Fault Location Calculation Challenge: Use of Automated and Manual Tools

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Abstract - **More and more intelligent electronic devices (IEDs) are being installed and utilized in power system substations. Majority of these new devices come with event recording feature and some even provide fault location calculation. In case of power system faults, protection and fault analysis engineers are often presented with event recording coming from various substations and also from multiple devices. There are several challenges in processing these files efficiently in order to perform analysis and make decision based on the event data.**

This paper focuses on the fault location calculation based on event recordings from IEDs such as digital fault recorders or protective relays. The paper addresses requirements and obstacles when the event data is to be processed automatically in order to enable automated fault location calculation. On the other side, the paper shows examples where combining automated and manual data analytics tools create additional benefits through the use of new fault location calculation tool.

Index terms – ***data analytics, substation automation, fault location, fault analysis, power system restoration.***

I. Introduction

The benefits of automated processing and analysis of vast fault and disturbance data available in power system substations are tremendous. We witness dramatic increase of intelligent electronic devices (IEDs) capable of recording voltage and current waveforms during faults and disturbances and making them widely available across the utility departments. This in a way created an "explosion" of substation data becoming available and waiting to be analyzed. Probably the biggest benefit of automated processing and analysis of substation data is being able to quickly assign the priorities and sort the disturbance records based on the importance of the content. Depending on the triggering conditions it is not uncommon that we face situation when IEDs are creating much more recordings that the number of actual faults or events worth being manually inspected and analyzed.

One of the key features of solutions for automated analysis of substation data is automated fault location calculation. Once the data has been classified and prioritized, we want the analysis to be capable of correctly selecting the affected transmission line, determining fault type, and performing fault location calculation [1]. Defining and implementing logic for such analysis is not always straightforward even though a trained and experienced protection engineer can quickly come up with some of the conclusions and classification by just glancing the waveforms. Actual fault location calculation can be tedious even when good waveform viewing tools are available.

This paper discusses the challenges of automated fault location calculation based on fault and disturbance recordings captured by substation IED. The paper gives an overview of the main requirements for automated fault location calculation and illustrates them with implementation examples both for fully automated and manual solutions. Manual solution in this context means a calculation where the input parameters are arranged and adjusted by an experienced user. A "real life" approach combining automated fault location with experience and knowledge of an expert, in this case experienced protection engineers, is introduced using some field examples that illustrate challenging situations. The approach illustrates how these challenges when determining fault location calculation can be overcome combining fully automated or manual fault location calculation tools.

The discussion in the paper starts with a background discussion and then introduces the fault location calculation challenges. Second half of the paper focuses on the real-life experience combining automated and manual data analytics software tools. Example of the fault analysis solution that is based on the use of new fault location calculation tool is given at the end.

II. BACKGROUND

Fault location calculation based on IED data collected in substations is indispensible part of the fault analysis. Traditionally, fault analysis based on substation IED event recordings is done off-line and the analysis results is not part of the decision making process. The expansion in number and variety of IEDs used in substations, as well as dramatic improvement of the computing power and communication speed is making it possible to move analysis of the substation IED data into the on-line mode [2]. In other words, the substation data and analysis results that were traditionally considered as non-operational are becoming operational.

In this paper we focus on the fault location calculation based on substation IED recordings, primarily digital fault recorders (DFRs) and digital protective relays (DPRs). Such fault location calculation can be part of the fault data analytics setup, which is in this case Fault Analysis data analytics (Figure 1).

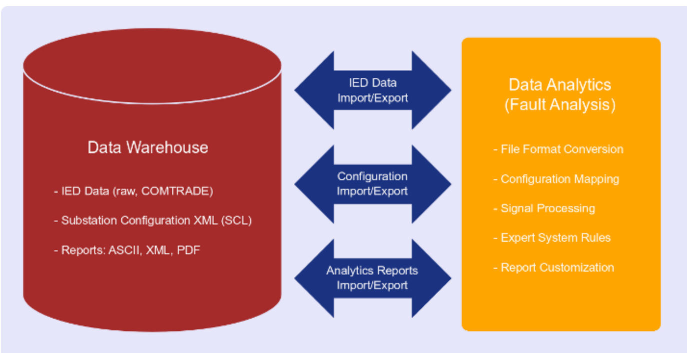

Fig. 1 Data analytics: fault analysis with fault location calculation

As shown in Figure 1, a fault analysis setup contains data warehouse, which is a repository for substation IED data, configuration settings, and finally, analysis results in a form of reports in various formats. The data analytics, in this case fault analysis, is responsible for interfacing to IED data, performing management and handling of configuration settings, and finally providing the analysis reports in the desired format. Additionally, both the data warehouse and the data analytics application can have their own separate user interface, or provide for a connection to a universal customizable user interface. Different personnel groups may have different views of the data and the analysis results.

III. FAULT LOCATION CHALLENGE

There are several challenges before us when we try to use event records obtained from DFRs and DPRs for manual or automated fault location calculation. This section will address some experience with the implementation of data analytics software tools developed to handle such challenges. The primary focus of the paper is on the implementation of phasor based fault location calculation.

A. *Data collection and data integration*

It is critical that the proper data collection and data integration is put in place. As foundation for any efficient use of substation IED recordings, the event data needs to be downloaded and made available in efficient and timely manner. Whenever possible, the connection to IEDs should take advantage of advanced communication infrastructure and utilize high-speed communication, i.e. Ethernet over dial-up, while at the same time satisfying cybersecurity requirements. In the case of digital fault recorders, we experienced situation when the event data records have been collected and processed within two-minute time frame after the event occurrence.

One of the challenges is that utilities typically deal with IEDs that are coming from different vendors and even different vintages. In order to maintain the system and keep it operational it is crucial that we always try to apply same approach when we configure various data collection software and hardware. The ultimate goal is to get the data in shortest period of time, maintain cybersecurity, and make the data available for an easy integration and conversion into non-proprietary and reusable data formats. Good examples of standard formats to consider are COMTRADE and COMFEDE [3,4]. It is also crucial that the data collection and data integration should be implemented as automatic functions regardless if we are going to calculate fault location using manual or automated tools.

B. *Quality of Data*

Regardless if we are planning on doing manual or automated fault location calculation the quality of the data plays very important role. As in most cases, the "garbage-in-garbage-out" is applicable here as well. We cannot expect an accurate and good fault location calculations if we do not have high quality input data available.

With respect to fault location calculation, the following quality attributes need to be considered:

- Monitoring of all phases and grouping of related signals,
- Duration of records including the availability of both pre- and post-triggering data,
- High sampling rate and quality of filtered vs. non-filtered data,
- Correct wiring, reduced noise level, elimination of "unreal" DC offset,
- Time stamping accuracy,
- Synchronized sampling, for some algorithms [5],
- Availability of raw vs. processed data,
- Communication and data collection in timely manner,
- Availability of IED settings such as channel assignments, scaling, line data, etc.

It is quite obvious that if something goes wrong with any of these, the actual fault location estimate and its efficient use will be affected. This will be illustrated with real life examples and fault data obtained from simulation, DFRs, and DPRs.

C. Algorithm Selection and Implementation

There are various fault location calculation methods and algorithms. In this paper, we illustrate use of phasor based fault location as proposed by IEEE guide for fault location calculation in power systems [6,7]. Different topologies, line configurations, and monitoring setup may affect the results and algorithm selection.

IV. Real-life Experience

This section illustrates the fault location calculation based on both simulated and actual field data. The results are obtained using an in-house configuration of the data integration and fault analysis tools [8].

TABLE I
CASE A: PHASOR-BASED FAULT LOCATION CALCULATION EVALUATED USING EMTP/ATP SIMULATED EVENT DATA

#	Fault Type	Loc A	Loc B	SE Err %	TE Err %
1	A-G	50	50	3.75	0.05
2	A-G	60	40	2.88	0.13
3	A-G	70	30	2.13	0.24
4	A-G	80	20	2.09	0.27
5	A-G	90	10	2.69	0.22
6	AB	50	50	2.09	0.01
7	AB	60	40	1.67	0.20
8	AB	70	30	1.51	0.41
9	AB	80	20	1.88	0.48
10	AB	90	10	2.57	0.44
11	AB-G	50	50	2.09	0.05
12	AB-G	60	40	1.85	0.08
13	AB-G	70	30	1.51	0.17
14	AB-G	80	20	1.88	0.21
15	AB-G	90	10	2.57	0.18
16	ABC	50	50	1.91	0.07
17	ABC	60	40	1.73	0.17
18	ABC	70	30	1.39	0.11
19	ABC	80	20	2.06	0.44
20	ABC	90	10	2.57	0.36

Note: error % calculated relative to the line length

A. Phasor-based single- and two-end fault location estimate

This first case uses EMPT/ATP generated fault records that would be an example of high-quality input data [9]. The simulated recordings were sampled at 10KHz sample rate, and the length was set to provide enough pre- and post-fault data samples. Due to the fact that the recordings were created by simulation, the data obtained from both ends of the faulted line were perfectly synchronized. Both single-end and two-end phasor based algorithms were implemented and tested using the simulated fault waveforms. The results are summarized in Table I. It is interesting to observe that the two-end algorithm in this scenario provides much better accuracy on the fault location estimate. This was expected and in a way verifies the implementation correctness.

Once the same calculation setup was applied to DFR recordings from the field, it still shows some advantages to using two-end algorithm, but it was not always easy to maintain the quality of data. The main problem was with time stamping, and sometimes variety of the sampling rates, noise, missing phases, etc., did affect the results. It is preferred, when applying phasor-based two-end algorithm on DFR data, to have identical DFR types/vintages and use the same or very similar monitoring settings. In such cases it is expected that the sampling rate will be sufficient and similarly the data from both ends should have the time stamping of the same quality. This sensitivity was confirmed with DFR data from the field and consistent use of data shows good results.

Applying the same setup to DPRs shows oscillations in accuracy of results. As expected, the DPR data with 4 or 8 samples per cycle would not produce as good results when trying to use automated fault location calculation using the data from both ends of line. This was especially noticeable when the relays are coming from different vendors and vintages. In the case of using identical relays on both ends, with the similar time synchronization setup, we did experience good results in estimating fault location based on waveforms with higher sampling resolution such as 32 samples/seconds.

We had only a few examples of the field data where we tried to combine DFR and DPR data. We did not get good results with the two-end algorithm. Single-end algorithm stayed within expected accuracy, as it was not that much affected by the time stamping or even the sampling rate.

Generally, when using of IED data for automated analysis and fault location estimation, we should try to obtain the highest quality data whenever we have a choice. This is particularly applicable to DPRs as they often offer variety of options for event recording. Also, when attempting to use data from two ends of the line it does help a lot if the data is coming from same or similar devices. In case of DPRs we had a good experience with pairing data coming from same model of the relay on both end. We tested this with field data obtained form SEL-421 and GE D60 [10,11].

B. *Automated fault location calculation: field example*

The second example illustrates field event that was captured by substation DFR and both primary and backup relays. The discussion includes automated processing and fault analysis of both DFR and DPR data. The introduction of the tool for manual fault location calculation allows user to interact with the results from the automated analysis and manually inspect and tune settings that may be affecting the location estimate.

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Substation Assistant(TM) - Expert System for Automated Analysis of DFR Rec
Copyright: Test Laboratories International, Inc., 1996-2010

*** Expert System Log ***
The "RC" signal is not monitored for this circuit!
The "TC" signal is not monitored for this circuit!
The bus breaker is not monitored!
The middle breaker is not monitored!
Line breaker(s) open after the disturbance!
The event is a ground fault!
The event is a phase A to ground fault!
The fault is cleared by the protection at this substation!
Primary relay is not monitored!
Backup relay is not monitored!

*** Event Origin ***
DFR Assistant Client:          Demo
Substation:                    Sub2
DFR Native File Name:          ZQ136c9
Affected Circuit:              Line 3

*** Event Summary ***
Trigger Date and Time:         2008-07-20 11:59:34.207
Start Date and Time:           2008-07-20 11:59:34.132
Disturbance Start, End:        65, 106 [ms]
Duration:                      41 [ms]
Event Description:             AGND_FAULT
Fault Location:                23.7 [Miles]

Event Outcome:                 EV_CLR_LOCAL
Breaker Operation:   1st,      CB_OK
Breaker Operation:   2nd,      CB_OK
Relay Operation:     PRIM,     RL_NOT_MONITORED
Relay Operation:     BACK,     RL_NOT_MONITORED

*** Analog signal Values ***
Prefault Values:           Fault Values:             Postfault Values:
IO  =   0.0118 [kA]        IO  =   6.5834 [kA]       IO  =   0.0038 [kA]
Ia  =   0.5158 [kA]        Ia  =   6.6937 [kA]       Ia  =   0.0006 [kA]
Ib  =   0.5478 [kA]        Ib  =   0.5190 [kA]       Ib  =   0.0037 [kA]
Ic  =   0.5638 [kA]        Ic  =   0.6320 [kA]       Ic  =   0.0004 [kA]

VO  =  19.3244 [kV]        VO  =  45.3375 [kV]       VO  = 195.1439 [kV]
Va  = 198.0319 [kV]        Va  = 162.1927 [kV]       Va  = 198.0891 [kV]
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Fig. 2 Case B: automated fault analysis report based on DFR data

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DFR/DPR Assistant - Automated Analysis of DFR Recordings
Copyright: Test Laboratories International, Inc., 1996-2008

*** Relay Event Summary ***
DFR Assistant Client:          Demo
Substation:                    Sub2 DPR Line 3 BU
DFR Native File Name:          Relay BU, 080720.EVE
Affected Circuit:              Line 3 BU
Trigger Date and Time:         2008-07-20 11:59:34.307
Start Date and Time:           2008-07-20 11:59:34.207
Event Description:             AGND_FAULT
Fault Location:                24.93 [Miles]
Event Outcome:                 -

*** Native File ***


"FID","RID","SID","03E2"
"FID=SEL-421-3-R123-V0-Z010010-D20070223","SUB2 LINE3 BU","SUB2 LINE3 BU","1da
"MONTH","DAY","YEAR","HOUR","MIN","SEC","MSEC","0ACA"
7,20,2008,11,59,34,307,"0468"
"EVENT_NUM","EVENT","LOCATION","FREQ","NFREQ","SAM/CYC_A","SAM/CYC_D","NUM_OF_
10468,"AG T",24.93,60.00,60,8,8,30.125,"2007241325","YES",1.0,1.0,1.0,1.0,1.0
"IA(A)","IB(A)","IC(A)","IG(A)","VA(kV)","VB(kV)","VC(kV)","VS1(kV)","VS2(kV)
142,-552,422,12,8.32,-181.42,176.62,-0.09,0.03,7.34,60.00, ,"00140000002000000
471,-491,25,5,153.92,-197.59,46.37,-0.02,0.01,152.27,60.00, ,"00140000002000000
524,-143,-386,-5,209.37,-98.02,-111.06,0.06,-0.01,207.99,60.00, ,"0014000000020
```

Fig. 3 Case B: automated fault analysis report based on parsing DFR data

A report example from the automated fault analysis based on DFR recording is given in Figure 2. The fault analysis on DFR data was configured to perform full-blown processing and analytics captured at the time of the fault occurrence. As seen in the report, the automated data analytics correctly selected the affected circuit, fault type, disturbance start and end time, and finally, it automatically ran single-end fault location calculation. The fault location was calculated to be at 23.7 miles, which was in this case a perfect match with the location of the tower where the fault occurred.

Processing of the protective relay data was configured to automatically parse the event reports and extract the fault location calculation as it was calculated by relays. In this particular case both primary and backup relay calculated the fault location to be at around 25 miles. Figure 3 displays the event report based on the data from backup relay. Besides the extracted information shown in the summary, the report also includes the original event report as it came from the relay.

For this particular event we also tried to apply data analytics on the relay waveform, but automated fault analysis was not giving us results as good as the parsing primarily due to lower sampling rate. To explore the data analytics, we introduced an addition to the waveform and report viewer that allows for user's manual interaction with the fault location calculation module (Figure 4).

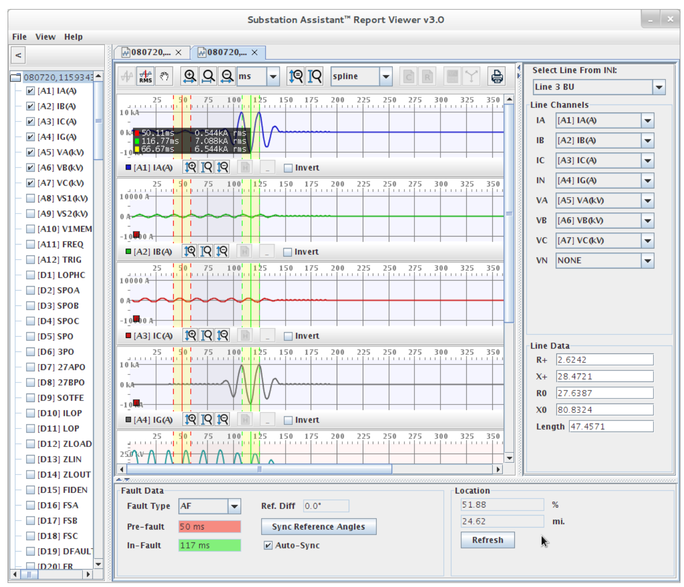

Fig. 4 Case B: introducing add-on tool for manual fault location calculation

The manual fault location tool displays the waveforms and settings and lets the user manually adjust or set the conditions for the fault location calculation. User can select channels, configure line impedance and length, and also position cursors for the calculation of pre- and fault phasors used for the estimation of the fault location. As seen in Figure 4, this particular fault was fairly short, around three cycles, and the relay did some smoothing due to filtering at the start and end of the disturbance. However, if the cursors were correctly positioned the fault location calculation would be fairly accurate (around 24 miles). To illustrate sensitivity of the fault location calculation we briefly moved the cursor towards the beginning of the disturbance region, which immediately caused the fault location calculation to "jump" to over 31 miles (Figure 5). This error is expected since the calculation of phasor in the fault time window is affected by the cycle that was "smoothed" out by the filtering and low sample rate. This also gives a good illustration why automated fault location sometimes gives unexpectedly inaccurate results.

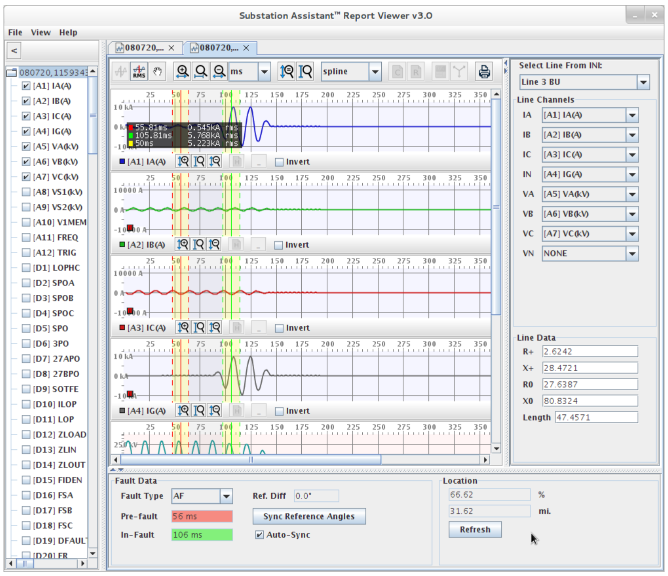

Fig. 5 Case B: illustration of sensitivity of the fault location calculation

It is important to note that the use of the fault location tool that allows for manual interaction does help users to gain confidence in the calculation results. While making variations on which phasor data is used for the calculation user can quickly assess the whole range of the fault location results and feel more or less confident about the location estimate. Overall, in this particular example we actually had a very good match between fault calculation done by DRPs, data analytics based on the DFR data, and even calculation performed later based on the DFR data obtained from the neighboring utility.

C. Manual fault location calculation: field example

This example is interesting as it demonstrates use of the tool for manual fault location calculation. The disturbance recorded by DFR appears to be fairly long. The fault was far away and it took the protection long time to trip. The duration of the recorded disturbance is around 31cycles. Based on the inspection of the waveforms it can be seen that some tripping did occur at equipment at other substions as well. There is a change in disturbance current around 6th cycle and later around 25th cycle. In the specific configuration, the automated fault analysis was configured to target the middle cycle of the faulted region in order to calculate phasor values used in fault location calculation (Figure 6). In this particular case, this resulted in inaccurate fault location calculation estimated at around 24 miles. The automated data analytics correctly identified the faulted line and phase. All the parameters used for fault location calculation are automatically pre-set for a user upon opening of the toll for manual fault location calculation as seen in Figure 6.

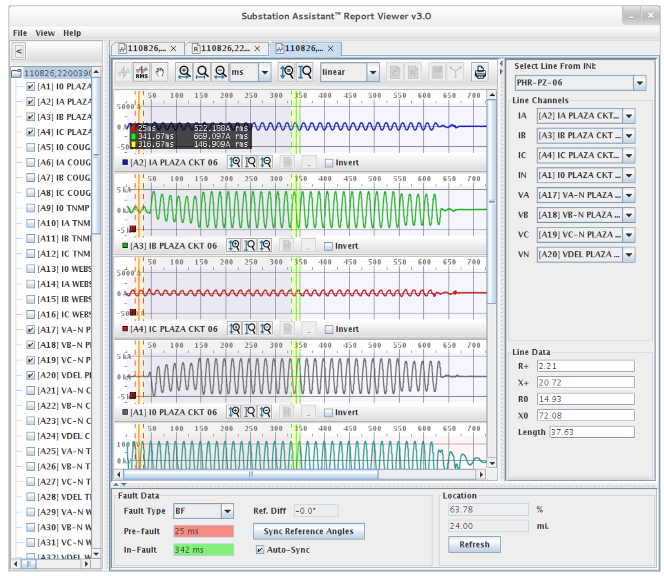

Fig. 6 Case C: automated analytics selects the middle cycle of the fault window

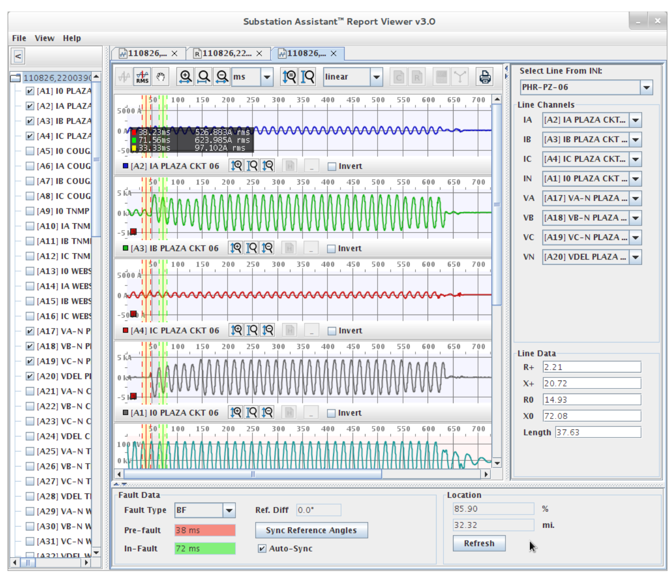

Fig. 7 Case C: manual tool allowed for focusing on the area of the interest

The manual fault location tool proved to be very useful in this situation as it allowed protection engineers to manually vary the position of the second cursor in the faulted region and obtain more accurate fault location calculation. As a matter of fact, when positioning cursor very close after the fault instance the fault location calculation was almost a perfect match with the actual fault location, which was at around 32 miles from the monitoring bus. Figure 7 illustrates this result and the position of the second cursor. Making a judgment where to place cursors is driven by user's experience, expertise, knowledge of the system, and information obtained from other sources such as data from other IEDs and substations, SCADA, etc.

In this case it was the combination of the automated and manual data analytics tools that enabled quick and precise fault location estimate. The automated fault data analytics processed all the incoming IED event recordings and made the data and reports readily available to users in very short time after the fault occurrence. Automated fault data analytics sent out notifications via pager and email messages. The web access to event table allowed users to quickly browse and focus on the event data files of interest. The report viewer with manual fault location calculation tool enabled quick variation of the parameters needed to obtain better results. Finally, the experience of the users was a critical factor in understanding the topology and making a judgment which results should be favored.

V. Conclusions

The paper considers aspects of using substation IED data; primarily event triggered data collected from substation DFRs and DPRs, for fault location calculation. Conclusions of the discussions presented in the paper can be summarized as follows:

- The amount of the data collected from substation IEDs requires automation and use of intelligent software tools to improve data integration, initial processing and visualization, as well as intelligent tools that enable engineers and experts to use their knowledge and expertise to the full extent.
- Use of automated data analytics dramatically saves time and enables focus of the experts on the subset of the IED data that may be critical for decision-making process.
- The use of experts, in this example protection engineers and fault analysts, is indispensible and extremely valuable, especially when combined with modern fault data analytics tools.
- In addition to automated data analytics software, we need the tools that can be combined with the knowledge and experience of the engineers and help them utilize their expertise to the full extent in efficient and timely manner.

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