Study Committee B5 Colloquium
October 19-24, 2009
Jeju Island, Korea

319

Fault Location Using Sparse Wide Area Measurements

KEZUNOVIC, M., DUTTA, P. (Texas A & M University, USA)

Summary

Transmission line fault location allows quick repair of the damage caused by the fault and timely restoration of the line affected by the fault. Accuracy of the fault location is quite important since it affects repair crew's ability to physically locate the damage part quickly. Typically, the desirable accuracy is to be able to locate a fault within a span of the transmission line towers. This paper presents a new fault location scheme which uses synchronized phasor measurements from different substations sparsely located near the region where the fault has occurred. When fault occurs different Intelligent Electronic Devices (IEDs) such as Phasor Measurement Units (PMUs) and Digital Fault Recorders (DFRs) connected to Global Positioning System (GPS) receivers and installed in some of the substations in the region will be automatically triggered by the change in monitored signals and will record corresponding current, voltage and status signals. Apart from these sparse measurements, the proposed method also uses SCADA PI Historian data which is utilized for tuning the power system model data with the pre-fault condition in real time information. The paper presents how the technique is implemented and shows test results using actual power system model as well as actual field data from a utility company that supported demonstration of the technique. The results are quite encouraging since the sparse measurement problem for such unique transmission line configurations does not allow any other known techniques to produce accurate and reliable results while the proposed technique produces satisfactory results.

Keywords

Fault Location, Wide area measurement, Digital Fault Recorders, SCADA PI Historian data.

1. Introduction and Background

Transmission lines occasionally suffer from faults which are generally caused by several random and unpredictable events. Protective device (relay) senses these faults and isolates the faulty line as soon as possible. Distance relays typically used for transmission line protection contain algorithms that give some idea about the fault location, but they may over-reach or under-reach due to several unknown parameters, such as pre-fault loading, fault resistance, remote infeed etc. Particularly difficult case for relay-based fault location algorithms is an application where tapped lines are used, which does not allow direct measurement of voltage or current at all the line ends However, to restore service, an accurate location of the fault is highly desirable in all circumstances to help the maintenance crew find and repair the faulted line as soon as possible.

Transmission line fault location approaches can be broadly classified into two categories [1] such as Phasor based and Time-domain based methods. Phasor based methods using fundamental frequency component of the signal and lumped parameter model of the line can be subdivided into another two broad classes depending upon the availability of recorded data: single-end methods where data from only one terminal of the transmission line is available and double-end methods where data from both (or multiple) ends of the transmission line can be used. Double ended methods can use synchronized or unsynchronized phasor measurements, as well as synchronized sample Measurements. Time-domain based methods use transient components of the signal and distributed parameter model of the line. Some advanced methods as Traveling wave-based fault location also exists in the literature. Each of the techniques requires very specific measurements from one or both ends of the line to produce results with desired accuracy. In some applications, the measurements from both ends of the transmission line are not available and single-ended algorithms cannot perform well due to the unique configuration of the transmission lines (multi-terminal lines, taps, etc). In such cases some unconventional techniques based on wide area measurements may have to be used.

Typical power system may contain hundreds of transmission lines. Installation of recording devices at the ends of each transmission line is very expensive and it is not in practice today. Installing DFRs in critical substations is a common practice. Although protective relays exist on every transmission line, most of them may still be electromechanical and they do not have capability to record measurements. Sometimes, all the DFRs installed may not be triggered by a fault. As a result, in some cases it may happen that there are no recordings at all available at line ends close to a fault. The proposed system-wide sparse measurement based fault location method can be applied in such Instances. This fault location scheme uses phasor measurements from different substations located in the region where the fault has occurred. The measurements may be sparse, i.e. they may come from only some of so many transmission line ends (substations) in the region. This method requires synchronization of the measurements, which may be obtained by using either Phasor Measurement Units or Digital Fault Recorders connected to Global Positioning System (GPS) receivers. Besides the sparse measurements, the technique also uses short circuit program, which is initialized utilizing power system model data and tuned with SCADA PI Historian data associated with the time of the fault occurrence. The technique compares measured data with data generated by the short circuit simulation of possible fault locations. The measured and simulated data from the locations where measurements are taken is compared while the location of the fault is changed in the short circuit program. This process is repeated automatically until the measured and simulated values have minimal difference, which indicates that the fault location used in the short circuit program is the actual one in the field. The criteria for the minimal difference are based on a global optimization technique that uses Genetic Algorithm to perform the global optimization.

2. Fault Location Scheme

The proposed approach uses the concept of waveform matching [2] between the current and voltage waveforms recorded in a substation and simulated ones using a commercial short circuit program tool (PSS/E™ 30 [3]) for a fault event. The waveforms can be matched using phasors or transients. In our present approach field-recorded waveforms are used to calculate phasors and they are in turn matched with the phasors obtained using short circuit study. The matching degree can be formulated as [2]:

$$f_c(x,R_f)=\sum_{k=1}^{Nv} r_{kv}\left|V_{ks}-V_{kr}\right|+\sum_{k=1}^{Ni} r_{ki}\left|I_{ks}-I_{kr}\right| \tag{1}$$

Where,

$f_c(x,R_f)$ -the cost function used for phasors for matching

x, R_f -the fault location and fault resistance

r_{kv}, r_{ki} -weights for the errors of the voltages and currents respectively

V_{ks}, V_{kr} -simulated and recorded during-fault voltages respectively

I_{ks}, I_{kr} -simulated and recorded during-fault currents respectively

N_s, N_r -total number of voltage and current phasors to be matched respectively

k -the index of voltage or current phasors

Theoretically the cost function equals to zero when the simulated and recorded waveforms match completely. In practical solution, the cost function is not zero and should be minimized. To obtain good waveform matching the fault search range should be extensive. All possible faulted branches and fault resistance should be included in the search range which makes the search two-dimensional and exhaustive. For a large system, multiple searches should be run in parallel which can be achieved using population based optimization methods such as Genetic Algorithm (GA) [4].

GA is a population based stochastic search technique which was inspired by the principles of natural genetics and evolution. The main principle of GA is based on the survival of the fittest. GA is initialized using a randomly generated population of chromosomes (consisting of unique gene structure) within a feasible search space (determined by the problem to be solved). The members of this initial population are each evaluated for their *fitness* or goodness in solving the problem. This population evolves over successive generations with the help of three operators –natural selection, crossover and mutation. Basically, in GA the objective is to maximize the fitness value. Therefore it can be applied to a maximization problem. To apply GA, equation (1) can be converted into a maximization problem by defining the fitness function as:

$$f_f(x, R_f) = -f_c(x, R_f) \quad (2)$$

3. Implementation of the Fault Location Scheme

The architecture of the fault location scheme is shown in Figure 1. The input data include the DFR data, interpretation file for DFR data, system model file in the PSS/E format and the PI Historian data matched to the model. The detailed description of this data requirement will be discussed in subsequent section. The operation procedure of the software is briefly described, with detailed illustration presented in succeeding sections. First a discussion of the required data for this implementation is given which is followed by the handling of the data to extract information and utilize such information to obtain fault location.

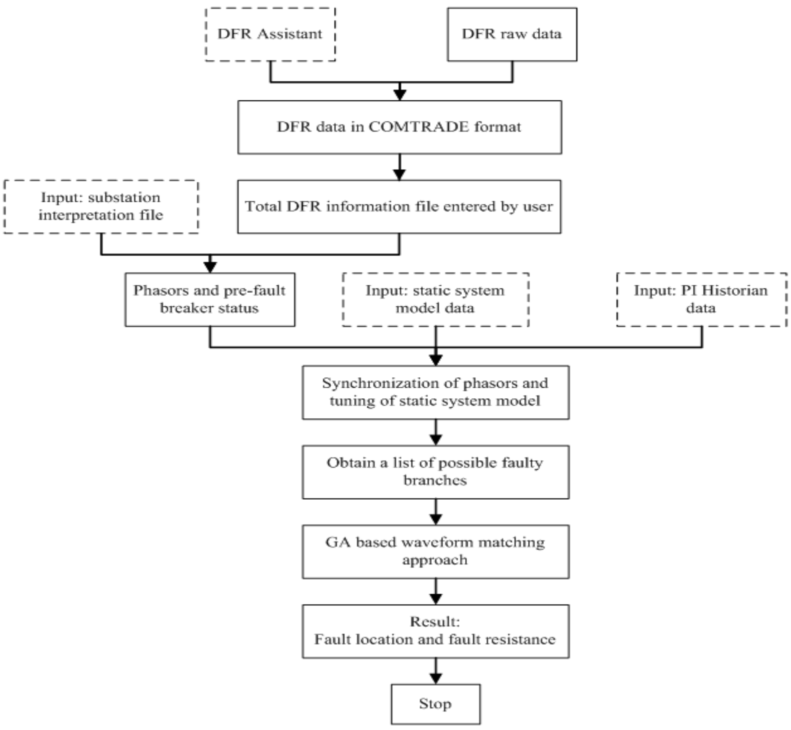

Figure 1 Architecture of the Fault Location Scheme

3.1 Data Requirements

Several commercial packages are used to implement this solution. The static power system is modeled using PSS/E™ 30 [3]. To tune the power grid with pre-fault data, SCADA PI-Historian data is used [5].The required data for this approach can be broadly classified into

System level data: these include power system model data (in saved case format *.sav) and data reflecting real time changes in power system (PI Historian data). The power flow input data (in *.raw format) contains power flow system specification data for the establishment of a static system model used by PSS/E to run the power flow analysis. Sequence data (*.seq) contains the negative and zero sequence impedance data needed for short circuit study. SCADA PI Historian data contains the latest load, branch and generator data to tune the static system data with the actual pre and post fault conditions.

Field data: these include event data recorded by different IEDs after occurrence of any abnormality. The field recorded data (DFR data) should follow the COMTRADE format. Using this format, the measured data (*.dat), configuration (*.cfg) should be described. The DFR data contains analog and digital sample values for all input channels for a specific substation. The configuration data contains information for interpreting the allocation of measured data to the equipment in substation. The DFR recorded data supplied in native DFR format are converted to COMTRADE file using DFR Assistant software [6] which can generate an analysis report (containing the type of fault and a possible faulted line) in addition to generating the COMTRADE files.

In addition we need substation interpretation data for each substation correlating between the nomenclature used in DFR files and those used in PSS/E file. The interpretation files should be modified as frequently as needed to reflect the DFR configuration or system model changes.

3.2 Data Handling

The event data obtained from DFRs should be pre-processed before using in the applications. This section will illustrate how the data captured by DFRs are converted into information and integrated with system level data to be used in the fault location application.

Extraction of phasors

Once the disturbance events are obtained from the IEDs, two processing steps are taken to obtain phasors from the samples of recorded analog signals :(1) Removal of high-frequency noise by low-pass filtering and (2) Use of an improved Fourier algorithm to effectively remove decaying dc-offset component and obtain the pre-fault and during-fault phasors of voltages and currents [7].The pre-fault phasor can be calculated using first cycle of the recorded waveform. The during-fault phasor can be calculated using any fault cycle following the fault inception and prior to fault clearance. The fault inception moment is determined from waveforms recorded by DFR. It is possible to select different fault cycle to calculate the during-fault phasors from the different DFR recordings. This may introduce fault location error, especially for the arcing faults during which the fault resistance is changing. Under this situation, selecting different fault cycles means experiencing different impacts of fault resistance. An alternative is that the user checks the waveforms manually and specifies the same matching fault cycles across all recordings.

Synchronization of phasors

The PSS/E load flow study based on the modified system model (the real-time power system model obtained from SCADA PI Historian) is carried out to obtain the pre-fault phasors and during fault phasors. For a typical fault case, several DFRs may be triggered and the phasors calculated from the recorded waveforms may lack synchronism which will introduce phase angle difference among phasors. Thus time synchronization of the phasors obtained from different DFRs is necessary. The phasors calculated from each DFR recording are synchronized by rotating them in reference to the phasors obtained by the load flow study assuming the angle difference between the pre- and during-fault phasor, for the corresponding recorded current or voltage, is fixed. This way, all recorded pre- and post-fault phasors are synchronized using the same reference.

Tuning the power system model with real-time power system conditions

The saved case model from PSS/E may not reflect prevailing operating conditions of the system when fault occurs. To obtain simulated phasors corresponding to the time when fault occurred, the static system model should be tuned with real-time power system conditions. This tuning procedure may consist of updating power grid topology (switching status) and then updating generation and load data near the substations of interest. This is achieved by utilizing information from both DFR recordings and SCADA PI Historian data. The updated model is saved in a new saved case data (*.sav) which is used for further simulation.

Updating power grid topology: Topology describes connectivity of various components in a power system. In our case, the topology (i.e., connectivity between different buses), line status (whether the line is in service or not), line impedances and susceptances are extracted from the static system model provided in the simulation tool. The topology update is performed using information of the pre-fault breaker status and the pre-fault current magnitudes of the monitored branches derived from the DFR data. It is assumed that a zero magnitude (or smaller than 0.01 p.u.) of the current through a monitored branch indicates an out-of service status of the branch. If both the current and the breaker status of a branch are available, the current measurement will be used instead of the breaker status for topology update. This is based on the observation that the monitoring of currents is usually more reliable than the monitoring of the breaker status because the measurement contacts of the breaker may be unreliable or may not be monitored. In this way the service status (i.e., in or out of service status in the static model saved in the PSS/E file) of the branches will be updated.

Updating generation and load data: In a typical power system, operator is able to track changes in real time using Supervisory Control and Data Acquisition (SCADA) system. Through SCADA database, low sampling rate recording typically used to capture short term and long term disturbances is available. Captured data is typically scanned every few seconds and it is usually phasor or RMS data, not sampled data. The PI Historian data provided by the utility is load, branch and generator data scan (typically 10 sec interval) in a period before and after fault for each substation where DFRs triggered. These data were used to update the system.

Obtaining fault location using GA

The fault location solution using GA is performed in the following steps. First, the initial population is chosen randomly for this two dimensional (i.e. with two variables x, R_f) optimization problem. Fault location variable can be chosen from a range of zero to the length of the possible faulty line and fault resistance variable can be selected from typical possible fault resistance values. Second, short circuit studies are carried out using PSS/E and the fitness is evaluated for each of the possible fault locations. Thirdly, by using three GA operators (selection, crossover and mutation) fault posing for next iteration is obtained. By iteratively posing faults, running short circuit simulations, evaluating the fitness value, updating the fault location and resistance, the GA based search engine guides the search process for a globally optimal solution.

4. Evaluation of the Fault Location Scheme

The software is implemented using Java programming language. To interact between PSS/E activities and Java programming language, IPLAN [8] language (which is a part of PSS/E package) is used. The IPLAN language is able to modify the system topology, control the load flow and short circuit studies, and control the reporting of the results of the PSS/E activities. Like other programming languages, IPLAN language can be used to write programs, by which one can automatically control the PSS/E activities, as well as read and save the results in a disk file. The parameters used for GA are: population size = 30, crossover probability = 0.8, mutation probability = 0.05, coding binary string length for fault location = 8 and coding binary string length for fault resistance = 8. Fault resistance ranges from 0 to 0.4 p.u.

We have tested the fault location scheme for one test case provided by the utility. Two subsequent (in 5 ms gap) phase to ground faults occurred in one circuit between substation A and substation B. PI Historian data (extracted in *.xls format) is provided for both of the substations for 10 sec time interval for a duration from pre-fault to post-fault. DFR triggered for only substation A for both of the faults. For the 1st fault DFR-resident algorithm could estimate fault location and for the 2nd fault DFR-resident algorithm could not. The fault location scheme estimated the location accurately for both of the cases.

5. Conclusion

A system-wide sparse measurement based fault location approach using genetic algorithm is proposed. This method locates fault on a transmission line using recordings from different IEDs (presently DFRs used only) triggered by a fault occurrence and makes use of SCADA data to update the power system model prior to the occurrence of the fault which makes the approach robust and accurate as well. The main advantages of this approach are:

- It is possible to calculate fault location accurately for the cases where other relay- or DFR-resident algorithms may fail due to the lack of measurements close to the fault
- The fault location is robust since the same measurements may be obtained by multiple IEDs, which allows redundancy that can be explored to account for bad measurements
- The computation may be totally automated allowing obtaining rather quick answer about the fault location even if performing the match may involve rather complex steps

Bibliography

[1] M. Kezunovic, B. Perunicic, "Fault Location", Wiley Encyclopedia of Electrical and Electronics Terminology , Vol.7, pp. 276-285, John Wiley 1999.

[2] M. Kezunovic, Y. Liao, "Fault Location Estimation Based on Matching the Simulated and Recorded Waveforms Using Genetic Algorithms", Development in Power System Protection, Amsterdam, The Netherlands, April 2001.

[3] PSS™E Load Flow ©Siemens Power Transmission & Distribution, Inc., PTI, Schenectady, NY, USA

[4] Goldberg D E, 1989, "Genetic Algorithms in Search, Optimization and Machine Learning", Addison Wesley, Reading, MA.

[5] http://techsupport.osisoft.com/

[6] Test Laboratories International, Inc.: "DFR Assistant - Software for Automated Analysis and Archival of DFR records with Integrated Fault Location Calculation" [Online]. Available: http://www.tliinc.com.

[7] Yong Guo, M. Kezunovic, Deshu Chen, "Simplified algorithms for removal of the effect of exponentially decaying dc-offset on the Fourier algorithm", IEEE Transaction on Power Delivery, Vol.18, No.3, pp. 711-717, July 2003.

[8] IPLAN Program Manual, PSS™E 31.0, Release 17.