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# Automated Fault Location Analysis – Analytics Update II

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## SUMMARY

FirstEnergy Service Company on behalf of its transmission owning affiliates determined there was a need to improve the accuracy and speed of its fault location process especially for the 138 and 69 kV system. This system is heavily tapped with industrial customers and substations. The main objective of this project was to see if the need to call out staff, usually overnight, to run the fault-location program could be eliminated for the majority of faults that occur in a pilot/test area.

The overall objective of this effort is to reduce the time to determine where a fault has occurred with sufficient certainty to route field crews to the location of the fault quickly and improve restoration times. At some locations, there may be the ability to sectionalize the 69 kV or 138 kV transmission network so that operations staff can begin restoring customers in areas not directly affected by the faulted line section.

This update paper will provide additional details regarding the implementation of the analytics methods and data handling and transformation required to fully automate the process. Furthermore, a recent enhancement in the automated determination of the appropriate fault current to use will be provided. This enhancement more appropriately removes the impact of the DC offset often present within the fault measurement made by the digital fault recorder.

## KEYWORDS

Fault Location, Fault Analysis, Digital Fault Record, DC Offset, Event Record
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## Problem Statement

FirstEnergy Service Company on behalf of its transmission owning affiliates determined there was a need to improve the speed of its fault location process especially for the 138 and 69 kV system. This system can be tapped with industrial customers and distribution substations. The main objective of this project was to see if the need to call out staff, usually overnight, to run the fault-location program could be eliminated for the majority of faults that occur in a pilot/test area.

The authors have previously written about the automation process including fault record data gathering and processing and the linking of data between applications. This effort required development of translation tables and automation of the actual fault location process. In this update we will discuss further enhancements to the translation process and the process to adjust the fault current for DC offset.

When a fault occurs on a major transmission line, it is important that a protection engineer rapidly assess the situation and accurately determine the location of the fault. This information may then be used to minimize the outage duration. This task involves several steps.

First, the source of the trip and the associated line must be identified by SCADA operations. Then the appropriate sensor/instrumentation data associated with the tripped line needs to be evaluated. This data can be in the form of microprocessor relay records and/or DFR – Digital Fault Recorder files, which can sometimes be in a proprietary format. In addition to the different recording formats, the DFR records may only implement a few of the current or voltage measurements of the faulted line. Once the protection engineer has gathered all the appropriate data they must analyze the waveforms to determine the nature of the fault (phase -> ground, phase -> phase), the correct branch in the short circuit model and the maximum fault current (usually in RMS). All of this is then manually entered into a fault analysis program software and a fault study is initiated to determine the approximate location of the fault. The goal of this project is to automate most of these steps to significantly reduce the amount of time required to determine the fault location and impact on the protection engineer.

## Objective

The overall objective of this effort is to reduce the time to determine where a fault has occurred with sufficient certainty to route field crews to the location of the fault quickly and improve restoration times. In addition, there may be the ability to sectionalize the transmission network so that operations staff can begin restoring customers in areas not directly affected by the faulted line section. The expectation is that by automating the analysis, the time previously spent in off-hour periods to contact a protection engineer, provide him or her with the needed information, and then perform the analysis would be greatly reduced. Streamlining this process should help improve restoration times and decrease the length of outages for customers.

## Approach

Using an interpreted, high-level, general-purpose programming language, two programs have been developed to help automate the manual process of calculating a fault location. The first of these programs, COG (COMTRADE Organizer) actively polls selected folders on a server for fault records and notifications that a line has tripped. When found, this program moves these recent files to a different folder and prepares them for the second program, CTA (COMTRADE Analyzer) which performs the analysis. COG will also move historical records out of the folders when they should no longer be used for analysis. Once a fault record is moved to the appropriate folder, CTA will parse the fault information, start the fault analysis program, call upon a fault location macro within the fault analysis program, parse the fault analysis program results and e-mail the results to a specified e-mail group. Finally, the application moves this studied fault record to a historical folder so that each fault record is only studied once [1] [5].

## Data Sources and Format

The two primary sources for fault information at FirstEnergy for the pilot area chosen are from microprocessor relay fault records and DFR records. The microprocessor relay files typically contain waveform data sampled at 16 samples/cycle for all the key electrical parameters (IA, IB, IC, IR, VA, VB, VC) as well as digital/trip states within the relay. The DFR format is a proprietary format of the vendor and requires special software to decode the output. Unlike the microprocessor relay fault files that are associated with a single relay/line, the DFRs can record waveform data for multiple lines (up to 32 possible analog channels per device). DFRs also record at a higher sampling rate of 96 samples per cycle. An additional challenge encountered was the limited number of analog channels monitored by the DFR at some older substations; as little as one phase current plus the residual current on a line. Also, since DFRs are necessarily not as common as microprocessor line protection relays, DFR records from a few buses away may need to be used for event analysis.

*Figure 1* is an example of the data found in a typical DFR record.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| channel | analogue | 1 | "kV" | 80.00 | 254.500 | 0 | 0.000 | AC |
| channel | analogue | 2 | "kV" | 80.00 | 254.500 | 0 | 0.000 | AC |
| channel | analogue | 3 | "kV" | 80.00 | 254.500 | 0 | 0.000 | AC |
| channel | analogue | 4 | | 80.00 | 15155.000 | 0 | 0.000 | AC |
| channel | analogue | 5 | "A" | 240.00 | 45418.000 | 0 | 0.000 | AC |
| channel | analogue | 6 | "A" | 800.00 | 30226.000 | 0 | 0.000 | AC |
| channel | analogue | 7 | "A" | 800.00 | 31593.000 | 0 | 0.000 | AC |
| channel | analogue | 8 | "A" | 240.00 | 45472.000 | 0 | 0.000 | AC |
| channel | analogue | 9 | "A" | 1200.00 | 47536.000 | 0 | 0.000 | AC |
| channel | analogue | 10 | "A" | 1200.00 | 45460.000 | 0 | 0.000 | AC |
| channel | analogue | 11 | "A" | 240.00 | 45533.000 | 0 | 0.000 | AC |
| channel | analogue | 12 | "A" | 1200.00 | 45411.000 | 0 | 0.000 | AC |
| channel | analogue | 13 | "A" | 1200.00 | 47311.000 | 0 | 0.000 | AC |
| channel | analogue | 14 | "A" | 160.00 | 30274.000 | 0 | 0.000 | AC |
| channel | analogue | 15 | "A" | 800.00 | 30266.000 | 0 | 0.000 | AC |
| channel | analogue | 16 | "A" | 800.00 | 31558.000 | 0 | 0.000 | AC |
| channel | analogue | 17 | "A" | 120.00 | 22724.000 | 0 | 0.000 | AC |
| channel | analogue | 18 | "A" | 120.00 | 22700.000 | 0 | 0.000 | AC |

*Figure 1*
*Typical DFR record*

To perform an automated fault location calculation, specific data will need to be parsed from both types of fault record. This information will in turn be used to prepare commands to be used to run a fault location macro within the fault analysis program.

## COMTRADE Standard

Since the DFRs are proprietary format, it was decided to use the industry standard COMTRADE (Common Format for the Transient Data Exchange for Power Systems) format to analyze the DFR fault records. One would think that once a single COMTRADE file had been decoded, that COMTRADE files from any DFR or relay would be able to be analyzed by the program. However, while developing the waveform analysis application it became apparent that the COMTRADE formats from different equipment are not the same. Due to these differences, a revised CTA program is needed to handle the different types of relay and DFR files. (At this time the program can only handle the COMTRADE exported from DFR records).

**EDOA**

EDOA (Energy Delivery Outage Analysis) is a program that FirstEnergy uses to track transmission operations. Transmission System Operators create event records in EDOA whenever a transmission trip occurs. An email is then sent from the EDOA system to a distribution list to inform personnel of the trip that occurred. As discussed below, it was decided to use these notifications as the trigger to begin the automated event analysis process.

**Data Cleansing**

For a variety of historical reasons, most naming conventions are not standardized between applications and devices. As a result, the name of the line in fault analysis program, the corresponding DFR COMTRADE file line/location names, and the EDOA names may be different. Differences may include names that are abbreviated differently, a dash that replaces a blank, or the suffix "LINE" may be appended to the name. Any automation program will need a cross-reference table, a form of "Rosetta Stone" to deal with the inconsistences between the various data sources. Figure 2 shows the process developed to automatically generating a master list of all EDOA line names and match them to the fault analysis program names using regular expression (REGEX) tools. The resulting table forms the basis for the EDOA cross-reference table data join that includes the EDOA line name, fault analysis program name and line length in meters. Once created, this table will need to be updated as system changes occur.

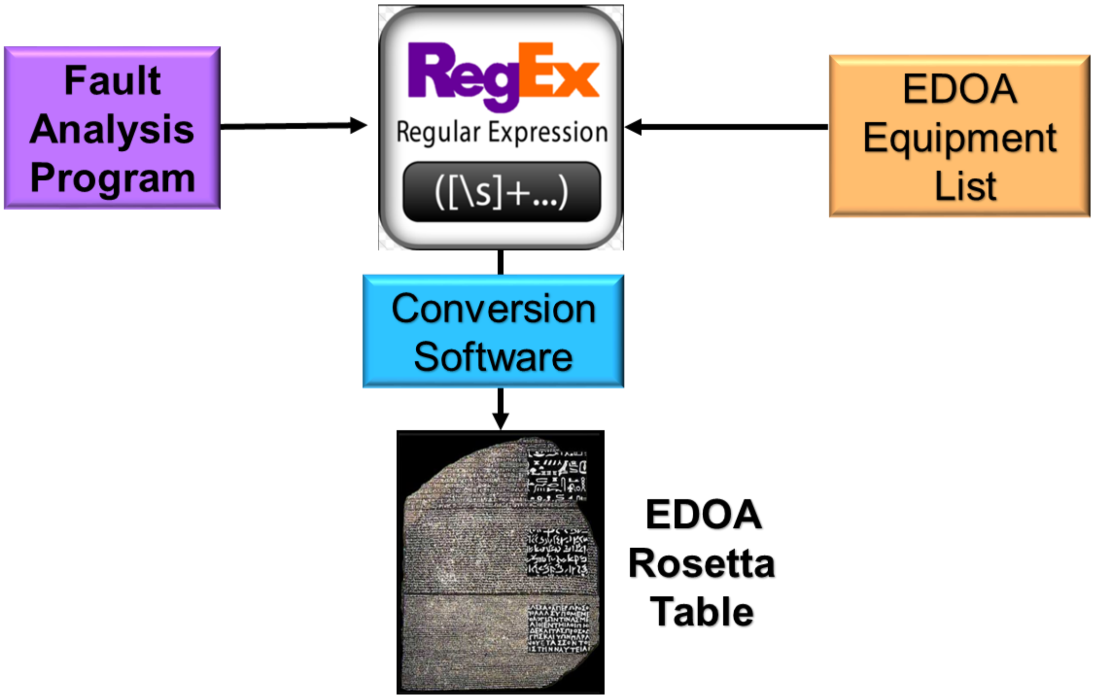


*Figure 2*
*Build EDOA Rosetta Database – "Fuzzy" (regex) search*

The DFR cross-reference table of records is the most challenging since a DFR installation at a single location (using multiple boxes) can monitor about 100 analog sensors. A special program using an array walking library was written to digest and walk all the configuration files and produce the DFR Cross-reference table. The columns include: Fault Analysis Program NAME, DFR Location, IA, IB, IC, IR, VA, VB, VC.

Also, experience has shown that DFRs can be triggered by events other than line faults (such as a capacitor bank tripping). To avoid the processing of spurious event records, it was decided to initiate the automation process from an event generated by FirstEnergy Transmission Operators in the EDOA system. [3]

**Fault Analysis Program database and automation**

FirstEnergy's primary fault analysis tool that was used is based on an extensive internal database of over 250 tables that describe in detail transmission lines and transformers, protective relays, breakers and their associated physical and electrical properties. It is constantly maintained and updated to accurately represent the current state of the electrical transmission grid.

The fault analysis program uses an open source database to hold all needed system information including line names, connectivity and electrical and physical (length) properties. Tables associated with the short circuit model were exported into a Microsoft Access database so specific tables and fields could be used in the automation process. Figure 3 is an example of using selected fault analysis program tables to build translation tables and provide electrical and physical data (line mileage) to CTA. [2]

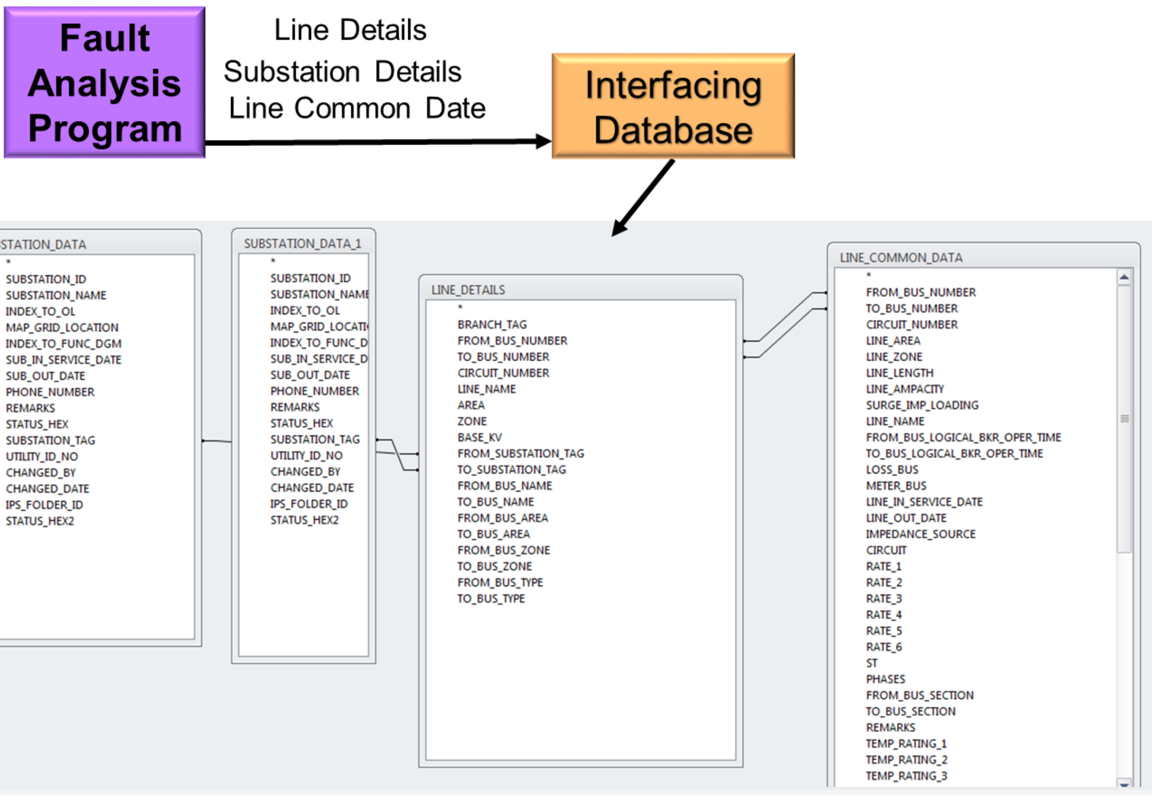


*Figure 3*
*Build EDOA Rosetta Database – Fault Analysis Program data "join"*

## Cross Reference Tables

Using the process noted above, two independent cross-reference tables were created to deal with the inconsistences between the various data sources. After investigating the different formats of transmission line models in the short circuit database, it was found that this cross reference initially created was not robust enough to handle the complexity of the database. A new cross reference was needed.

Figure 4 is a representation of the real and fictitious buses along a sample transmission line model. Buses 9050 (Substation A) and 9509 (Substation B) are real busses that have protection modeled on them in the fault analysis program database. Tapped transformers are connected at buses 10602 and 402600 through fictitious busses 10601 and 239617 respectively. Using the fact that the real bus terminals of the line at Substations A and B have protection modeled at them, an SQL query was created and applied to the short circuit model database to provide the baseline for the revised cross reference table. That is, the query provided the fault analysis program information shown below only where a bus had relay data modeled at it.


*Figure 4*
*Short Circuit model (displaying line length in miles)*

From this new query, a preferred cross reference table layout has been created.

- Station Location of IED (DFR or Relay)
- IED Name (For multiple recorders or PR vs BU relays)
- Line Exit (from the IED)
- IED (DFR or Relay) Channels
- Line Name
- External Branch ID (Reserved as future location where EDOA Line Name can be stored)
- Circuit Number
- Line kV
- Circuit Number Line Length
- From Bus Number
- From Bus Name
- To Bus Number
- To Bus Name
- From Sub Number
- From Sub
- To Sub Number
- To Sub
- LZOP ID
- LZOP Name
- LZOP Substation Tag/ID
- From Bus/To Bus Flip

To compute a calculated fault location, the required fault analysis program commands are based upon a fault analysis program ‘from bus – to bus pair’. Since DFR and microprocessor records are based upon the IED location and the channel (terminal) name, care must be taken to supply these in the correct order for the fault analysis program analysis.  The “From Bus / To Bus Flip” field is used to indicate where the fault analysis program from bus is not the same location as the DFR Station Location

| BRANCH_ | LINE_NAME | EXTERNAL | CIRCUIT_N | LINEBASE | LINE_LEN | FROM_BU | FROM_BU | FROM_BU | FROM_BU | TO_BUS_N | TO_BUS_N | TO_BUS_K | TO_BUS_T | LZOP_ID | LZOP_NAI | SUBSTATI | SUBSTATI | From Bus = 1; To Bus = 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11786 | SUBSTATION_A_SUBSTATON_B_138KV | | 1 | 138 | 1.93365 | SUBA138 | 9050 | 138 | B2 | TAPA | 10601 | 138 | LT | 11786 | SubA LZOI | 127 | SUB_A | 1 |
| 14610 | SUBSTATION_A_SUBSTATON_B_138KV | | 1 | 138 | 4.82803 | TAPB | 239617 | 138 | LT | SUBB138 | 9509 | 138 | CO | 14610 | SubB LZOI | 772 | SUB_B | 0 |

*Figure 5*
*Fault analysis program Data Extract Example for sample line in Figure 4.*

Our plan is to revise the application to regenerate as single cross-reference data table as noted above.  The revised program will use the previously mentioned process that merged the EDOA and fault analysis program data using REGEX tools.  The application that analyzes the fault records and provides input parameters to fault analysis program (CTA) will have to be modified to handle this single cross reference.  However, for sustainability, a single cross reference table is preferred.

### Running fault analysis program

When using manual methods to calculate fault locations, fault analysis program is run using the standard GUI.  This gives the protection engineer the ability to select the appropriate faulted lines and a fault’s electrical parameters.  Alternatively, a macro can be executed using the fault analysis program command line to automate the fault location process.

To achieve the automation desired as part of this project, it was desirable to run fault analysis program without the standard GUI. A command line interface to fault analysis program already existed, and the ability to create a batch file to launch fault analysis program via. this interface was included in the CTA program.

The fault analysis program contains an "Equipment Category" feature which enables the user to include or exclude selected transmission facilities when using the program. Beyond a baseline model, a fault analysis program user can choose which power system elements to include in any particular fault analysis program session.  At our request, the vendor added the capability to choose Equipment Categories for a fault analysis program session which was launched via. the command line interface to utilize this feature for this project,

### Data Flow

Figure 6 shows the high-level data flow for the **a**nalysis application (CTA).  COMTRADE files from both microprocessor relays and DFR records are converted to COMTRADE format and placed into folders on the CTA server.  When a fault occurs, a file is sent from the FirstEnergy EDOA system and placed in the EDOA directory.  The CTA program is periodically polling the EDOA directory for new fault files.  Once CTA detects that a fault has occurred the following steps are taken:

1) The EDOA file is parsed and the name of the faulted line is extracted.
2) All CTA files in the CTA directory are inspected to determine if any are associated with the faulted line.
3) If an appropriate CTA file is found, all 3 of the COMTRADE files (.dat,.cfg,.hdr) are loaded and analyzed.

4) The oscillography/waveform data is analyzed to determine the maximum fault current and the type of fault.
5) Using the revised cross reference tables, a fault analysis program command string is created to run a fault location macro and provide the data needed to complete the analysis. (This is the same data that would be entered into the fault analysis program GUI if the calculation was being performed manually).
6) fault analysis program is launched using the defined parameters. Once fault analysis program is finished with its analysis, it returns to the interactive GUI mode waiting for user input. To avoid launching multiple fault analysis program sessions on the server as additional fault notifications are received, it was decided to have CTA wait for a predefined period (currently 30 seconds) and then automatically kills/aborts the fault analysis program session (within Windows).
7) The output from the fault analysis program run is analyzed and the fault analysis program results file is timestamped and moved to the fault analysis program History directory.

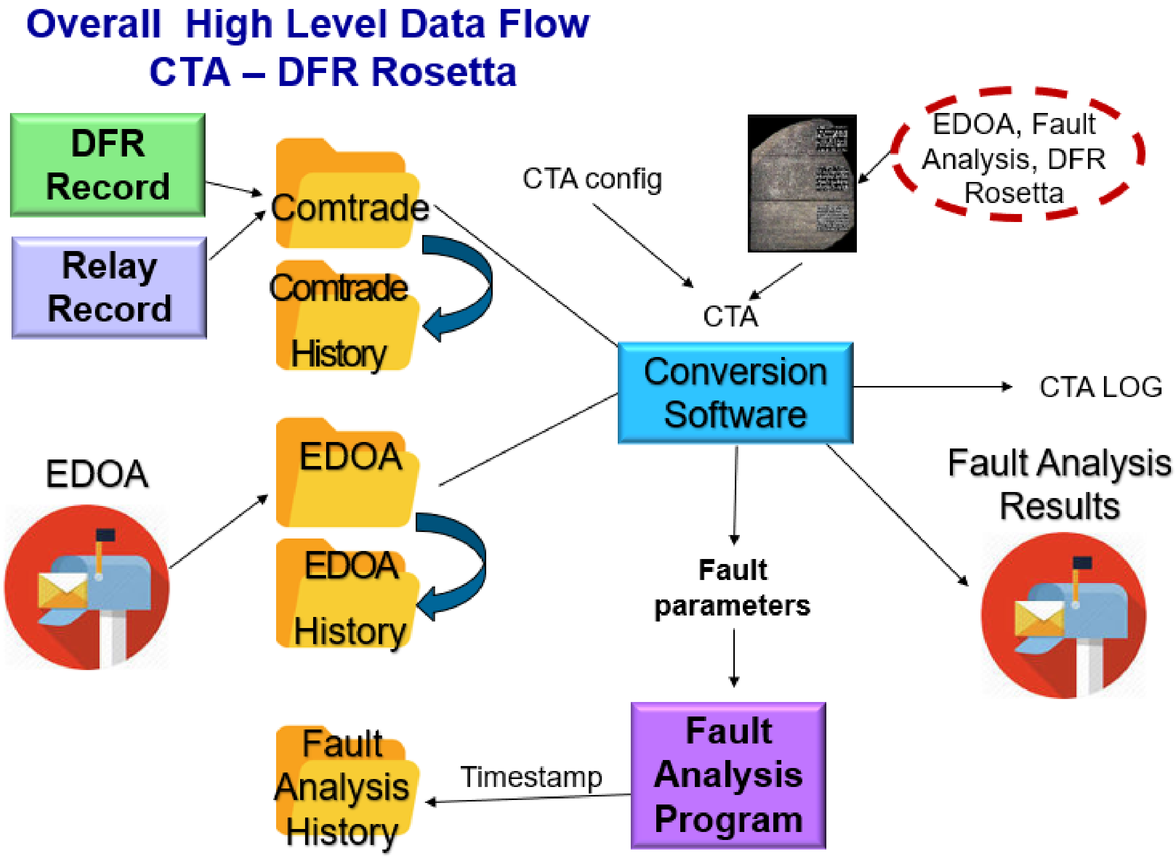


*Figure 6*
*Overall High Level Data Flow CTA – COMTRADE analyzer automation*

8) The EDOA file that started the entire process is moved to the EDOA history directory to avoid creating duplicate fault analysis program runs. It is possible that CTA files associated with a given fault will arrive after the EDOA notification. Therefore, an EDOA time window was implemented Figure 7 to keep the EDOA request “active” for a defined period after its arrival.
9) CTA returns to its polling mode waiting for another EDOA request to be generated

All the above steps and the results of the analysis are all logged to the CTA log file.

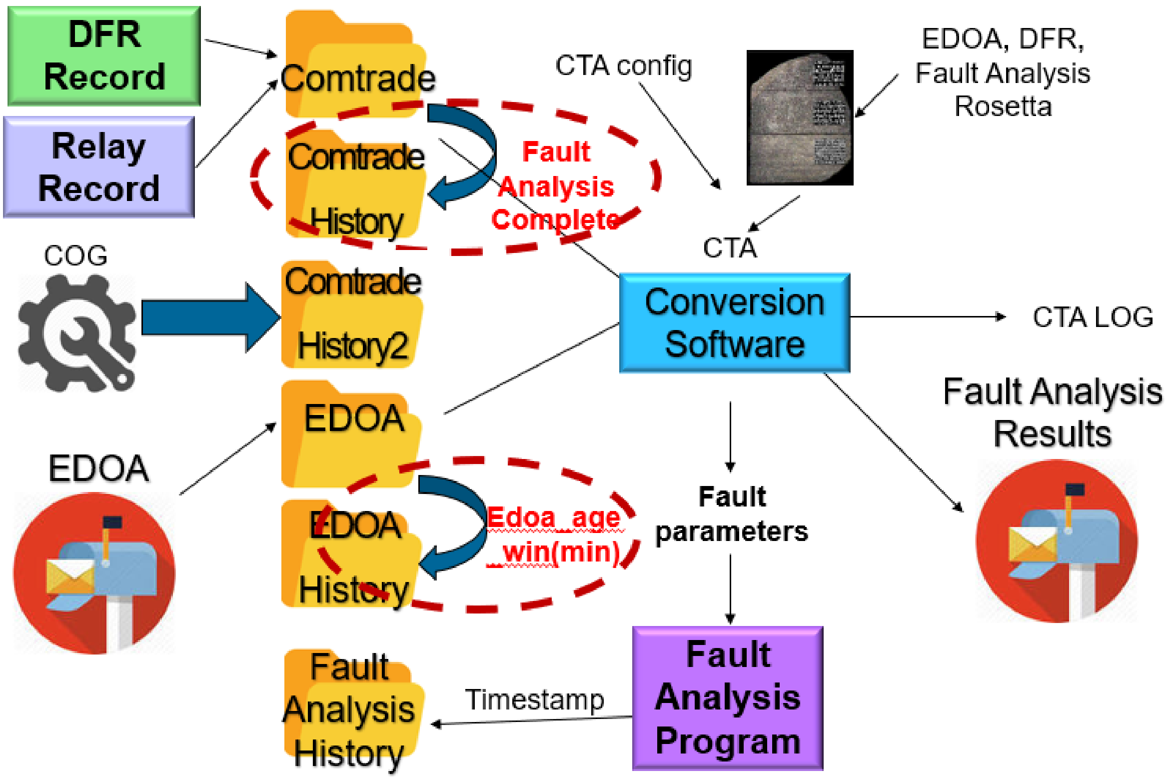


*Figure 7*
*EDOA request AGE Window*

## Looking to the Future

- The output from the fault analysis program macro provides locations in percentages of real bus to real bus. The post processing of the calculated fault location will look to be improved to calculate a length from a specific terminal. This will require adding the full real bus to real bus line length to the fault analysis program database. Beyond this, a geographical view showing pole location could be accomplished by plotting the fault on the transmission GIS.
- At this time, all faults location calculations are performed assuming system normal conditions. Further cross reference tables are being considered to tie together fault analysis program and historical equipment status from a utilities EMS system. The idea is to gather pre-fault conditions and apply a network change within fault analysis program so that the model more closely resembles the actual system prior to the fault.
- For a permanent fault, one or both terminals may attempt an automatic reclose. This may result in a second fault record. At this time, both fault records might be analyzed assuming normal system conditions. Investigations are ongoing to determine how to improve this portion of the process.

## Waveform Analysis - DC Offset Adjustment

In the manual process to determine the fault location, the protection engineer determines the fault magnitude. This involves interpreting the fault recorder waveforms and using engineering judgement to determine the approximate value of the fault current. In doing so, the engineer needs to take into account the DC offset and adjusts for the amount of offset. This occurs when a fault is suddenly applied to the system and the sine wave suddenly becomes asymmetrical (the positive and negative peaks are NOT equidistant from zero), and then returns to normal (symmetrical) after a few cycles. This asymmetrical response to the fault is called DC Offset and it is a naturally occurring phenomenon of the electrical system.

Protection engineers need to adjust for DC offset when processing the data for fault location purposes. In Figure 8 below is an example of a fault with DC offset.

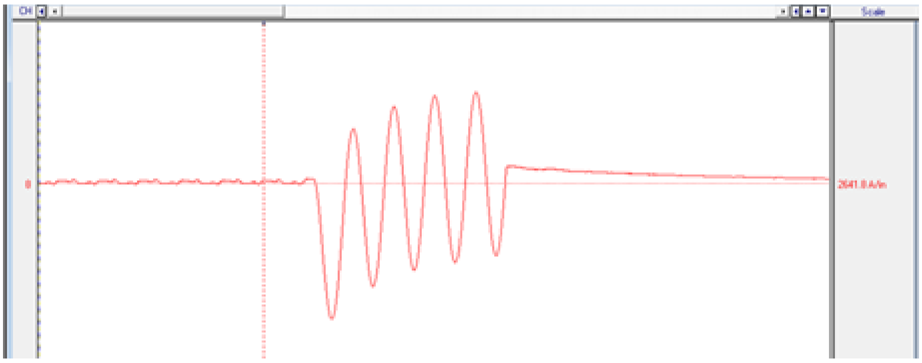

*Figure 8: Fault with DC Offset*

The authors have considered using harmonic analysis for faults to determine when the DC offset has diminished sufficiently to determine the fault magnitude. The Figure 9 below is a graphical representation of the harmonic analysis of a typical fault. In the example, the DC component is actually 156.8% of the fundamental 60 HZ value. Other prominent frequencies in the example are the 3rd and 5th harmonic which are at 73.8% and 41.1% respectively.

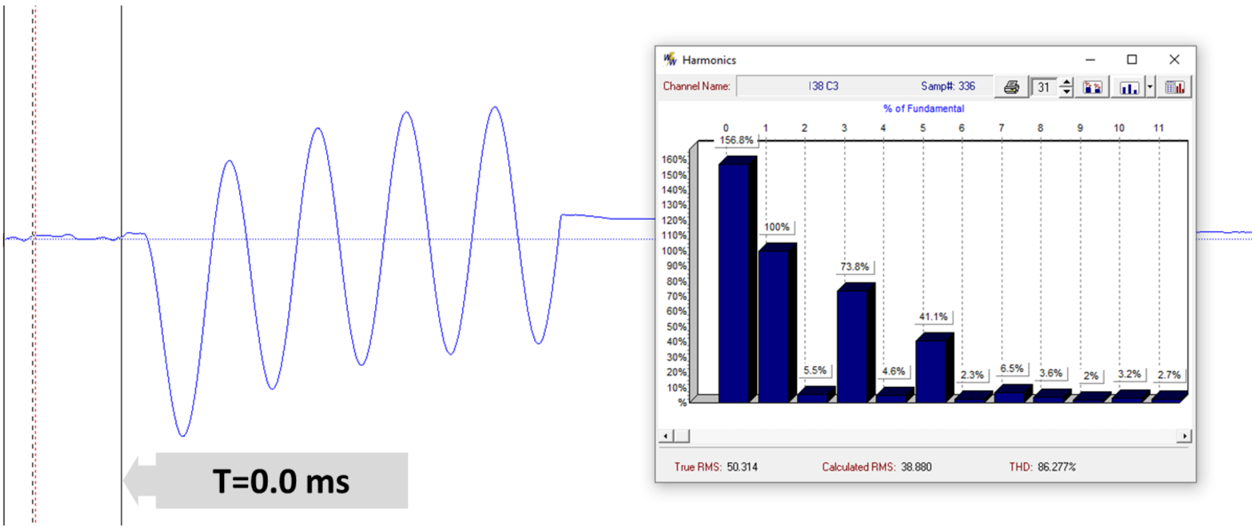


*Figure 9: Initial Fault vs Initial Harmonic Content*

As more time as shown in Figure 10 passes the DC offset begins to reduce. 67 samples or 11.63ms after the previous figure the DC offset has reduced to 110.3% of the fundamental. The sample rate is 5760 HZ or 1 sample every 0.1736 ms.

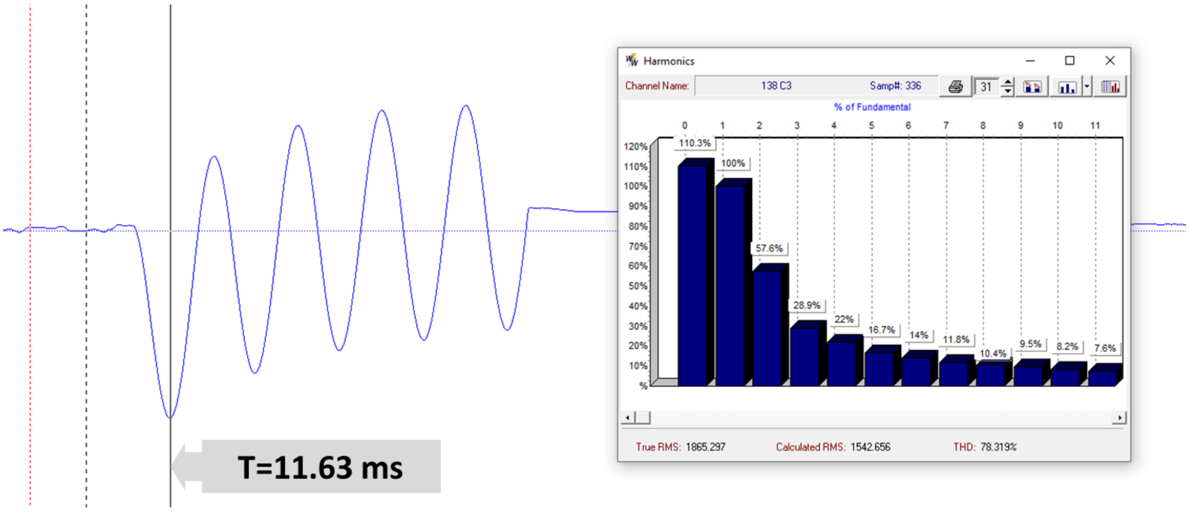


*Figure 10: DC Offset and Harmonics at T=11.63 ms*

After another 95 samples or 16.49 ms, the DC offset, as shown in Figure 11 below, has reduced to 74.7% of the fundamental.

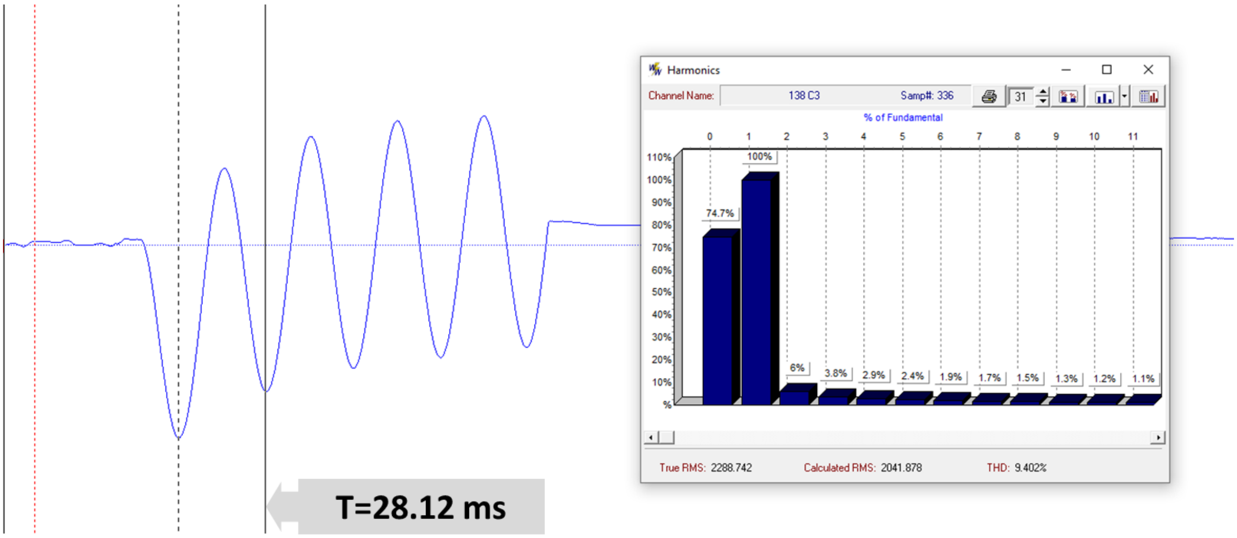


*Figure 11: DC Offset and Harmonics at T=28.12 ms*

In Figure 12, after 57 samples or 9.896 ms later the DC offset has reduced to 40% of the fundamental.

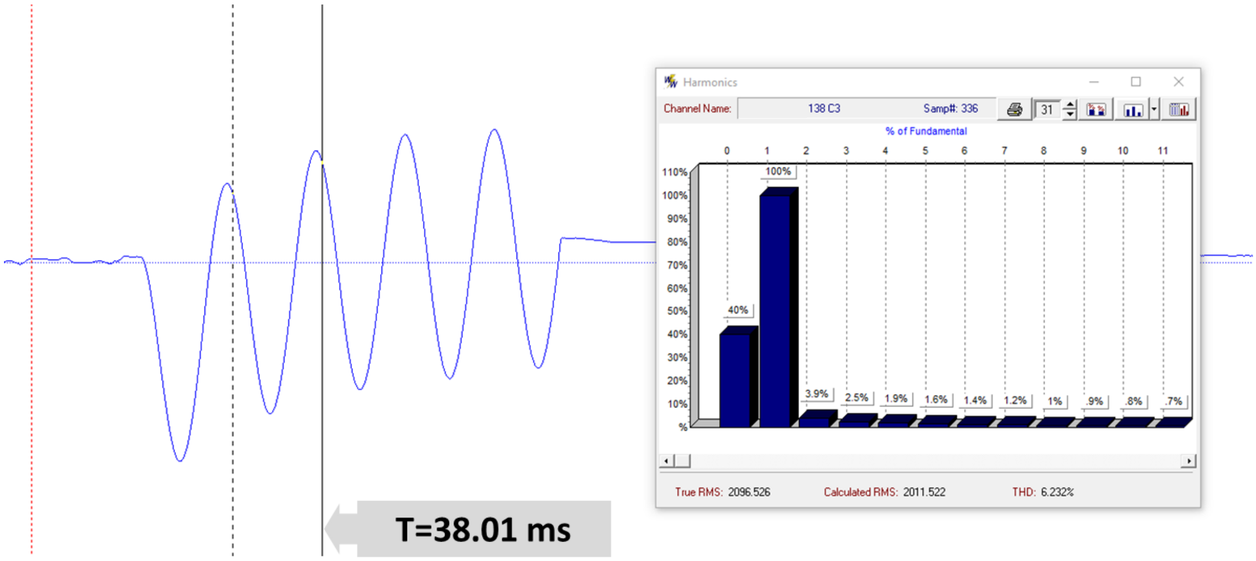


*Figure 12: DC Offset and Harmonics at T=38.01 ms*

Finally, in Figure 13 after 39 samples or 6.77 ms later the DC offset has settled down to only 20% of the fundamental. Also the Calculated RMS has begun to settle out also. The last three values were 2041, 2011, and 1986 amps. Based on these last three values the fault current to be used for the fault location calculation would be about 2000 amps. This value would be passed to the fault location macro along with other systems adjustments required by the current state conditions.

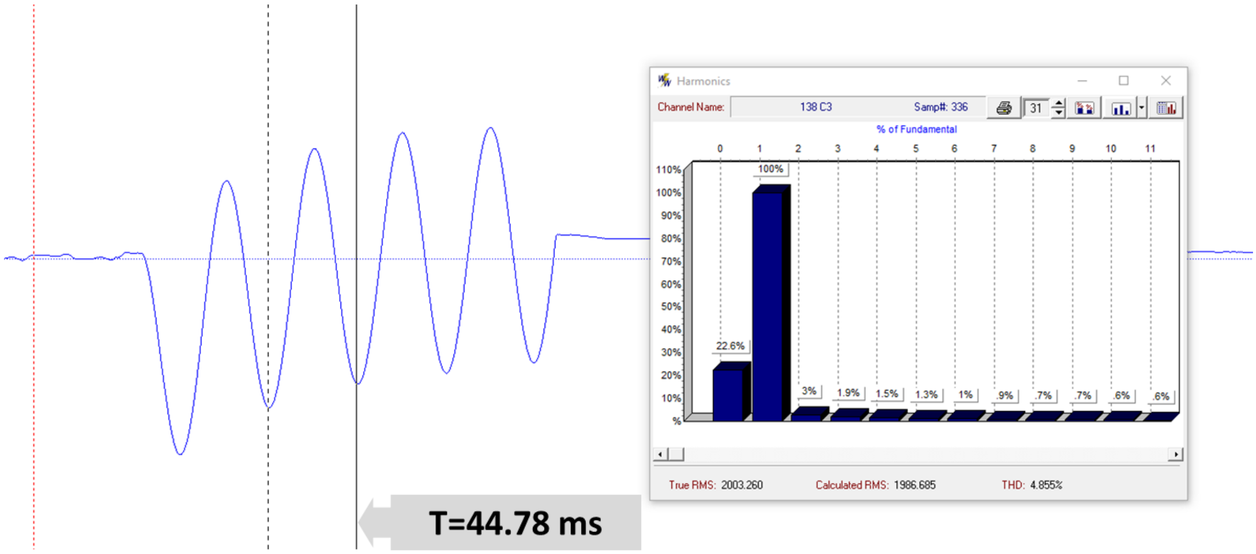


*Figure 13: Stable DC Component at 44.78 ms*

Based on the analysis just presented, the authors are proposing to use harmonic analysis to automatically process fault records and remove the effect of DC offset from the fault magnitude. The initial proposal is to process the fault record until the DC component is less than 40% of the fundamental frequency.  Once that point is reached determine the RMS value of the fault current and use that value for the fault location process.  The 40% value was determined by inspection of a number of faults.  This approach needs to be tested on a larger population to determine its effectiveness.  The authors have also manually tested a 20% value also which also seemed to provide consistent results base on the limited number of samples tested.  An even lower percentage may be used and the authors are considering a value below 5%.  An alternative approach that is being considered is to filter out the transients just for the 60Hz signal and use that for fault analysis program analysis, since fault analysis program is a 60Hz steady state analysis tool.  Lastly, a broader set of fault types needs to be investigated beyond phase to ground that were used in this initial test.

**Recent Additional Test of the DC Offset Adjustment**

To further validate the proposed process a recent line fault was processed manually through it and also by a protection engineer.  As can be seen in Figure 14 the DC component is at 3.4% and the fault current is at approximately 5524 amps.  The protection engineer interpreted the data as 5500 amps.  The fault currents at the other potential DC percentages can be seen in the table at the right,

| DC Percentage | Amps |
|---|---|
| 40% | 5900 |
| 20% | 5400 |
| 10% | 5550 |
| 3.4% | 5524 |

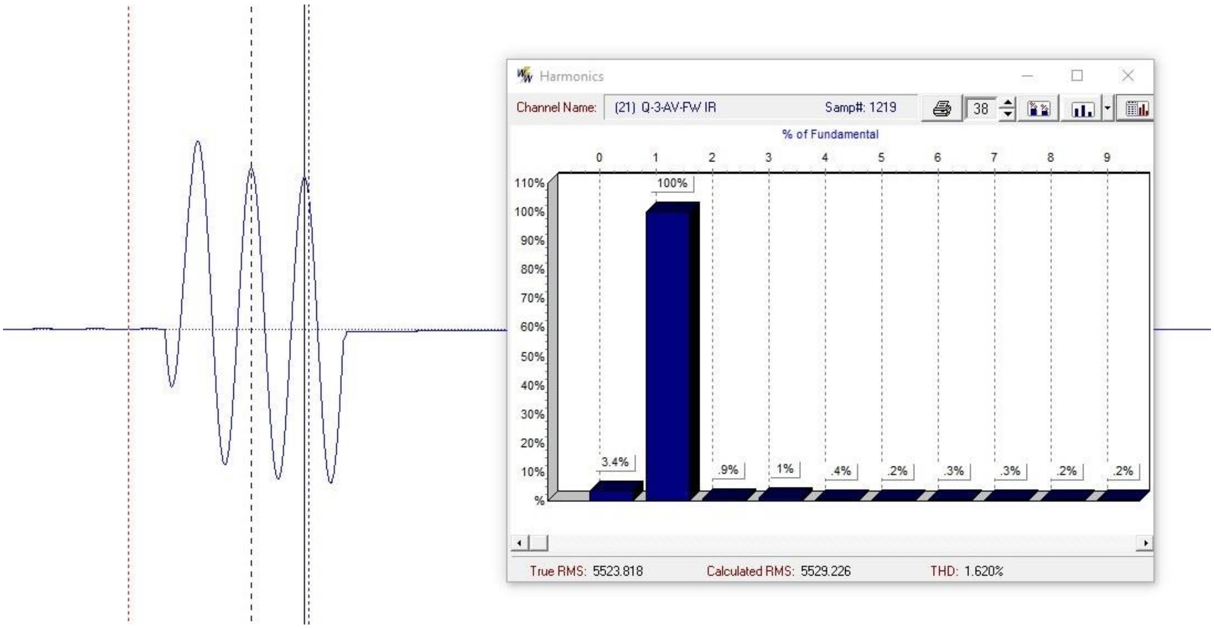


*Figure 14 – Recent Fault Processed Through Proposed Process*

**Conclusion**

This paper has presented how one can take the extracted data from fault records, adjust it to be able to "connect" across a single cross reference table (Rosetta Stone) using Fuzzy (regex) search tools and walking array tools.  The resultant data can then establish a data source that can be automatically run using a fault analysis program fault location macro to locate the possible fault location.  The results presented are a summary of the process flow and waveform analysis approach.  Even though it is still being finalized, this update shows that a very solid foundation has been built that can be used to fully automate the entire process.  This paper has also presented how analyzing the 60Hz component of an unfiltered fault record can be determined and then used as an appropriate fault magnitude for applying the fault within fault analysis program, where previous discussions were just taking the maximum current, without adjusting for DC offsets.  Further work to expand analyze fault records from relays is on-going.

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