Temporal and Spatial Requirements for Optimized Fault Location

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Abstract

With technological advancements data availability in power systems is drastically increased. Intelligent electronic devices are capable of communicating recorded data. Data can be stored, easily interfaced from different access points and, intelligent techniques can be used for automated fault analysis. After summarizing obstacles in the current framework of fault location analysis, this paper will explore temporal and spatial aspects of available data. This leads to introducing implementation framework of automated optimized fault location that is capable of taking advantage of both the time and space aspects of data.

1. Introduction

This paper focuses on the issues of time and space as they relate to fault analysis. With increased data acquisition capability and enhanced communicational performance at all levels of power system, implementation framework of automated offline fault location (FL) analysis drastically changed. Over the years, several approaches to FL were proposed in the literature [1]. They did not explore full range of implementation options available as a result of temporal and spatial considerations. As a consequence of the existing protective relaying concept, consisting of decentralized automata focused on local operation [2], single and two ended FL algorithms were considered the most in the past. Single ended phasor based algorithms have used the data from one location and extracted the phasors only [3]. Two ended phasor based algorithms used data from two ends of the transmission line and did not explore the synchronization of samples but phasors only [4]. In [5] authors proposed algorithm for selection of optimal FL algorithm based on available information. However, they cover only two groups of FL techniques: algorithms based on phasors recorded at one line end and algorithms that use measurements of voltages and currents from all line ends. Neither the time-domain algorithms that use synchronized samples from two ends of the line, nor the case when only sparse recordings are available are covered in that algorithm. This paper demonstrates how synchronization of samples taken by IEDs, and exploration of spatial data obtained through variety of techniques may significantly improve fault location process.

The paper starts with discussions of the fault location problem and current framework used for FL analysis. The spatial and temporal aspects are discussed next. Finally, an example of how merging the time and spatial considerations creates an optimized fault location approach is demonstrated.

2. Background

When fault appears in a power system different devices are triggered. Protection equipment consisting of protection relays and circuit breakers (CBs) will operate in order to de-energize faulted line. Different Intelligent Electronic Devices (IEDs) located in substations will be automatically triggered by the fault and will record corresponding current, voltage and status signals. Those records are later used by different utility groups for fault investigation. Depending on FL and nature of the fault, completely different approaches may be used for repairing faulted equipment. Correct information about FL and its nature should be extracted as fast as possible to allow timely inspection, repair and restoration.

2.1. Fault Location Problem

After a fault takes place automatic actions of relays and related switching equipment status is immediately seen by an operator in the control center who will make note of the fault event and inform other staff like protection group or maintenance. Protective relaying staff will be ready to analyze the fault in more detail and maintenance staff will be ready to take any repair action as needed. Protective relaying staff will typically retrieve IED recorded data from substations, which may last from few minutes to few days. Quite often, substantial time may be needed by the protective relaying staff to complete the analysis before informing others. Maintenance staff will be asked to go to the filed in the case of a permanent fault to inspect and repair the damaged equipment as needed. Their action will result in a report shared with other staff including operators and protection engineers. After the damage is repaired, the operators will restore the line making sure everything is in tact and will complete the event report, which then will be archived for any future uses. The time line of this process is shown in Fig. 1. It should be noticed that different data and information are available to different utility staff at different times.

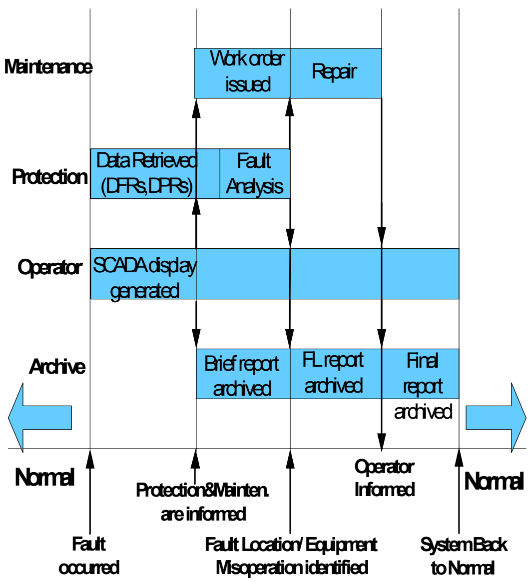

Figure 1. Timeline of utility personnel actions in case of permanent fault

The time line shown in Fig. 1 demonstrates how the current process requires considerable time to be spent by different groups retrieving the data and waiting for other groups to complete their tasks. Operators have access to SCADA system data all the time but protection group has to retrieve fault recordings from IEDs located in substations in order to do the fault analysis. Protection group does not have access to SCADA system information and relies on operators to tell them what they have observed. Maintenance staff is informed by the operator when permanent fault is present, but they do not have clear instructions about possible actions before they get FL estimation from the protection group. Maintenance staff typically does not have access to other data sources beside archived data. Before specific information is made available, the maintenance crew is not ready to take any actions. Once the maintenance crew inspects and repairs the damage, operators are informed and they can restore the system. Depending on the time response, correctness of available data and information entered by different groups, fault can be diagnosed in varying time intervals and with varying level of confidence.

2.2.The importance of the temporal and spatial aspects

If spatial aspects of the current situation are considered, it may be observed that IEDs used for obtaining fault event measurements are neither uniformly spread across power system nor equally capable to capture the events. Typical power system contains several hundreds of transmission lines. Installation of recording devices at each transmission line is very expensive and still cannot be found in practice. The common practice is to place DFRs in critical substations to record voltages and currents on several transmission lines connected to that substation. Protective relays are spread all over the system, but some of them may still be electromechanical and they do not have capability to record measurements. As a result, in some cases it can happen that there are no recordings at all available close to a fault. For a case shown on Fig. 2, depending on location of the fault, different DFRs may be triggered but all of them are distant to FL. This demonstrates the spatial dependency of available data and the importance of having an algorithm that can use such data for FL.

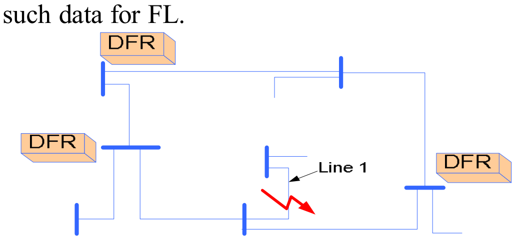

Figure 2. Layout of closest DFRs to a fault on Line1

If the temporal aspects of recorded data are observed, it may be noted that IEDs have different recording capabilities where some of them use GPS time reference for sampling synchronization while the others do not have such a capability. It may be observed that if data obtained from several IEDs is not synchronized, most time-based FL algorithms are not applicable. This demonstrates the importance of the temporal dependency of available data, which need to be synchronized to be utilized in the most accurate algorithms.

Depending on data availability, different FL algorithms may be utilized. Beside captured fault recordings most FL algorithms need some additional data. Some of the algorithms require determination of fault type, others the parameters of the faulted transmission line. Some algorithms use pre-fault, some use post-fault phasors. In either case it is necessary that extracted information is valid and input data accurate before applying the corresponding algorithm. This clearly shows that it is not possible to pick only one FL algorithm that is applicable in all situations and for all possible data measurement locations. Before FL analysis, temporal and spatial considerations should be carefully taken into account to select the best algorithms for a given spatial and temporal disposition of faults and related recorded data.

3. The Spatial Considerations

In [2] authors made general classification of spatial considerations in the context of monitoring, control and protection. Focus of this section is to define spatial consideration in the context of the centralized FL analysis.

1) *Space as Reference for Placements of Physical Measurements:* In general, IEDs used for obtaining fault event measurements are not spread uniformly across the power system. Critical substations may be equipped with greater number of IEDs that are capable of recording and communicating data, while less accessible locations like tapped lines may be poorly instrumented with recording equipment. Once fault occurs, different IEDs are triggered. Some of them may be located close to the fault, while some of them might be far away. It is important to recognize that depending on the spatial origin of available recordings with respect to the possible FL, different FL algorithms may be applicable. The following cases may be observed from the example given in Fig. 3: a) DFR recording is available from only one end the faulted section AB, b) there are no direct recordings available from the faulted section BC but only one recording far from the fault at point A is available, c) measurements from both ends of the faulted section AB are available, and d) direct recording from one end of the faulted section and a recording far from the fault at point A are available.

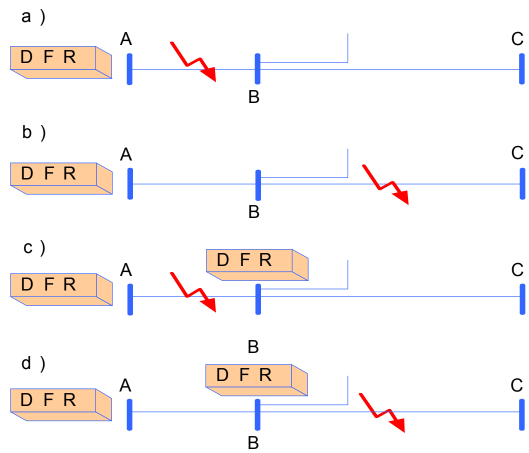

Figure 3. Layout of triggered DFRs

From the mentioned cases, three types of spatial placement of measurements relative to FL may be recognized:

- Single ended
- Multiple ended (two, three etc.)
- Sparse system-wide

In each of these cases different FL algorithms are the most suitable and it is very important that correct type of the placement is recognized so that the best algorithm for the given measurement placement case may be selected. Illustration of this observation can be seen from Fig. 3 where in cases c) and d) the same IEDs were triggered even though the fault was occurring at different locations. It is obvious that some additional data beside recordings is needed in order to narrow down possible faulted area. By obtaining CBs status information at the time when fault occurred, it is possible to determine correct faulted section and determine which case of the placement of measurements is relevant.

2) *Space as Reference for Power System Model Accuracy*: For various fault events in power system only specific power system components are involved in the event. Since the accuracy of the FL analysis depends on input data, model of the faulted area should be precisely determined. By knowing the faulted line length, whether the line is parallel or transposed, different models can be utilized and the selection influences the choice for the most

accurate FL algorithm.

There are some non-traditional ways that could also be used to improve spatial considerations. By using precise satellite images for viewing faulted area, it can easily be determined what type of towers surround the fault, which could be used as additional information for modeling of the faulted area. It could also be possible to see if there are some trees close to transmission lines or bird nests that might be causing fault, which may be taken into account in confirming the location.

Many faults in power system are caused by bad weather conditions. The National Lightning Detection Network (NLDN) reports within seconds the time and place where a lightning strike has occurred [6]. By combining the NLDN data with other information about fault it might be possible to localize the faulted area better.

Finally, Geographic Information System (GIS) technology [7] can be used for better presentation of spatial data. It is a computer system capable of capturing, storing, analyzing, and displaying geographically referenced information related to FL. One example of GIS application is to show fault events archive data in a geographic framework. This would reveal locations in the system where faults are more frequent and the equipment more likely to fail due to frequent exposure may also be identified.

4. The Temporal Considerations

Once placement of recordings and model of faulted area are known, temporal considerations should be evaluated. In [2] authors made general classification of temporal considerations in the context of monitoring, control and protection. Focus of this section is to recognize the temporal consideration in the context of FL analysis.

1) *Time as a Reference for Correlating Power System Events:* It is important to note that before FL estimation can be calculated many algorithms require that both the network topology and measurements are determined for the same time instant. So, besides estimating FL, fault analysis also needs to determine fault-clearing sequence. This involves fault detection, fault classification, relay communication channel actions, relay trip decision, CB operation, interruption of fault currents, autoreclosing sequence, etc [8]. Fig. 4 shows how DFR recordings can be correlated with corresponding switching sequence of CBs.

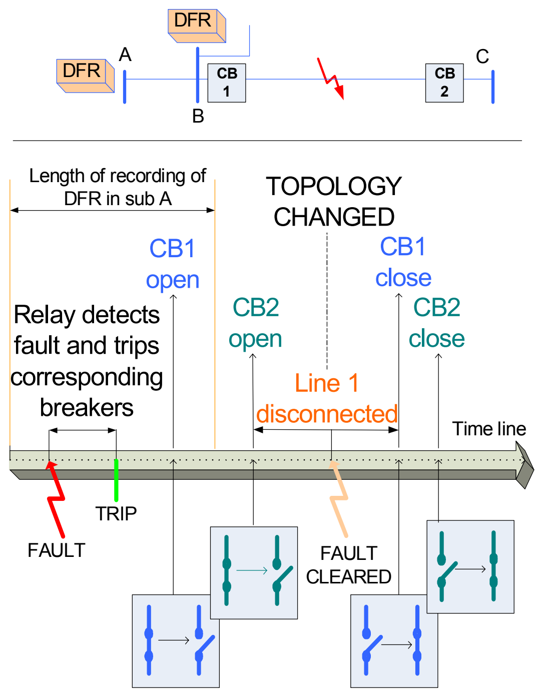

Figure 4. Correlating power system events

2) *Time as a Reference for Signal Waveform Sampling:* In order to perform the FL calculations, samples of current and voltage waveforms need to be taken. Samples of input signal waveforms are taken by performing analog-to-digital (A/D) conversion at the time the measurement is taken. As shown in Fig. 5, samples are taken by sample and hold (S/H) circuit, where clock used for initiating S/H circuit can be applied either synchronously for all measured channels or sequentially as each channel is sampled (scanning) [8].

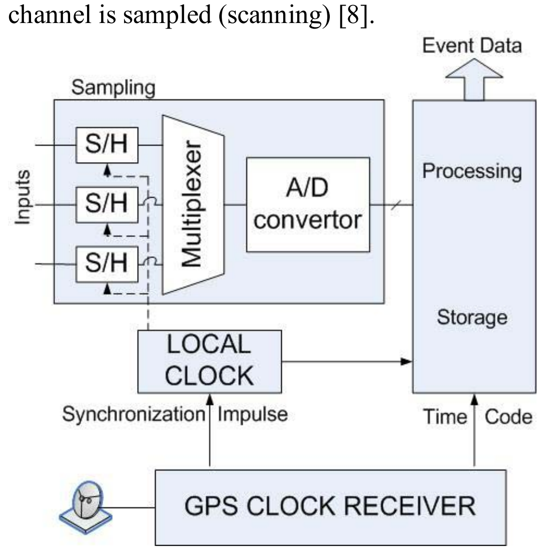

Figure 5. Synchronized sampling

Recovery of the signal information from data samples depends heavily on whether the waveforms were sampled synchronously or scanned. Although still not so commonly implemented, synchronized sampling is more desirable from stand point of FL algorithms. Knowing phase difference between the signals during fault analysis may be critical, which can be easily obtained from the signals that are synchronously sampled [9]. In order to achieve this, a reference clock from Global Positioning System (GPS) of satellites is used in practice.

3) *Time as a Reference for Waveform Representation:* Currents and voltages may be measured to determine time-domain representation or to reconstruct a phasor [8]. During fault event current and voltage recordings experience transient behavior as they change status from pre-fault to post-fault steady state. Fig. 6 illustrates the different states that current waveforms of faulted line can experience. Depending on the available input data, different FL algorithms are applicable. Phasor-based algorithms are standard approaches for FL.

There are some non-traditional ways that could be used to improve temporal considerations. A lightning detection system uses GPS for time synchronizing, which makes it possible to use NLDN data to improve analysis of fault clearing sequence through the improved timing reference.

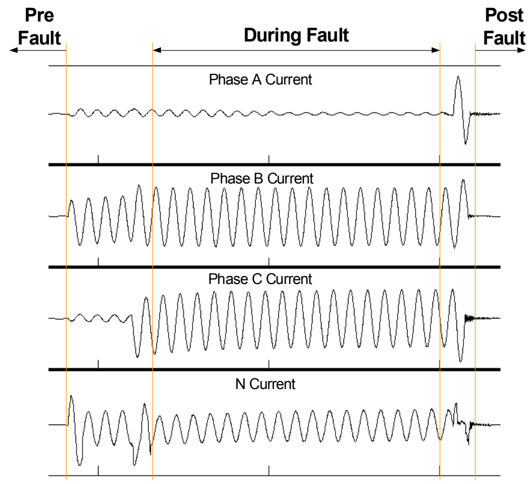

Figure 6. Historical measurements

5. Optimized Fault Location

The spatial and temporal considerations in the previous sections indicate that there is no universal FL algorithm suitable for all situations. In order to take into account both spatial and temporal aspects different data sources should be utilized. Architecture of a software module developed to do this is shown on Fig. 7. The FL module updates power system switching status using retrieved data, processes new event files, decides the most suitable FL algorithm and executes it. The proposed solution automates

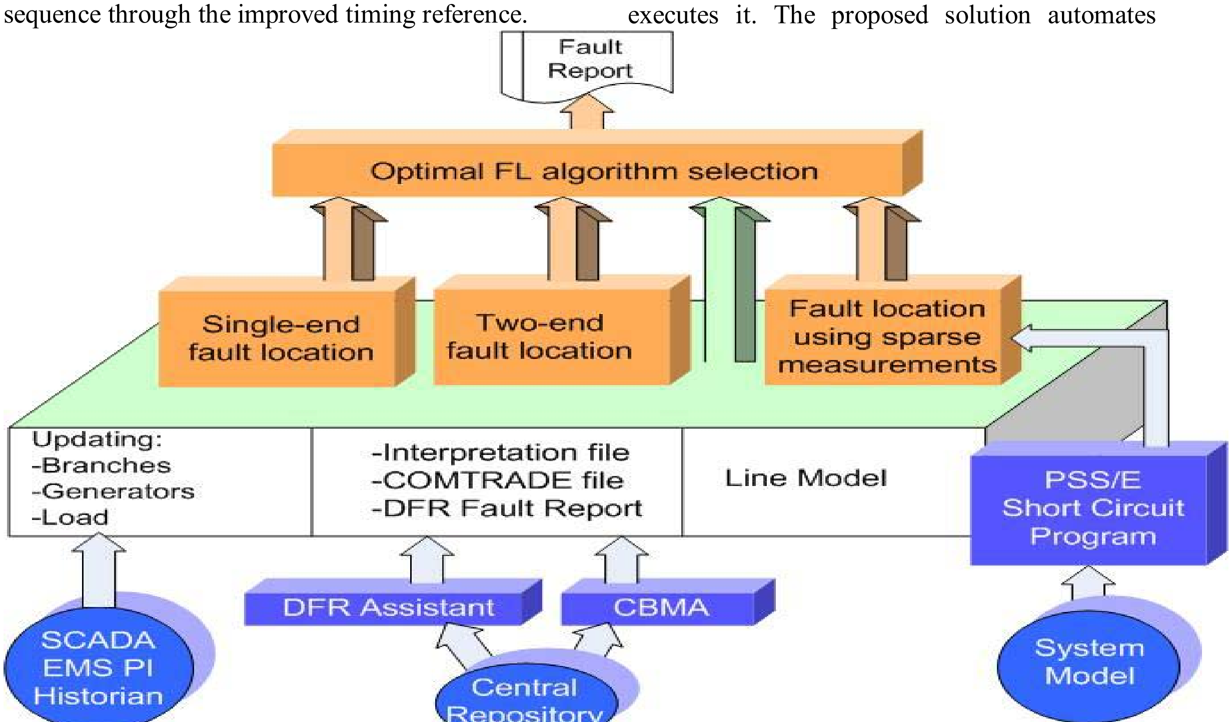

Figure 7. Architecture of optimized fault location module

the data retrieval process, as well as FL analysis. This enables utility staff located in different offices to access collected data automatically. At the same time each utility user can get results fast as soon as automatic fault analysis is done.

Proposed solution is capable of using different FL algorithms but it has to use various external tools in order to achieve the optimal performance of each algorithm. Those tools will be discussed in the next section and their role in meeting the spatial and temporal requirements will be reviewed.

5.1. External Tools

In existing fault analysis procedure the fault recordings are retrieved manually, which additionally increases time needed for fault analysis because data from different locations should be obtained. In order to solve this problem architecture that uses central repository for data storage is needed. In [10] author proposes solution in which recordings from different IEDs are automatically transferred to central repository. It is assumed that such repository of Digital Fault Recorder (DFR) and Circuit Breaker Monitoring (CBM) files is available.

External tools used by proposed optimized FL module consist of:

a) SCADA PI Historian, which is used for obtaining the latest load, branch and generator data in order to update system model status before FL calculation starts.

b) DFR Assistant [11], which provides new event recordings from central repository in COMTRADE format [12] and preliminary fault report. Report describes behavior of protection equipment and recognizes type of fault, which is used by other algorithms as input file.

c) PSS/E Short Circuit program [13], which is accessed during fault calculation by some algorithms in order to run power flow and short circuit analysis automatically.

d) System model in PSS/E format, which is updated before any calculation starts in order to reflect system state prior to a fault. This is very important feature especially if topological changes take place in the mean time.

e) Circuit breaker monitoring (CBM) application [14], which provides recordings of CB operation in a central repository in COMTRADE format [12] and an expert system report about CB switching event. Report describes CB behavior during the executed operation, final switching status of the equipment and provides precise timings of event, which can be used to align group of operations that belong to the same event. This data is utilized to track the CB switching sequences and make conclusions about their performance and final outcome [15].

5.2. Spatial and Temporal Characteristics

In real applications spatial and temporal characteristics are deeply intertwined and it becomes hard to illustrate them separately. In the rest of the section the spatial and temporal considerations are shown by describing behavior of the proposed solution in presence of fault event.

Once a fault event recording from DFR Assistant is available FL analysis module is automatically triggered. First step in the analysis is to determine the starting time of fault event. This is done by correlating timings obtained from DFR and CBM recordings. Next step is to evaluate spatial characteristics of the fault case. Using SCADA PI Historian power system model in the PSS/E format is updated to match the power system status at the time the fault occurred. Since CBs status represents the topology change (connectivity of various components in power system), switching sequence of CBs is also analyzed. Since CBM tracks the behavior of CBs with more detail than what is shown by the statuses available from SCADA, CBM results are utilized for executing this step. Once system connectivity is known the case of the placement of physical measurements is determined. According to the case of the placement, possible FL algorithms are reduced to a smaller group. FL algorithms that are used as a possible selection include:

a) Synchronized sampling two-ended FL [16]
b) Unsynchronized sampling two-end FL [17]
c) System-wide sparse measurement FL [18]
d) Phasor-based single ended FL [3]
e) Single ended FL using symmetrical components [4]

Depending whether available samples are synchronized, whether fault type is known etc. optimal fault location algorithm is chosen automatically.

5.3. Case Studies

The FL software prototype was developed and set-up for specific electric power system data. This system has thirty-three substations equipped with digital fault recorders (DFRs). An automated system capable of processing, analyzing and archiving DFR data is installed. Although it was not possible to automatically retrieve data, description of 15 real-life cases was manually furnished by utility. Run time of complete FL analysis consisting of processing fault event recordings and other input files, correlating recordings that belong to same event, and executing applicable FL algorithm lasts 5 to 10 seconds. Only in the case of sparse measurement algorithm the analysis lasts up to several minutes. Processing time of this algorithm depends on the number of input files. In the case when two recordings are available it takes about 3 minutes for calculation. This processing time is mostly influenced by the need to access external application, namely PSS/E Short Circuit program, several times during the processing.

During testing using real-life cases, tests were done without EMS PI Historian and CBMA input, because this input for available fault cases is not furnished by the participating utility. Results obtained from testing using two real-life cases are presented in the rest of this section.

Topology of the faulted area in case1 is shown on Fig. 8. Event data related to this case are:

Event Date/Time: 7-19-2000, 05:15:34
Event Type: Phase A-B fault
Fault location: Ckt. 84, in Warren substation
Triggered DFRs: D and E substations

Two DFRs were triggered by this event and both of them were distant to the fault. DFR Assistant, used for recognizing faulted section, wrongly marked circuit 86 as the affected one. If additional data from SCADA and CBM were available correct faulted line would be recognized. Two tests were run. One comparison of results is done when correct circuit 84 is marked as affected and the other comparison is done when wrong circuit 86 is marked as affected. Each case is run at least five times and error is calculated. After running same case several times average error is calculated for each group of test settings.

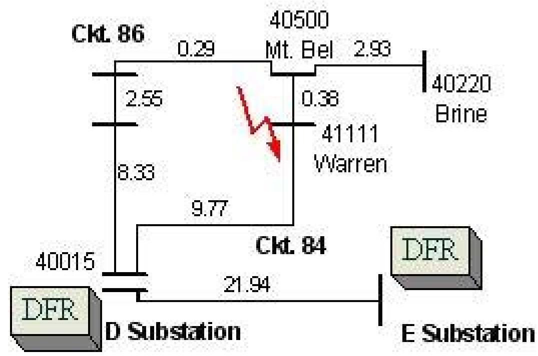

Figure 8. Faulted area in case1

Procedure for optimal algorithm selection properly recognized that sparse measurement algorithm is the only one applicable in this situation. In the case when correct circuit is assumed as the input parameter, average error is very small. If we change one parameter of the genetic algorithm, same average values of errors may be computed. In the case when circuit 86 is chosen as being affected, individual results oscillate quite a bit. The error of individual result is big. But if we average the errors, they cancel each other and the average error becomes smaller as seen from Table 1.

Table 1: Comparison of results

CASE 1	Err (miles)
Ckt 84 as faulted, All V and I matched	
out_iter 2, n_parent 30, resist 0.8, matching method Phase, matched values Mag	0.0144
out_iter 1, n_parent 30, resist 0.8, matching method Phase, matched values Mag	0.0144
Ckt 86 as faulted, All I matched	
out_iter 1, n_parent 30, resist 0.8, matching method Seq, matched values Phasor	0.75 Averaging 5 results
	0.58 Averaging 10 results

Topology of faulted area in case 2 is shown on Fig. 9. Event data related to this case are:

Event Date/Time: 08-23-2000 10:05:50
Event Type: Phase B-GND fault
Fault location: Ckt. 03, 2.5 miles from substation A
Triggered DFRs: A, B and C substation

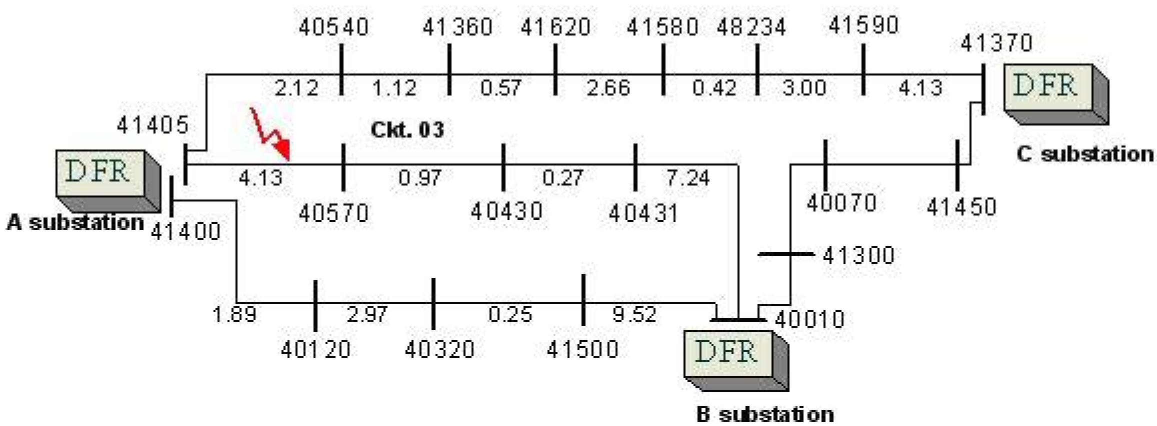

Figure 9. Faulted area in case 2

Table 2 demonstrates results from test case 2. The best results are achieved when faulted section of the faulted circuit is narrowed down. This result did not change much with the change in fault resistance value. In the cases when only faulted circuit was known adding additional event file from the second DFR and fault resistance parameter had influence on the test results. This again confirms importance of narrowing down the faulted area using SCADA and CBM data.

Table 2: Comparison of results

CASE 2 Ckt 03 as faulted	Err (miles)
Ckt 03 as faulted, Recording from sub. A only	
All I, none V matched, out_iter 1, n_parent 30, resist 0.4, matching method Phase, matched values Mag	0.328
All I and V matched, out_iter 1, n_parent 30, resist 0.8, matching method Phase, matched values Mag	0.728
Ckt 03 as faulted, Recording from sub. A &B	
All I, none V matched, out_iter 1, n_parent 30, resist 0.4, matching method Phase, matched values Mag	0.838
All I, none V matched, out_iter 1, n_parent 30, resist 0.8, matching method Phase, matched values Mag	0.302
Section 41405-40570 marked as faulted Recording from sub. A only	
All I, none V matched, out_iter 1, n_parent 30, resist 0.4, matching method Phase, matched values Mag	0.11
All I and V matched, out_iter 1, n_parent 30, resist 0.8, matching method Phase, matched values Mag	0.11

Specific electric power system that was used for testing contains taps on many lines in the system. As a consequence, only sparse measurement algorithm was applicable in almost all the cases. None of the existing FL algorithms currently used in utilities is able to deal with presence of taps on faulted line without degradation of accuracy. As may be seen from the reported test results, our algorithm was capable of determining fault location even in this difficult case with reasonable accuracy.

6. Conclusions

The following is a summary of the improvements in FL analysis based on spatial and temporal considerations. Correlating power system events in time and space domain helps:

- Narrow down possible FL area with high accuracy because multiple data sources can be used
- Select recordings involved in the same event
- Identify historical measurements (pre fault, during fault and post fault) of single recording
- Differentiate between synchronized and unsynchronized recordings involved in the same event
- Reveal frequency of fault events in the space domain that may be used for estimating condition of equipment at particular locations

The above improvements contribute to the selection of an optimal algorithm, which in turn provides following benefits:

- System operators: New approach speeds up decision-making process by the operator hence speeds up the restoration of the system.

• Protection engineers: New approach is performed automatically and frees the time of protection engineers to concentrate on complicated cases that require their further attention and involvement.

• Maintenance staff: New approach enables them to immediately take some actions, instead of waiting for instructions from other groups, leading to more timely action and as a consequence faster system restoration.

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