Overview of an Automatic Subtransmission Fault Location System at DTE Energy

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***Abstract*—In 2009, DTE Energy - Detroit Edison began a pilot project to use power quality monitors to locate faults on numerous trunk lines and tie lines of its 24-kV and 41.57-kV systems. Fault measurements captured by the meters are downloaded automatically, integrated into a relational database, and processed for reactance calculations. The reactance calculations are combined with detailed subtransmission circuit models and geographic information system data to build estimated fault location tables and web-based map displays. The systems are integrated on the company intranet and used in real-time by numerous groups within Detroit Edison including system supervisors, field operations, and system planning. The algorithm used for waveform processing can distinguish between single-phase faults, multi-phase faults, subcycle faults, and feeder energizing magnetizing inrush. The system integrates the measurements from the power quality monitors with circuit breaker operations stored in the SCADA historian. This paper will present an overview of some of the parameters and practices for finding faults in place every day at Detroit Edison.**

***Index Terms*—fault location, power quality, power system restoration, power system transients, relational databases, geographic information system.**

I. Introduction

THE automatic fault location system (AFLS) on the subtransmission system of DTE Energy – Detroit Edison (DECo) was first put into use during 2009. It incorporates power quality monitors, database applications, up-to-date circuit models, and geographic information system (GIS) databases in order to provide automatic fault identification and fault location estimation. The AFLS is becoming a valuable tool for quickly and accurately identifying the location of faults on the DECo subtransmission (24-kV and 41.57-kV) system.

The AFLS uses measurements recorded at stations. These measurements are downloaded automatically and incorporated into a relational database. Calculations on these measurements estimate the reactance from the station to the fault. The calculations are based on phasor measurements derived from the voltage and current samples and calibration constants based on previous fault data and known locations. The result of these calculations is an estimated "reactance to fault," or XTF. The XTF values are compared with line models that estimate the positive-sequence impedance between station and line structures. The estimated locations can be viewed in tabular format on the corporate intranet and can be displayed graphically using maps derived from a GIS database. The calculated fault locations are typically available on the DECo intranet within ten minutes after a line fault.

II. Power Quality Monitoring at Detroit Edison

Installation of monitors for recording power quality measurements at DECo began in 1995 in order to administrate a ten-year Special Manufacturing Contract (SMC) between DECo and Chrysler Corporation, General Motors Corporation, and Ford Motor Company. The SMC covered voltage interruptions and voltage sags. DECo became liable for interruptions that exceeded performance targets effective January 1995. The voltage sag amendment to the SMC, effective January 1998, made DECo liable to the customers if voltage sag measures exceeded performance targets. DECo installed power quality monitoring at 56 locations of the three customers throughout the southeastern Michigan service area. The power quality monitors on the customers' 4.8-kV and 13.2-kV services allowed DECo to determine the frequency and severity of voltage sags that occur at the customer locations.

Numerous reports were developed to administrate the SMC service agreements. Figure 1 illustrates an example of a report that shows the location and voltage sag time stamp along with the minimum voltage on each phase, duration, cause category, and the faulted system element. The report also shows a voltage sag score, which is the average voltage lost across the three phases. Reference [5] describes the five rules of the SMC service agreements that pertain to voltage sags and provides more information about the sag score concept.

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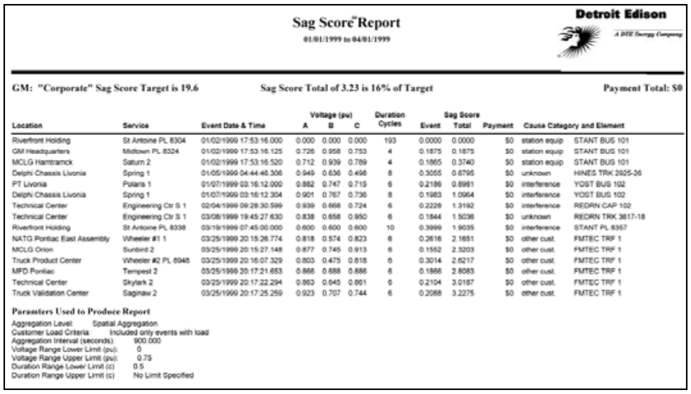


Sag Score™ Report

01/01/1999 to 04/01/1999

Detroit Edison
A DTE Energy Company

GM: "Corporate" Sag Score Target is 19.6 — Sag Score Total of 3.23 is 16% of Target — Payment Total: $0

Location	Service	Event Date & Time	Voltage (pu) A	Voltage (pu) B	Voltage (pu) C	Duration Cycles	Sag Score Event	Sag Score Total	Payment	Cause Category and Element	
Riverfront Holding	St Antoine PL 8304	01/02/1999 17:53:16.000	0.000	0.000	0.000	193	0.0000	0.0000	$0	station equip	STANT BUS 101
GM Headquarters	Midtown PL 8324	01/02/1999 17:53:16.125	0.726	0.958	0.753	4	0.1875	0.1875	$0	station equip	STANT BUS 101
MCLG Hamtramck	Saturn 2	01/02/1999 17:53:16.520	0.712	0.939	0.789	4	0.1865	0.3740	$0	station equip	STANT BUS 101
Delphi Chassis Livonia	Spring 1	01/05/1999 04:44:46.306	0.949	0.636	0.498	8	0.3055	0.6795	$0	unknown	HINES TRK 2925-26
PT Livonia	Polaris 1	01/07/1999 03:16:12.000	0.882	0.747	0.715	6	0.2186	0.8981	$0	interference	YOST BUS 102
Delphi Chassis Livonia	Spring 1	01/07/1999 03:16:12.304	0.901	0.767	0.736	8	0.1983	1.0964	$0	interference	YOST BUS 102
Technical Center	Engineering Ctr S 1	02/04/1999 09:28:30.599	0.939	0.668	0.724	6	0.2228	1.3192	$0	interference	REDRN CAP 102
Technical Center	Engineering Ctr S 1	03/08/1999 19:45:27.630	0.838	0.658	0.950	6	0.1844	1.5036	$0	unknown	REDRN TRK 3617-18
Riverfront Holding	St Antoine PL 8338	03/19/1999 07:45:00.000	0.600	0.600	0.600	10	0.3999	1.9035	$0	interference	STANT PL 8357
NATG Pontiac East Assembly	Wheeler #1 1	03/25/1999 20:15:26.774	0.818	0.574	0.823	6	0.2616	2.1651	$0	other cust.	FMTEC TRF 1
MCLG Orion	Sunbird 2	03/25/1999 20:15:27.148	0.877	0.745	0.913	6	0.1552	2.3203	$0	other cust.	FMTEC TRF 1
Truck Product Center	Wheeler #2 PL 8948	03/25/1999 20:16:07.329	0.803	0.475	0.818	6	0.3014	2.6217	$0	other cust.	FMTEC TRF 1
MFD Pontiac	Tempest 2	03/25/1999 20:17:21.653	0.866	0.688	0.886	6	0.1866	2.8083	$0	other cust.	FMTEC TRF 1
Technical Center	Skylark 2	03/25/1999 20:17:22.294	0.863	0.645	0.861	6	0.2104	3.0187	$0	other cust.	FMTEC TRF 1
Truck Validation Center	Saginaw 2	03/25/1999 20:17:25.259	0.923	0.707	0.744	6	0.2088	3.2275	$0	other cust.	FMTEC TRF 1

Parameters Used to Produce Report

Aggregation Level: Spatial Aggregation
Customer Load Criteria: Included only events with load
Aggregation Interval (seconds): 900.000
Voltage Range Lower Limit (pu): 0
Voltage Range Upper Limit (pu): 0.75
Duration Range Lower Limit (c) 0.5
Duration Range Upper Limit (c) No Limit Specified

Figure 1: Example Sag Score Report for a DECo SMC Customer

The SMC expired year-end 2005, but the voltage sag monitoring and analysis processes developed during the SMC period continues to the present time. The power quality monitoring system was expanded over time to include distribution substations, industrial substations and subtransmission buses. The subtransmission monitors were installed for trending area SARFI, voltage fluctuations, harmonics, and as a means to identify the location of permanent faults to achieve faster restoration, thereby reducing SAIDI. The goal of the AFLS is also to identify and locate nonpermanent faults before they become permanent, thereby reducing SAIFI [2].

III. Fault Identification and Location Process

A. Fault Measurements

Measurements are recorded on the subtransmission buses using power quality monitors installed on the secondary of 120-24 kV and 120-41.57 kV transformers. Each bus group is typically supplied by two to four parallel transformers. These locations serve from five to 28 lines. Most lines are single-ended (trunk line) whereas some are connected to other buses (tie line). The DECo system consists of 478 trunk lines and 95 tie lines. The AFLS is being applied predominately for the trunk lines. Some tie lines are included since one end is at monitored location.

At present, the lines are monitored by a single power quality monitor. A monitor records voltage and current at the output of a single transformer, which means that each monitor measures a fraction of the total current supplied to a trunk or tie line fault. DECo uses a short-circuit program to determine the portion of fault current supplied by the monitored transformer. For example, the phase currents from the power quality monitor on the secondary of the transformer shown in Figure 2 are multiplied by 2.91 to represent the total fault for reactance-to-fault calculations on the seven lines.

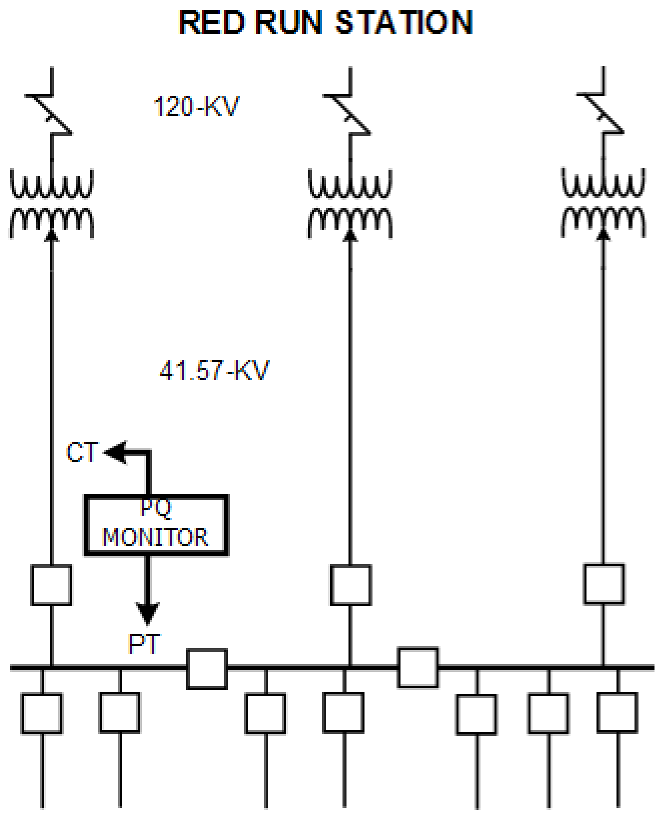


Figure 2: Each power quality monitor records voltage and current at the secondary of a transformer in parallel with other transformers that serve the load on several lines

Figure 3 represents a single-line-to-ground (SLG) fault measured on a DECo trunk line. The fault was recorded up-line from the fault.

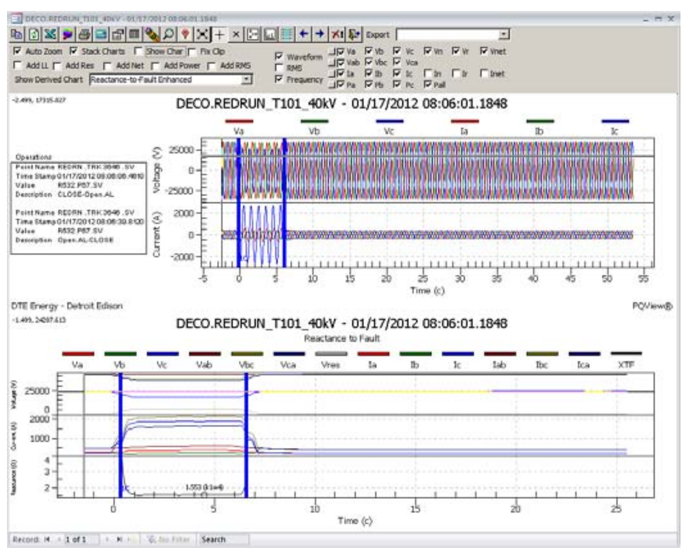


Figure 3: Example of a SLG fault on a DECo trunk line estimated to be j1.553 ohms downline from the monitored buses

Figure 4 presents an example of a three-phase fault measured by an upline power quality monitor.

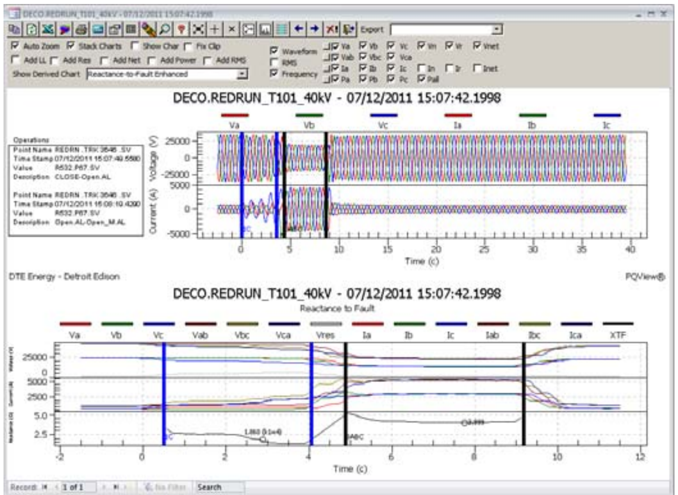


Figure 4: Example three-phase fault on a DECo trunk line estimate of j3.999 ohms from the monitored buses.

Measurements by the power quality monitors are triggered using high and low rms voltage thresholds. When a voltage sag or voltage swell is detected, it will trigger voltage and current waveform samples and rms samples to be recorded. RMS voltage and current values and estimated reactance values to the fault are computed from the waveforms. The DECo power quality monitors are configured to record voltage and current waveform samples at a rate of 64 points per 60 Hz cycle with three cycles of pre-trigger and at least 25 cycles of post-trigger data.

The power quality monitors communicate with a server via a broadband Ethernet connection provided by a mobile telephone provider or a DECo field-communications-network. This allows the fault measurements to be downloaded from the monitors to the corporate network typically within one minute.

B. Circuit Models

The quality of the geospatial data for the lines associated with the conductor type that is stored in the DECo GIS system is not sufficient at this time. Thus for this project, a new approach was taken. Each line's geospatial coordinates are defined using Google Earth. Typically, each pole can be seen using Google Earth's aerial imagery whereas underground structure locating often requires use of additional references. All structures are included in the geospatial model. The line data is exported from Google Earth as KML.

A custom database application was developed for importing the XML coordinates of the polylines for the model (See Figure 5). The conductor type is specified for each conductor section defined in Google Earth. Care is taken when building the model to establish each unique conductor type as a single polyline. Each record in the line models database represents the line sections in a sequential order, their conductor types, and structure coordinates.

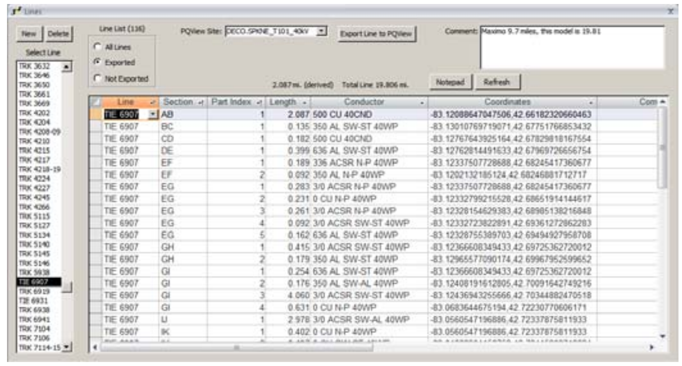


Figure 5: Custom Line Modeling Database Application used at DECo in the AFLS

The polyline coordinates are matched with positive-sequence and zero-sequence impedance for the conductor type used with each line section. If the line section being modeled is a single circuit, then the impedance for the line section is distributed evenly between the points that comprise that line section. However, if the line section being modeled is in actuality two parallel underground or overhead conductors, then the total impedance for the line section is distributed using an inverse relationship based on the distance of a given structure back to the start of the parallel conductor section. Estimates for faults within line sections consisting of three parallel conductors are complicated in that the impedance is at a maximum at about 75% of the total length of the line section rather than at the end of the line section as with a single conductor or two parallel conductors. See Figure 6.

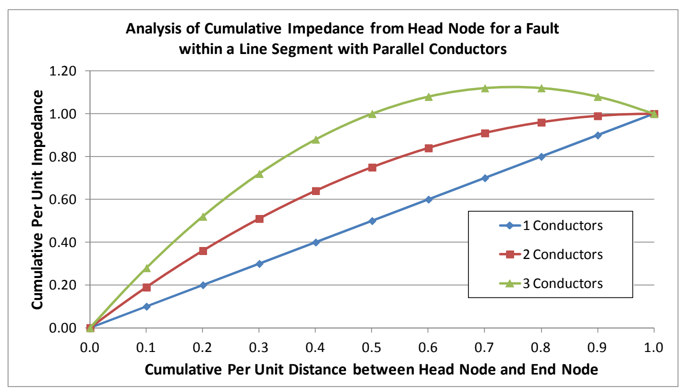


Figure 6: Analysis of Cumulative Impedance from Head Node for a Fault within a Line Segment with Parallel Conductors

The cumulative impedance to each underground and overhead structure is stored in a relational database. At present, 108 line models (19% of the total trunks and ties) are written to the database. The typical time to build each line is a few hours.

C. Data Integration

Once downloaded from the substation, data from the power quality monitors is integrated automatically into a relational database [3]. The waveforms from the power quality monitors are stored in a proprietary database format provided by the monitor vendor.

The fault measurements are incorporated into an ODBC compliant relational database usually within a few minutes of a fault occurrence. Once in the relational database, the measurements can be queried and analyzed directly using workstation computer applications or indirectly via intranet web applications.

The measurement captured from the power quality monitor is correlated with circuit breaker open and/or close operations recorded simultaneously in the commercial SCADA historian system. The timestamp and line associated with the SCADA operation is stored in the ODBC compliant relational database along with the waveforms to make it easier to determine on which line a fault occurred. This is important because each power quality monitor is measuring the current to more than one line simultaneously.

D. Fault Identification

Each measurement downloaded by the remote power quality monitors is analyzed by a power quality database management and analysis software system for voltage characteristics and zero-sequence current characteristics that indicate a SLG fault has occurred. Other line-line voltage characteristics are examined that indicate that a two-phase or three-phase fault has occurred.

The harmonic content of each measurement is used to estimate if the measurement is not a fault measurement but rather a magnetizing inrush current measurement. When an inrush is measured without a subsequent fault, an e-mail alert is sent in order to help operations differentiate a repaired line that has opened automatically due to a new fault, from a repaired line that has tripped because of a large magnetizing inrush current transient.

A single measurement may be classified as more than one type of fault. This means that the AFLS is able to identify single-phase faults that evolve into multi-phase faults. As another example, the system is able to identify the start and end of each stage of a fault that begins as transformer energizing transient but degrades into a fault condition.

The AFLS computes two durations. One duration is related to the start time and end time of the fault itself. Another duration is related to the rms voltage sag related to the fault or to system recovery. When the duration of the voltage sag exceeds a set number of cycles, then another type of e-mail message alert is sent.

E. Reactance Estimation

For SLG faults, the XTF is estimated using (1), where V_f is the magnitude of the voltage measured on the phase showing a voltage sag, N_T is the number of transformers in service during the fault, I_0 is the magnitude of the zero-sequence current, and θ is the phase angle between V_f and I_0.

$$XTF = \frac{V_f}{N_T k_1 I_0} \sin\theta \quad (1)$$

The constant k_1 is a calibration factor that is determined using previous faults recorded at the bus in the recent past. The historical faults must have occurred when the network was in the same configuration for the fault that occurs in the present. Practical use of the fault location at DECo indicates that the actual distance in reactive ohms for historical faults can be used to determine a value of k_1 that will estimate the reactance to fault for future events. The k_1 constant can be computed at the bus level for all lines supplied by a station, or can be computed for each line. The line-level k_1 constants typically are more accurate than the bus-level constants.

For multi-phase faults, a more traditional method is used for fault location. The approach described in IEEE C37.114 for single-ended impedance-based measurements has been applied successfully to the DECo subtransmission faults [1]. This method requires computation of line-line voltage and current phasors before the fault and during the fault.

F. Fault Location Visualization

There are multiple applications available for displaying estimates of fault location. Figure 6 presents an example one-line diagram showing the estimated fault locations as circles and the actual fault location with a callout annotation line. Multiple estimated locations are possible whenever a line has laterals. This one-line is visible via desktop computer programs or within a web page display. Figure 7 presents the same one-line diagram, but overlaid on an aerial map available from Google Earth.

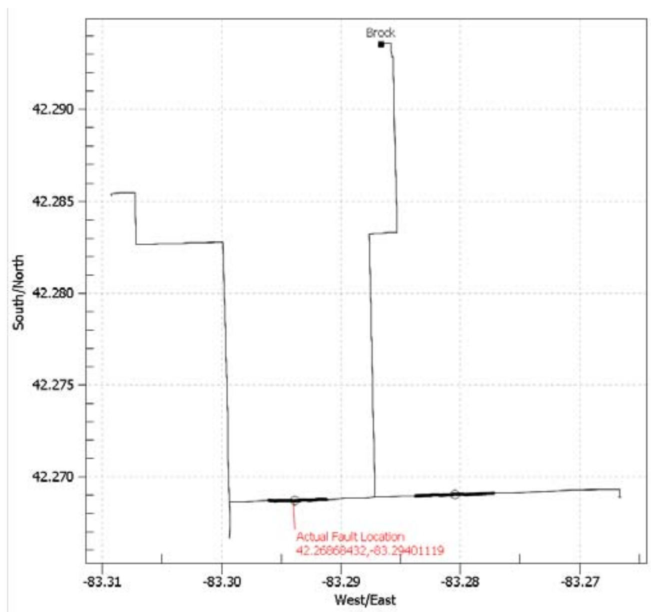


Figure 7: Example One-Line Diagram Showing Estimated Fault Locations and Actual Location with Coordinates

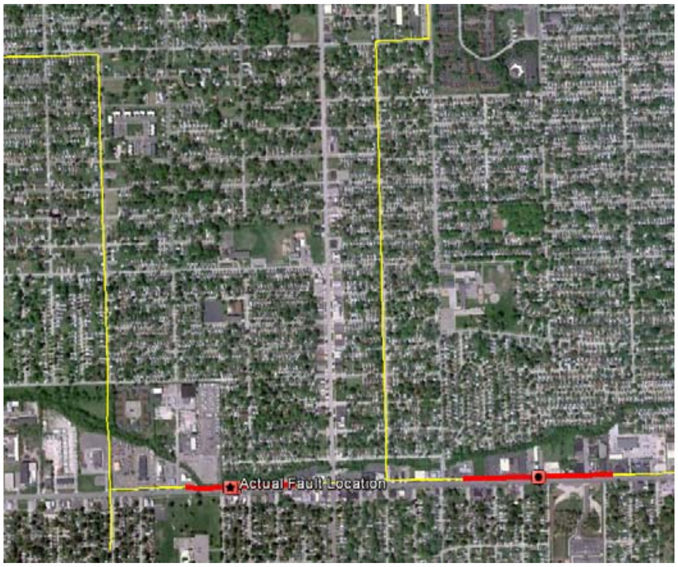
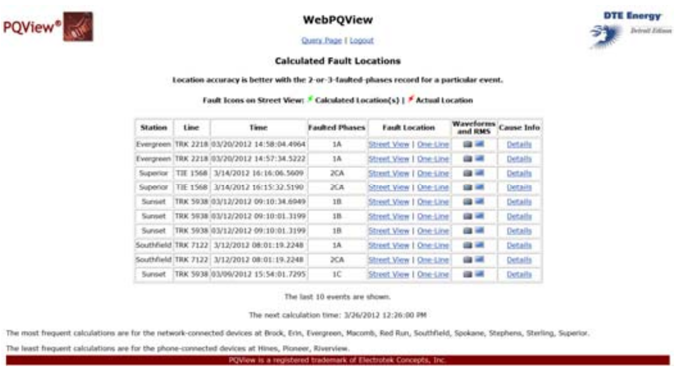


Figure 8: Example One-Line Diagram Showing Estimated Fault Locations and Actual Location Displayed with Aerial Map Data Provided by Google Earth

On the DECo intranet, several applications provide system operations and engineering with estimated fault locations. A web page picture listing estimated fault locations is presented in Figure 8. The system supervisors that respond to subtransmission events are reminded with the message "Calculated Fault Locations Available" on their SCADA displays so that this information is promptly used.


PQView®

WebPQView

Query Page | Logout

DTE Energy

Calculated Fault Locations

Location accuracy is better with the 2-or-3-faulted-phases record for a particular event.

Fault Icons on Street View: Calculated Location(s) | Actual Location

Station	Line	Time	Faulted Phases	Fault Location	Waveforms and RMS	Cause Info
Evergreen	TRK 2218	03/20/2012 14:58:04.4964	1A	Street View | One-Line		Details
Evergreen	TRK 2218	03/20/2012 14:57:34.5222	1A	Street View | One-Line		Details
Superior	TIE 1568	3/14/2012 16:16:06.5609	2CA	Street View | One-Line		Details
Superior	TIE 1568	3/14/2012 16:15:32.5190	2CA	Street View | One-Line		Details
Sunset	TRK 5938	03/12/2012 09:10:34.6949	1B	Street View | One-Line		Details
Sunset	TRK 5938	03/12/2012 09:10:01.3199	1B	Street View | One-Line		Details
Sunset	TRK 5938	03/12/2012 09:10:01.3199	1B	Street View | One-Line		Details
Southfield	TRK 7122	3/12/2012 08:01:19.2248	1A	Street View | One-Line		Details
Southfield	TRK 7122	3/12/2012 08:01:19.2248	2CA	Street View | One-Line		Details
Sunset	TRK 5938	03/09/2012 15:54:01.7295	1C	Street View | One-Line		Details

The last 10 events are shown.

The next calculation time: 3/26/2012 12:26:00 PM

The most frequent calculations are for the network-connected devices at Brock, Erin, Evergreen, Macomb, Red Run, Southfield, Spokane, Stephens, Sterling, Superior.

The least frequent calculations are for the phone-connected devices at Hines, Pioneer, Riverview.

PQView is a registered trademark of Electrotek Concepts, Inc.

Figure 9: Web Table Display of Estimated Fault Locations

In Figure 9, an example of a one-line diagram from another intranet web application is shown for the feeder with an estimated fault location. This map display was drawn using data from a commercial GIS database system. The lightning bolt icons represent the estimated (green) and actual (red) location of the fault. This application can also display the locations on satellite imagery.

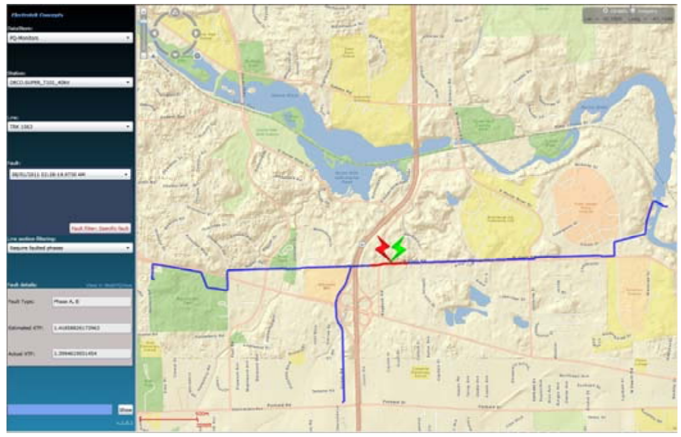
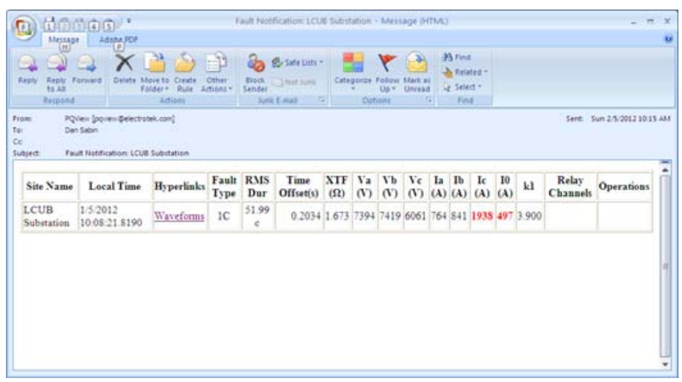


Figure 10: Example Street View Map of Estimated and Actual Fault Location

IV. AUTOMATIC NOTIFICATION REPORTING

For each fault measurement identified by the AFLS, an e-mail message is sent. The e-mail message includes the following values for each fault (See Figure 10):

- Database Event Number
- Substation Name
- Local Time
- Hyperlinks to web-based waveform samples and derived rms samples of the fault
- Fault Type
- Duration of the rms voltage sag associated with the fault
- Estimated Reactance to Fault
- Magnitude and Phase Angle of All Voltage and Current Phasors during the Fault
- SLG Calibration Constant (k_1)
- Digital relay channels that change value during fault (not used at present at DECo)
- Correlated circuit breaker operations from SCADA historian



Site Name	Local Time	Hyperlinks	Fault Type	RMS Dur	Time Offset(s)	XTF (Ω)	Va (V)	Vb (V)	Vc (V)	Ia (A)	Ib (A)	Ic (A)	I0 (A)	k1	Relay Channels	Operations
LCUB Substation	1/5/2012 10:08:21.8190	Waveforms	1C	51.99 c	0.2034	1.673	7394	7419	6061	764	841	1938	497	3.900		

Figure 10: Example of an Automatic E-mail Notification after Fault Processing

An alternative e-mail notification of some event characteristics and the line operations that displays well on cell phones is shown in Figure 11.

```
Site: DECO.SUPER_T101_40kV
Time: 08/01/2011 02:28:19.9730
Fault Type: 2AB
RMS Dur (c): 6
Offset: 0.07503 seconds
XTF: 6.516 ohms
Va: 18812 V
Vb: 17749 V
Vc: 24141 V
Ia: 2369 A
Ib: 1883 A
Ic: 636 A
I0: 13 A
k1: 1
Operations: 2011-08-01 02:28:24
SUPER .TRK 1563 .SV
R611.P33.SV
CLOSE-Open.AL

2011-08-01 02:28:52
SUPER .TRK 1563 .SV
R611.P33.SV
Open.AL-CLOSE
```

Figure 11: Example of an Automatic E-mail Notification Sent to Mobile Telephones after Fault Processing

V. Results

The process and information described in this paper is gradually replacing the slow methods of fault locating. These slow methods include manually using various sets of data collected during the fault and a short circuit program to simulate faults and derive a location which can take hours to complete if an engineer and information are available [4]. Then, patrols are requested, often from the beginning of the line to its end(s). The time-of-day, line length, line location and weather impact the duration and safety of this activity. As a last resort, lines have been progressively sectionalized with the intent of isolating a hard to find fault on a lateral and allow partial line restoration.

In contrast, fault location estimates have been provided for about 50 faults since January 2011 using the AFLS. Since July 2011, the estimates have been available to the system supervisors within 10 minutes of a fault in either the street view, one-line or satellite image fashion. The street view is preferred since an intersection of the location estimate is readily available for issuing instructions and logging.

The typical distance between the estimated and actual locations for multi-phase faults has been 180 meters or less. SLG fault comparisons have been initially more distant but become closer with the ability to tune the calculations with k_I. The accuracy of the estimates has earned a higher priority for a patrol due to temporary faults since only a small fraction of the line must be inspected.

Abnormal system configurations have caused a few invalid estimates. Some of these have been corrected by changing the transformer factor N_T in (1) and in the IEEE C37.114 approach.

VI. Conclusion

The AFLS at DECo was developed from 2009 to 2011. Regular usage by the system supervisors and others started in July 2011. The AFLS has proven very dependable and has become a favorite application. Its users are anxious for the inclusion of many more lines. Orders to install more monitors and creation of line models are ongoing. Four sets of power quality monitors and cellular modems have been mounted in portable boxes for short term use to take advantage of the AFLS prior to permanent equipment installation.

Planned enhancements to the AFLS include calculations to support fault location within line sections that consist of three parallel conductors; the use of line-level k_I constants to improve the accuracy of SLG fault location estimates; the ability to quickly or automatically compensate for some types of abnormal system conditions and web page improvements.

References

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[2] *IEEE Guide for Electric Power Distribution Reliability Indices*, IEEE Std. 1366-2003.

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VII. Biographies

D. Daniel Sabin is a Monitoring System Application Architect with Electrotek Concepts, Inc. in Beverly, Massachusetts, USA. He is currently the chief application architect of PQView. This software database application is used by electric utilities worldwide for managing and analyzing the gigabytes of measurements recorded by power quality monitors, digital fault recorders, and electronic relays. He developed customized database software for the Detroit Edison that administers the voltage sag and service interruption contracts with Ford Motor Company, General Motors Corporation, and Chrysler Corporation. He has developed automatic fault location systems used by the Consolidated Edison Company of New York, the United Illuminating Company, and Detroit Edison.

He was a project manager with the Electric Power Research Institute, Inc. (EPRI) and its subsidiary EPRI Solutions, Inc. from 2005 to 2008. He managed and completed power quality monitoring and distribution fault location projects.

He has a Bachelor of Science degree in Electrical Engineering from Worcester Polytechnic Institute in Massachusetts and a Master of Engineering degree in Electric Power Engineering from Rensselaer Polytechnic Institute in New York. Dan is registered as a Professional Engineer in the State of Tennessee. He is the chair of the IEEE Power Quality Subcommittee, chair of the IEEE P1564 Voltage Sag Indices Task Force, and an editorial board member for *IEEE Transactions on Power Delivery.* Previously, he was the vice chair of the IEEE Distribution Subcommittee, chair of IEEE Standards Coordinating Committee 22 on Power Quality (SCC-22), and a chair of the IEEE P1049 Task Force on Distribution Custom Power.

Andrew R. Dettloff is a Principal Engineer with DTE Energy in Detroit, Michigan, USA. He has been with DTE Energy since 1981. He has a Bachelor of Science degree in Electrical Engineering from Wayne State University in Detroit. He has been an active member of the IEEE P1564 Voltage Sag Indices Task Force and the IEEE P1049 Task Force on Distribution Custom Power.

He is the lead engineer responsible for the planning, installation and power quality for large DECo customers who are served with dedicated services from the transmission and subtransmission systems. He created the voltage sag amendments for the Special Manufacturing Contracts with Ford Motor Company, General Motors Corporation, and Chrysler Corporation and specified the requirements for the database software customized by Electrotek Concepts, Inc. for use in administering the contract. He is responsible for the operation and development of the company’s power quality monitoring system.