and other recording devices)
   a) Waveform disturbances
   b) RMS disturbances
   c) Trends of steady state data (harmonics, unbalance, reactive power, flicker, other)

2) Electrical system characteristics
   a) Important feeder characteristics
   b) Source characteristics
   c) Protection system characteristics
3) Event documentation
   a) Fault data – type, location, cause, etc.
   b) Protection device operation
   c) Equipment impacts (failures, customer impacts, etc.)

The library is not meant to be a one-time development limited to this project. The documentation and users guide will provide guidelines for continuing submission of disturbance data for the library, allowing it to continue to grow and be a more valuable resource for intelligent system development. Web-based methods for submitting information and verifying the information will be implemented and EPRI will continue to manage the library for open access after the completion of the project.

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