Fault Location Analysis using PQ and DFR Data with GIS Integration

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***Abstract*— This paper describes an open-source software suite implementing a set of fault location algorithms using data from power quality (PQ) meters and disturbance fault recorders (DFRs). The algorithms also include the use of data from the GIS system to increase accuracy and display additional information.**

The paper also describes the automation techniques used to distribute the results in a timely manner and display any relevant information from the GIS system and the data analysis.

Keywords—Data Integration, PQ Data, Disturbance Analysis, automation, Fault Distance Estimation

I. Introduction

With improvements in substation intelligent electronic devices (IEDs) such as power quality monitors (PQMs) and digital fault recorders (DFRs) and with the increased deployment of these devices, many utilities now have a large number of devices providing power quality (PQ) data and DFR data. As the number of these devices grows, utilities have started using this data for various business and operational applications, including Fault Location Analysis.

With the increase in use cases information integration has enabled processes to be established to automate data integration opportunities to include static and dynamic data from various operational and enterprise systems, such as the Geographic Information System (GIS).

This paper focuses on the fault location analysis use case and its integration with GIS systems. Section II describes an open-source software suite designed to automatically collect data from IEDs; run automated fault detection, fault classification, probable fault cause analysis, and fault location analysis; and provide display and reporting tools to allow utilities to better understand events and their causes.

Section III describes the fault location algorithms used in greater detail and discusses some of the advantages gained from including sectionalized lines in the algorithms.

Section IV describes some of the visualization and notification tools developed to display fault location results as well as associated GIS information to various users and discusses the implementation of this system at the Tennessee Valley Authority (TVA). Finally, Section V summarizes and concludes this paper.

II. Overview of the Automated Data Flow

The functional components of the software suite that automatically process PQ and disturbance data are typically divided into four major groups:

1. Acquire
2. Analyze & Notify
3. Archive
4. Display

Fig.1 shows the data flows among these four functional components which are explained in the sections below. For this paper, a fifth functional component "integration", has been added. Fig.1 highlights some of the major systems among which disturbance analytics can be integrated. The information integration points are introduced in this section. The remainder of the paper focuses on fault location analysis in the Analyze & Notify part of the software suite.

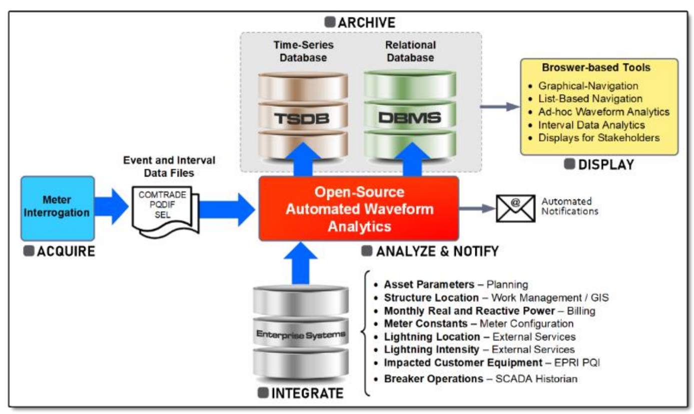

Fig. 1. General Architecture.

A. Acquire

The "acquire" architectural element is responsible for obtaining disturbance event record data from the various IEDs so that a file can be produced in a format that can be easily parsed, such as the IEEE standard formats PQDIF [1] and COMTRADE [2].

The open-source software suite mentioned in this paper contains a generalized IED interrogation component that provides scalable (load-balanced) capability to quickly poll and download data from the very largest utility IED fleets through multiple protocols, such as FTP, DNP3 and Modbus.

In addition to downloading raw event data some IEDs, such as relays, may also provide out of the box fault location estimates. These estimates can also be acquired as part of the data acquisition process and can be compared to the fault location results provided by the algorithms presented in Section III.

B. Analyze and Notify

The core of the architecture shown in Fig.1 is to analyze and then notify responsible engineers, field technicians, transmission operators, line and electrician crews, account managers and management about the nature of a disturbance.

The analytics can include general algorithms such as event detection, fault classification, asset health indices, as well as multiple specialized algorithms. Section III describes the fault location algorithms implemented as part of this open-source software suit in more detail.

Automated notifications are the sharp point of business value for a disturbance data system. While the software suite mentioned support a wide variety of notifications, and associated visualizations this paper will focus on fault location notifications and visualizations only. Section IV describes some of the visualizations and notifications developed specifically for fault location analysis results.

C. Archive

To achieve full value from a disturbance data system an open data layer, or archive, is critical. Without it, innovation and process improvement are fully controlled by the vendor that provides the closed system. A relational data base is used for configuration information, event waveforms and for results of analytics on these waveforms.

Fig 1 also shows a time-series data base used for saving interval data, which is outside the scope of this paper.

D. Display

Multiple open-source tools are available as part of the software suite to facilitate engineering analysis and investigations as well as business reporting. In these tools, there are summary visualizations that allow the user to quickly identify geographic and temporal patterns in the disturbances. In addition, detailed visualizations are available to view the waveforms as well as to conduct ad-hoc calculations such as Fast Fourier Transforms (FFT) based on the displayed event waveform.

Those tools and displays including fault location results are discussed in Section IV. [3] contains additional information about some of the other displays and tools available as part of this software suite.

III. Fault Location Analysis

The open-source software suite described in this paper implements a variety of different fault location analysis, including double-ended and single-ended algorithms. For simplicity this paper focuses on single-ended algorithms only, but most of the conclusions can be generalized to apply to doubled-ended algorithms as well.

The sections below describe the integration of segmentation information from GIS systems, as well as the effect this information has on 2 of the 5 algorithms implemented:

(1) Simple Impedance based:

(2) Reactance based:

In addition the software suite implements:

(3) Takagi

(4) Modified Takagi

(5) Novosel

However, all of these algorithms are modified versions of (2) so the details of these are omitted.

A. Segmentation of Lines

Traditionally impedance based fault location algorithms use a line model based on uniform impedance. This means the line parameters are specified as

$$Z(l) = (R_U + jX_U) * l$$

Where $Z(l)$ is the impedance at distance l from the substation and R_U and Z_U are the uniform Line resistance and reactance given in per unit per mile.

However, real transmission lines are not always uniform. Impedance of the line at any point depends on changing factors, including transposition of the phases, type and size of conductor, age of conductor and other factors [4]. Some of this information can be supplied by a GIS system by sectionalizing the line into several uniform sections. These sections may have different characteristics, resulting in a piecewise uniform impedance.

In a sectionalized line the impedance of the Line is given by

$$Z(l) = \begin{cases} (R_1 + jX_1) * l, \ l < L_1 \\ (R_2 + jX_2) * (l - L_1) + Z_1 \ l < L_2 \\ (R_3 + jX_3) * (l - L_2) + Z_1 + Z_2, \ l < L_3 \\ ... \ l > L_3 \end{cases}$$

Where each R_i, X_i are the uniform resistance and reactance of the ith segment and L_i is the length of that segment.

Fig 2. shows the resistance and reactance of a transmission line when using the uniform model and the segmented model based on the information obtained from the GIS system. The line displayed in Fig 2 is representative of a line modeled at TVA. The reactance of the segmented model closely follows the uniform model, while there is a more significant difference in the resistance of the two models.

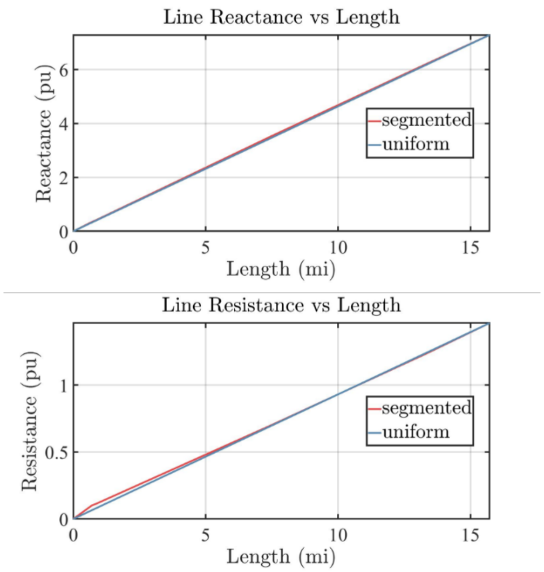

Fig. 2. line resistance and line reactance for a uniform and segmented model.

B. Simple Impedance Algorithms

For the simple impedance based algorithm the current and voltage during the fault are used to compute the fault impedance as

$$Z_f = \frac{V_f}{I_f}$$

The estimated fault distance is then found by rotating the fault impedance onto the impedance of the segmented line. This is given by

$$argmin(\,|Z_F| - |Z(l)|)$$

Fig 3 shows an example of the line impedance, the fault impedance as well as the individual segment impedances. The blue circle indicates the point at which $|Z_F| = |Z(l)|$. The difference in angle between the fault impedance and the line impedance is larger than the difference between the segmented and uniform line model. Based on this, it was concluded that for the simple impedance algorithm is not significantly aided by the use of segmented line information.

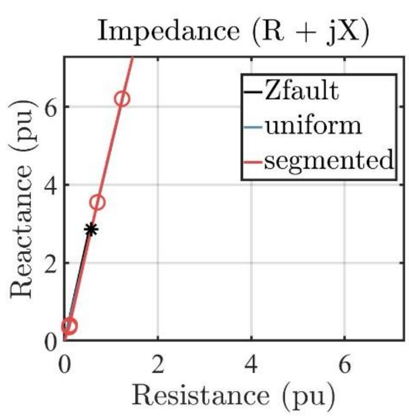

Fig. 3. Line impedance and fault impedance for impedance based estimation.

C. Reactance Based Algorithms

For the Reactance based algorithm the same fault impedance is computed. However, the estimated fault distance is then computed by comparing reactance only

$$argmin\big(X_F - X(l)\big)$$

Fig 4. Shows an example of the line impedance, as well as the fault impedance and the result obtained using the reactance based method.

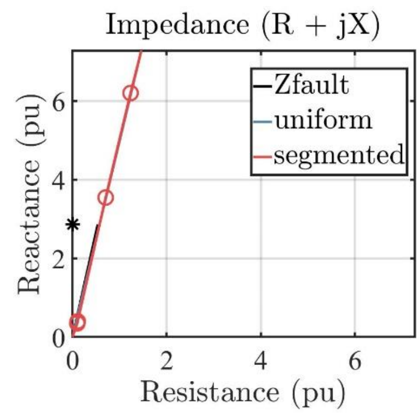

Fig. 4. Line impedance and fault impedance for impedance based estimation.

Because line resistance is ignored in this method the results are only affected by a variation in reactance in each section. Fig 2. shows that the reactance does not vary significantly across the line so the difference in estimated fault location is not significant

Fig 5. shows the line reactance for the same line as Fig 2, with the true fault location and the two estimated fault locations indicated by the vertical lines. In this specific case the impedance based method was slightly closer to the true fault locations indicated by the linemen, however both are within 0.1 miles or $< 1\%$ of total line length.

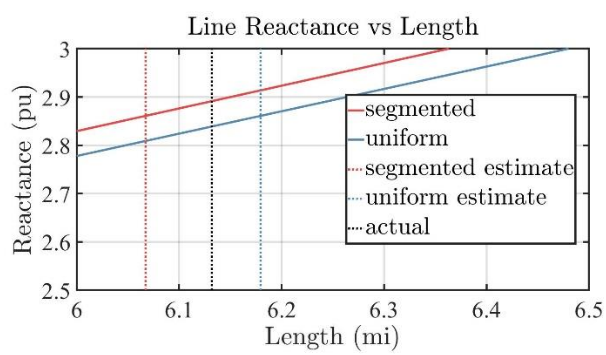

Fig. 5. Line Reactance vs length around the fault

D. Double-ended Fault Location

In cases where a line is monitored by IEDs at two separate locations, the data from each device can be joined in order to perform double-ended fault location to produce fault location results that are theoretically more accurate than the traditional single-ended impedance-based algorithms. For this approach, the automation asset model must provide information about which IEDs are monitoring the line and the locations at which they are monitoring. The data from each of these IEDs can then be time-correlated and brought together for the double-ended fault location algorithm. However this algorithm is highly sensitive to timing errors of the IEDs which are usually not synchronized with sufficient accuracy, so it is excluded from this analysis.

IV. Visualization and Notification at TVA

This system was implemented at TVA and automatically analyzes IED records as described in Section II. Once a record is analyzed the results are combined with additional information from GIS system including, but not limited to:

(1) The closest transmission structure to the fault

(2) Any lightning strikes close to the estimated fault location

(3) The exact location of the fault and terrain surrounding this location

Fig 5 shows an example email that is sent out to relevant personnel. This email includes the fault location estimated by various algorithms, as well as a best estimate based on a consensus algorithm. The email also includes additional information on the line such as length and line parameters.

In addition the closest structure is named in the email and a link is included to indicate the structure on a satellite image. The same information including additional map and information layers provided by the GIS system is also available in the visualization tools provided by the open-source software suite used to implement these algorithms.

Fault 1 - 1999-01-02 11:11:11.1234567

Station:	Gotham City (S12345)
DFR:	Gotham City DFR 1
File:	File_1234.RCD
Breaker:	B98/99
Fault Type:	CN
Inception Time:	11:11:11.2345678
Fault Duration:	84.375 msec (5.06 cycles)
Fault Current:	7560.5 Amps (RMS)
Distance Method:	Takagi
Single-ended Distance:	Structure # 12 (6.132 miles from Gotham City SS)
Click for fault report:	9825311

	Probability of Fault Cause
DFR:	Gotham City DFR 1
Tree:	Low (Rf = 0.19)
Lightning:	No lightning found
Insulation Flashover:	Medium (18.93° from peak)
Arrester Failure:	Low (0.01)
Conductor Slap / Debris Midspan:	No (applies only to multi-phase faults)
Broken Conductor:	Low (0.96)

Line Parameters:	Value:	Per Mile:
Length (Mi)	15.72	1.0
Loop Imp ZS (Ohm) (LG)	7.4236∠78.6341° 1.4360+j7.2780	0.4722∠78.6341° 0.0931+j0.4630

To manage your automated fault notification subscription, or to unsubscribe, click on this link.

Fig 6. Email notification including fault location estimation

V. Summary of Automation and Integration Benefits

Integrating GIS information into fault location analysis can result in significant time savings for crews and engineers in gathering all available information and identifying any challenges early in the restoration process. However, in most standard transmission lines, including the information in the fault location estimation algorithm does not lead to any significant improvements over using simplified network models. While this conclusion holds for a majority of transmission lines, ongoing work has shown that there are a number of scenarios, such as tapped lines or multi-circuit lines, where significant improvements can be achieved by using segmented models.

References

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