Smart Fault Location for Smart Grids

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***Abstract*—Fault location is an important application among intelligent monitoring and outage management tasks used for realization of self healing networks, one of the most attractive features of smart grids. The data gathered from various intelligent electronic devices (IEDs) installed throughout the power system could be utilized for smart approaches to locating faults in both transmission and distribution systems. This paper discusses issues associated with improving accuracy of fault location methods in smart grids using an abundance of IED data. Two examples of how the gathered data from different IEDs is used to improve fault location accuracy in transmission and distribution systems are discussed in detail.**

***Index Terms*—Data integration, distribution faults, fault location, intelligent electronic devices, smart grid, transmission faults.**

I. Introduction

According to the U.S. Department of Energy's modern grid initiative [1], a smart grid integrates advanced sensing technologies, control methods, and integrated communications into the electricity grid. In this paper we will be discussing smart fault location schemes for both transmission and distribution systems developed taking advantage of available modern technologies used for data recording, information extraction, and integration as well as intelligent approaches to selecting fault location algorithms (for both transmission and distribution systems).

Traditionally, in a substation, remote terminal units (RTUs) acquire analog and digital measurements (bus voltages, branch flows, frequency, breaker status, transformer tap position, etc.), collectively called supervisory control and data acquisition (SCADA) measurements, which are sent to the energy management systems (EMS) in every two to ten seconds. With the rapid advancement of technology, other intelligent electronic devices (IEDs) besides RTUs are now widely used in substations. These computer-based devices can record and store a huge amount of data (both operational and nonoperational) with a periodicity depending upon the intended purpose of the device. Such devices are typically characterized with sampling rates much higher than what is found in RTUs and with much higher accuracy. Thus, a great amount of data is recorded, which if used properly could be of great benefit for the EMS operators when trying to predict, monitor, and postmortem analyze power system events.

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Fault location has always served an important role in facilitating quick repair and restoration of faulted transmission lines or distribution feeders. With the deployments of smart grids, fault location methods can benefit from the abundance of data provided by smart grid IEDs.

While many fault location algorithms have been introduced over the years, it became apparent that matching the algorithms to the data in a smart way needs to be explored since it may be the key to improving the accuracy, robustness, and speed of the process. It has been recognized for some time that some algorithms provide best results for certain network configurations or network conditions but how an optimal solution could be selected to produce best results for varying network and data conditions was not explored. It is a well known problem that with current level of penetration of IEDs it is quite possible to have multiple IEDs reporting fault location results for the same event, and yet the results may be quite different. This raises a need for an optimal solution that is able to determine the best result using the knowledge about network parameters, current topology of the network and type of data and algorithms that may be used to calculate the fault location. Such a solution will be referred as "Smart Fault Location" (SFL) in this paper.

The proposed SFL methods are demonstrated in this paper through examples of solution implementation at both the transmission and distribution levels. In each case the emphasis is on a smart way of utilizing fault location algorithms to match power system conditions and availability of IED data. With the deployment of smart grid IEDs for monitoring, control, and protection, supported by high-speed broadband communications, the optimal fault location solutions will become the norm in the future grids, both at the transmission and distribution levels. The ability to produce fault location results efficiently, reliably, and with high level of confidence will be the smart grid requirement.

This paper explains how abundance of IED data could be used to improve accuracy, robustness, and speed of the fault location process. In Section II, data integration for smart fault location is explained. In Sections III and IV, examples of fault location solutions for transmission lines and distribution systems are discussed. Finally, Section V provides conclusions.

II. Background

A. Transmission Line Fault Location

Transmission lines may generally be exposed to several types of faults which are generally caused by random and unpredictable events such as lighting, short circuits, overloading, equipment failure, aging, animal/tree contact with the line, human intended or unintended actions, lack of maintenance, etc. Protective relays, placed at both ends of a transmission line, sense the fault immediately and isolate the faulted line by opening the associated circuit breakers. Faults may be temporary (fault is cleared after breaker reclosing) or permanent (fault is not cleared even after several reclosing attempts). To restore service after permanent fault, an accurate location of the fault is highly desirable to help the maintenance crew find and repair the faulted line section as soon as possible. Though distance relays are the fast and reliable ways to locate the faulted area, they cannot meet the need of accurate fault location under all circumstances.

Transmission line faults may be calculated either using power frequency components of voltage and current or higher frequency transients generated by the fault [2]. Phasor-based methods use fundamental frequency component of the signal and lumped parameter model of the line while time-domain-based methods use transient components of the signal and distributed parameter model of the line. Both of these methods can be subdivided into another two broad classes within each category depending upon the availability of recorded data: single-end methods [3]–[8] where data from only one terminal of the transmission line is available and double-end methods [9]–[13] 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 or unsynchronized samples.

Impedance focused methods, either phasor or time domain based, generally estimate the distance to fault as a function of total line impedance (considering transmission line is homogeneous) using voltage and current measurements from single or multiple ends. Single-ended, impedance-based fault location methods are simple, fast, and only require local measurement data. The simplest approach is a reactance-based method which measures the apparent impedance ignoring fault resistance and effect of load current. This method may create large errors introduced by remote-end current in-feed, load impedance, power transmission angle, and angle difference between line and source impedances. Algorithms reported in [3]–[6] extend simple reactance method by making assumptions to eliminate effect of remote infeed and fault resistance. Algorithms reported in [7], [8] estimate fault location for parallel transmission lines using data from one end. Double-end methods work on equalizing voltage of fault point from both ends of the line and fundamentally are more accurate than single-end methods [9]. The calculations may be based on unsynchronized measurements from two ends [9]–[15]. References [10]–[12] use phasors and lumped parameter line model to compute location of the fault. Reference [13] uses distributed parameter model of the line implementing the same approach as described in [10]. Where all double-end methods are essentially accurate they need extra communication for data synchronization. This can be overcome by fully utilizing the advantages of modern digital technologies and signal processing to estimate the synchronizing difference between both ends using nonlinear mathematical optimization [14], [15]. Synchronized measurements were utilized in [16]–[18] making them more accurate and can be employed with current data capturing capability of IEDs.

Traveling wave based fault location approaches [19]–[21] use transient signals generated by the fault. They are based on the correlation between the forward and backward traveling waves along a line or direct detection of the arrival time of the waves at terminals.

Each of the techniques requires very specific measurements from one or both (multiple) ends of the line to produce results with desired accuracy. However, availability of data may be a challenging issue. Digital fault recorders (DFRs) and other IEDs are generally placed in critical substations and therefore in some cases it is not possible to get recorded measurements from both or any end of the faulted line if this source of data is used. Although protective relays exist on every transmission line, some of them may still be electromechanical and they do not have capability to record measurements. Sometimes, not all the DFRs installed may be triggered by a fault. Therefore, neither double- nor single-end methods can always be applied. In such cases some unconventional techniques based on wide area measurements may have to be used [22], [23].

A smart scheme to locate transmission line faults is proposed to deal with the selection of an optimal fault location method. It is capable of using different fault location algorithm depending on the availability and location of recorded data as well as network topology and circumstances surrounding faults.

B. *Distribution Feeder Fault Location*

Fault location in distribution systems, is an important function for outage management and service restoration directly impacting feeder reliability and quality of the electricity supply for the customer. Improving customer average interruption duration index (CAIDI) and system average interruption duration index (SAIDI) is possible by exploiting a suitable fault location method. Therefore, one of the main topics of the Department of Energy (DoE) Grid 2030 vision [1], improving reliability indices of the network, could be realized by improving fault location methods.

Methods proposed for fault location on transmission lines are not easily applicable to distribution systems. A suitable fault location method has to consider the limitation of the host processing platforms and requirements of the algorithm itself. Heterogeneity of the lines, presence of laterals, load taps, and comparatively a lower degree of instrumentation in distribution systems are among the limitations. Based on the type of the data that the fault location techniques use to find the location of the fault they may be categorized as follows:

- apparent impedance measurement;
- direct three-phase circuit analysis;
- superimposed components;
- traveling waves;
- power quality monitoring data;
- artificial intelligence.

In [24]–[26], the apparent impedance, defined as the ratio of selected voltage to selected current based on the fault type and faulted phases, is utilized for locating faults on distribution systems. This category of methods has been reviewed in [27]. The common drawback is that the fault location results in multiple estimations due to their reliance solely on measured voltage and current signals at the substation. In [28], data collected from fault indicators along the network, which determine the direction of the fault, are utilized to solve the problem of multiple fault location estimation for a single fault. Installation of fault indicators at the beginning of each tap increases the implementation cost and may not be a preferred solution.

In [29] and [30], a method based on direct circuit analysis, was suggested. Although it is suitable for unbalanced distribution systems, it does not yield unique results for fault location.

In [31] and [32], a method using superimposed components of the voltages and currents is proposed. In this method, an assumed fault point is varied systematically until the actual fault point is found. Fault is located based on the fact that the amount of the superimposed current in healthy lines should be at a minimum. This method also suffers from multiple fault location estimations for single fault.

Methods based on intelligent systems such as neural networks and fuzzy logic as powerful tools for classification purposes are proposed in [33], [34]. In [33], faulted area is detected by training an Adaptive Neuro-Fuzzy Inference System (ANFIS) net with extracted features based on knowledge about protective device settings. In [34] using the Learning Algorithm for Multivariable Data Analysis (LAMDA) classification technique, multiple fault location estimation solution is obviated. This method requires a large number of training data and a retraining subsequent to a change in power system structure (topology).

In [35]–[37], methods based on traveling waves generated by the fault have been suggested. The time difference between successively captured traveling waves' records is used for locating the fault. These methods need high-frequency sampling and depend on the tower configuration (propagation velocity) and desired accuracy, which increases implementation cost. Presence of laterals and load taps that reflect traveling waves, which may be confused with those created by the fault, is another difficulty related to application of these methods on distribution systems. These methods may be more applicable to transmission lines where lines are longer, and equipped with better monitors [38].

The fact that fault causes voltage sags with different characteristics at different nodes has been utilized for fault location in [39] and [40].

III. Data Integration for Smart Fault Location

A. Transmission Line

A smart integrated substation is normally equipped with various types of IEDs which can be used for monitoring, control, and protection purposes. Substation analog signals measured at high power level are transformed to instrumentation level (using current and voltage instrument transformers) and then filtered and digitized for being processed using IEDs.

The basic idea of integration of data is to collect all the IED data in a substation database and use it for extracting information automatically and then utilizing the extracted information for several power system applications. The functional diagram for substation data flow is shown in Fig. 1.

The substation database consists of the following data:

- measurements received from RTUs;
- measurements received from other IEDs;
- static system data containing description of the system components and their connections (i.e., topology);
- SCADA EMS PI Historian data, which may be used to tune the static system model with real-time data;
- substation interpretation data that allows one to correlate the naming convention of recording devices and that of the static system model with PI Historian data.

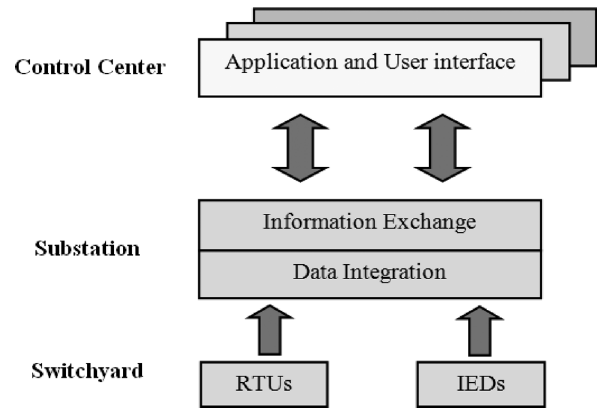

Fig. 1. Functional diagram for substation data flow.

Although, integrating a huge amount of data provides improved information by exploiting the redundancy, the quality of data is also a major concern. Ideally the output waveform should be an exact replica of the input signal, but the error introduced in several data processing stages makes the output distorted. Thus, the quality of data depends largely on the performance of devices used. The performance of these devices and the information extraction schemes are discussed elaborately in [41].

B. Distribution Feeder

As a part of smart grid deployment projects, IEDs for monitoring, protection, and other purposes including the smart metering systems, power quality monitoring, and distribution system automation have emerged in distribution systems. These smart sensors are installed all over the system, from substation down to the customer location. Their types vary, as well. Some provide samples (digital protection relays, digital fault recorders), some provide samples and synchronized phasors (digital protection relays), and some provide energy measurements and power quality indicators (smart meters and power quality meters). Development in smart grid communications makes the data captured by these new devices available to multi subscribers and serves multiple IED infrastructures. Hence, utilization of the gathered data from various IEDs installed along the feeders is quite feasible. Examples of such measuring devices include, but not limited to, substation and feeder relay, as well as intelligent controllers for capacitor bank switches or reclosers, automatic meter reading (AMR) systems installed at the customer sites, power quality meters installed at strategic locations in the system, low-cost optical current and voltage sensors that may be located at selected poles as a part of the broadband over power line (BPL) solutions. An example of such a variety of IED applications in the distribution network is shown in Fig. 2.

Availability of additional feeder data may help improve the accuracy of the fault location methods. However, there are standing concerns that should be taken into account: how different types of IEDs available in the network may affect the

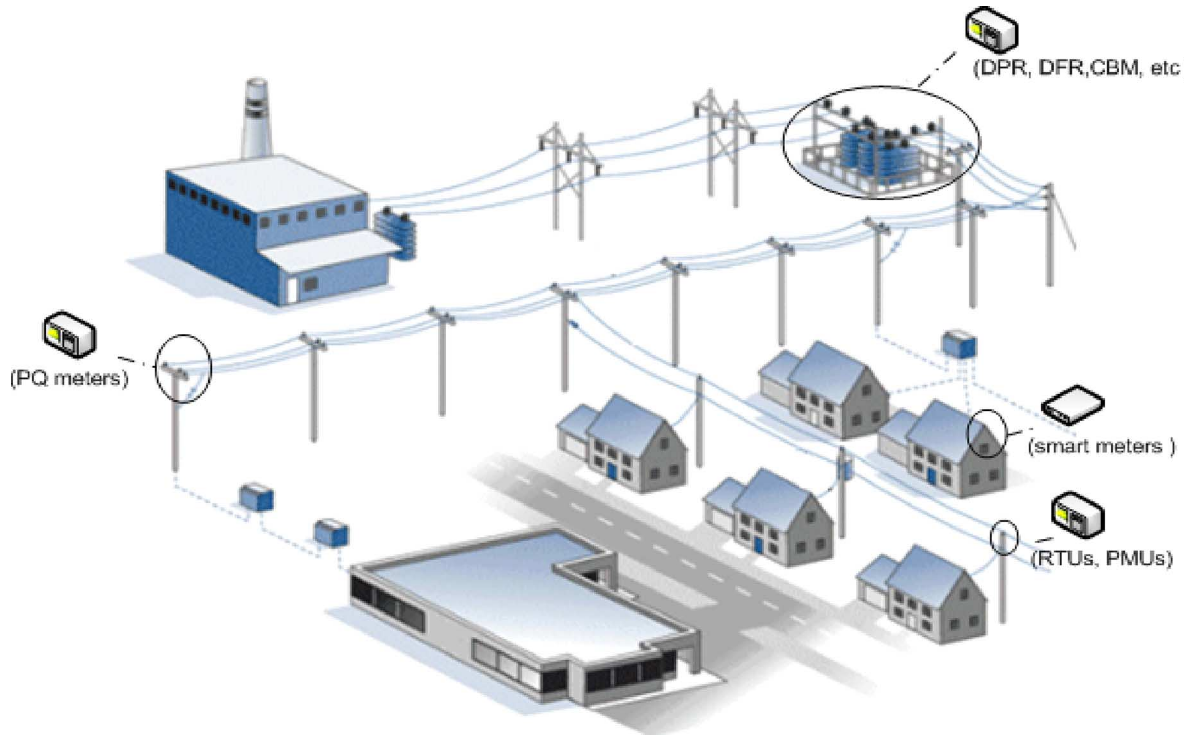

Fig. 2. Locations of different IEDs in a distribution network.

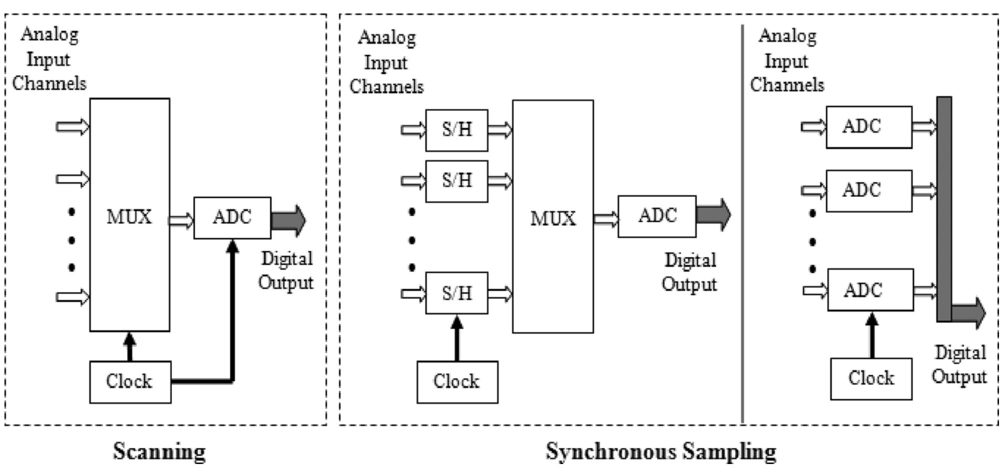

Fig. 3. Scanning and synchronous sampling of analog inputs.

fault location method selection, what are the factors that influence quality of recorded data, and how the feeder automation architectures impact the final availability of data.

First to note is that feeder automation (FA) architecture affects fault location method implementation. Centralized feeder automation solution acquires data from field devices, processes data in SCADA system and issues supervisory control commands. In the substation-centered approach, system is controlled by substation PLC or RTU, which are also used to process fault location data. Supervisory control commands are issued to field devices, as needed. In a peer-to-peer arrangement "local" data is acquired via local smart sensors and other IEDs and "remote" data via peer-to-peer communications with other controllers. In this case IEDs process data locally and no SCADA-based central station is required [42]. When a fault location method is suggested or selected from existing methods, the communication structure of the FA system should be taken into account. For instance, the first arrangement is suitable for control-center-based methods, the second one is suitable for substation-based methods and IEDs that are installed in substations and the last one is suitable for methods that can rely on IEDs installed along the feeder.

C. Data Sampling and Processing

Samples of input signal waveforms are taken by the sample and hold (S/H) circuit at the time defined by the sampling clock to be able to perform analog-to-digital conversion (ADC). There are several sampling methods as shown in Fig. 3.

In the scanning method, one analog input channel is sampled at a time and then converted to a digital word, which then is sequentially completed across all input channels. This creates a time skew between the corresponding samples on different

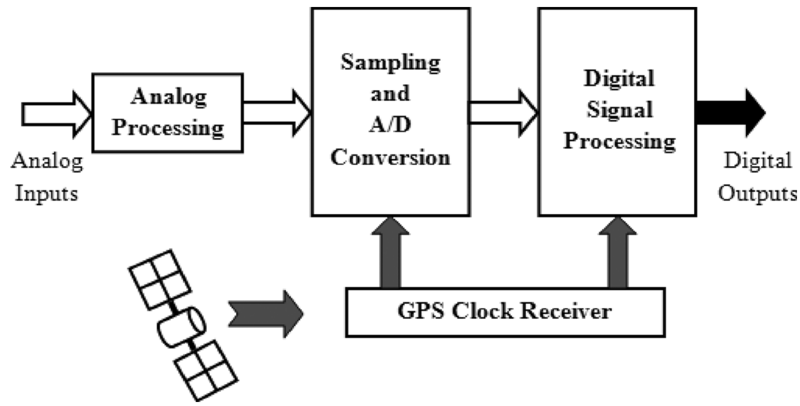

Fig. 4. GPS-based synchronized sampling.

channels. In synchronous sampling all the input signals at each channel are sampled at the same time and then sampled values are converted to a digital word. In this case there is no time skew between the corresponding samples on different channels. This may be accomplished by either using one ADC serving all channels but having separate S/H circuits on each channel and a multiplexer that feeds another S/H in front of the ADC, or using a separate S/H circuit and ADC on each channel.

When a fault location method is proposed it is important to consider which IED supplies the data. As a practical example, imagine available data are from SCADA RTU in substation and power quality meters (PQMs) along the feeder. The fact that usually PQMs operate on synchronous sampling and RTUs operate on scanning method makes it difficult to use a fault location method that works based on direct comparison of samples. In these cases a fault location method that does not rely on direct comparison of the samples should be selected. Moreover, if there is a choice in selecting IEDs in substation, in the case of having a fault location method based on direct comparison of the samples, IEDs like DFR or DPR that operate on synchronous sampling method should be selected.

In order to avoid aliasing phenomena in processing the signal, an antialiasing filter is used. The frequency and step responses of different type of antialiasing filters are discussed in detail in [43]. Difference in characteristics of antialiasing filters (type and cutoff frequency) has different impact depending on the frequency content of transient waveform. Therefore, different fault location methods will be affected by the characteristics of the antialising filters differently.

One source of uncertainty in the input data is the accuracy of ADC used to convert data. It is necessary for the selected fault location method to be robust under the worst uncertainty in the data. For instance, if data are captured by DPR and PQM, and ADC of DPRs has smaller word length compared to PQM, the selected fault location method should be able to produce good results irrespective which a data are used.

Sampling frequency is also affecting the accuracy of signal representation. The higher the sampling frequency, the better the signal representation (or better “horizontal” resolution) but not necessarily the accuracy, which is driven by the number of ADC bits (“vertical” resolution). Therefore, it is important to consider what kind of IEDs are used for fault location application. If the fault location method is based on transients contained in the signals like traveling-wave-based methods, IEDs with higher sampling frequencies and high-resolution ADC may be required. Moreover, if the method is based on time difference between samples it is necessary to check what kind of sampling (fix or variable) is used.

There are two ways in implementing clock signal distribution for data sampling synchronization: global positioning system (GPS) of satellites or computer network. Modern IEDs may be interfaced to GPS receivers as shown in Fig. 4 and those devices provide synchronization with accurate systemwide clock. An example of the connection of IEDs to GPS receivers in a substation is given in Fig. 5. The time synchronization signal is distributed among different IEDs: DPRs (SEL 421 and GE D60) and DFR (TR-2000) located in a substation control house and circuit breaker monitors (CBM01 and CBM 02) located in the switchyard.

If the IEDs are IP addressable, then the time synchronization signal may be distributed over the computer network. When selecting a fault location method, it is important to consider whether it needs synchronized sampling or not. This consideration is important from implementation point of view since in the network where synchronized sampling is not possible a less accurate method that does not need synchronized sampling will be preferred.

The accessible data may be different from the raw data seen by the IEDs depend upon functionality of that IED. For instance, DFRs only capture data for later display and analysis. So digital filtering and antialiasing may not even be used in older DFRs. DPRs make decision based on sampled data processed through analog (antialiasing) and digital filtering.

DPRs usually perform digital prefiltering before applying phasor estimation algorithms (such as the Fourier transform) to filter out unwanted components of the applied signals, the dc component in particular. DPRs tend to record sampled data after digital filtering (although newer ones operate similar to DFRs and record raw samples prior to digital filtering). Fig. 6 [44] illustrates the unfiltered versus filtered data.

For each type of IEDs one must review its specifications to understand the signal processing that needs to be carried out prior to the samples being recorded so that the impact on the selected fault location algorithm can be fully understood.

When considering a recording device, its triggering method should be well applied to make sure it captures the phenomena

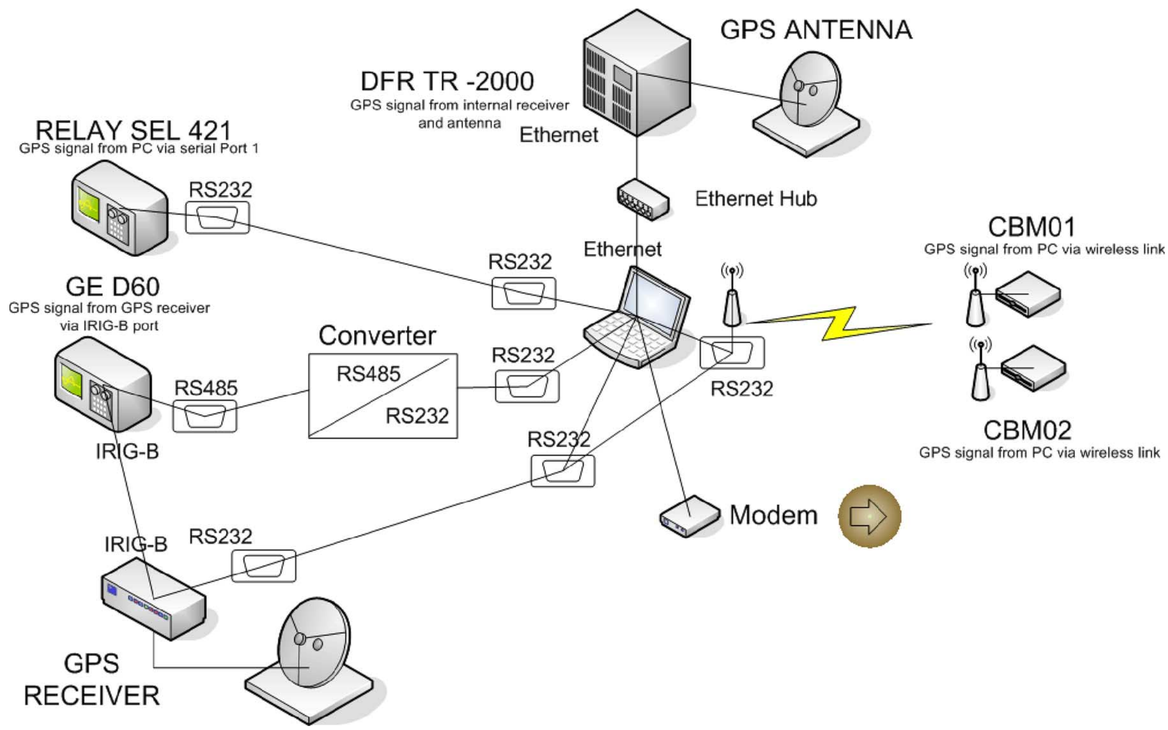

Fig. 5. Connection of IEDs to GPS receivers in a substation.

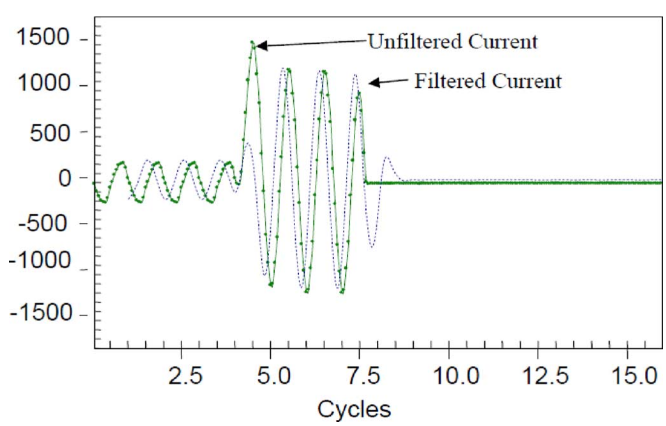

Fig. 6. Unfiltered versus filtered data.

that fault location algorithm is based on. For instance, some devices are allocated for recording power system disturbances like power swings. In such instances to be able to reduce the volume of recorded data, power system faults (such as line faults) are not recorded. Impedance rate-of-change trigger is one way of distinguishing between an equipment fault and a system disturbance. Therefore, this device setting may not be suitable for the data to be used for fault location purpose unless the triggers are modified.

IV. Selection of Optimal Solution for Transmission Line Fault Location

An optimal fault location approach which will select the most appropriate fault location algorithm depending on the availability and location of the data measured is explained next. The optimized fault location algorithm (OFLA) [45] will select the best result from the following algorithms using the flowchart shown in Fig. 7.

A. *Single-End Method [4]*

Estimates location of fault using measurement from only one end of the faulted line.

B. *Double-End Methods [14], [16]*

Estimate location of fault using either unsynchronized phasor measurements [14] or synchronized samples [16] from both ends of the faulted line.

1) Systemwide Sparse Measurement Method [22], [23]: Uses phasor measurements which may be sparse, i.e., recorded from few substations located in the region where the fault has occurred. The method works on comparing measured data versus simulated data (generated by the short circuit simulation of possible fault locations) 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.

Fig. 8 shows the flowchart used for the systemwide sparse measurement method. To obtain best 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) [46]. The fault location solution using GA is performed in the following steps. First, the initial population is chosen randomly by varying two variables: fault location and fault resistance. 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 software and the fitness

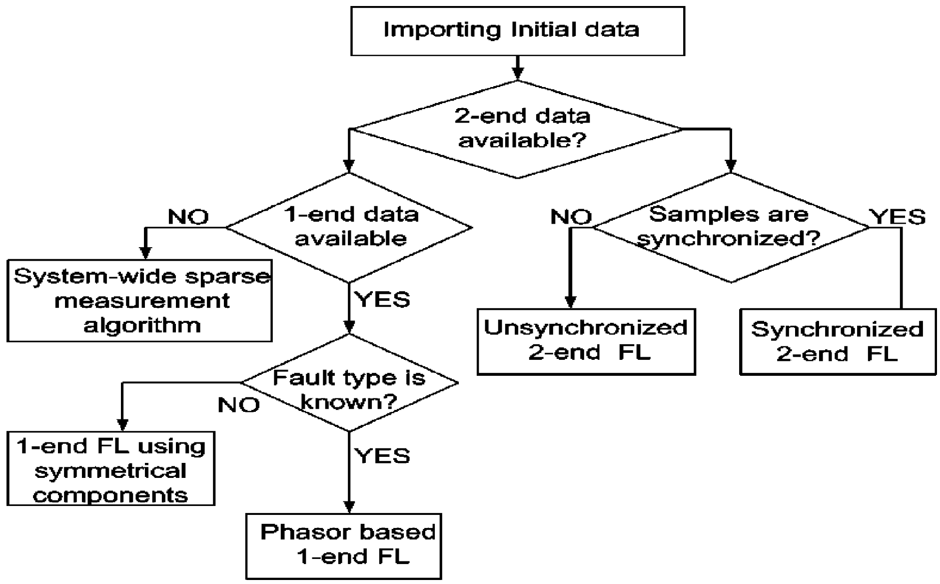

Fig. 7. Flowchart of optimized fault location algorithm.

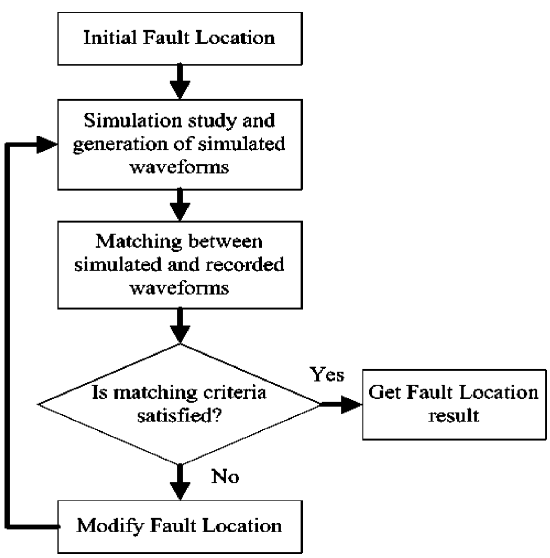

Fig. 8. Flowchart of systemwide sparse measurement method.

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.

Several commercial packages are used to implement this solution. The static power system is modeled using PSS/E 31 software [47]. To tune the power grid with prefault data, SCADA PI Historian data is used [48].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 software to run the power flow analysis. Sequence data (*.seq) contains the negative and zero sequence impedance data needed for short circuit study.

In a typical power system, operator is able to track changes in real time using Supervisory Control and Data Acquisition (SCADA) system. 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 s interval) in a period before and after fault for each substation where DFRs are located. These data can be used 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 [49]. The DFR data (*.dat) contains analog and digital sample values for all input channels for a specific substation. The configuration data (*.cfg) 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 [50] 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 the nomenclature used in DFR files and those one used in PSS/E file and those used in SCADA PI Historian. The interpretation files should be modified as frequently as needed to reflect the DFR configuration or system model changes.

Now we will discuss 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 and Synchronization of Phasors: The disturbance events obtained from the IEDs are processed to obtain phasors from the samples of recorded analog signals [51].The prefault phasor can be calculated using first cycle of the recorded

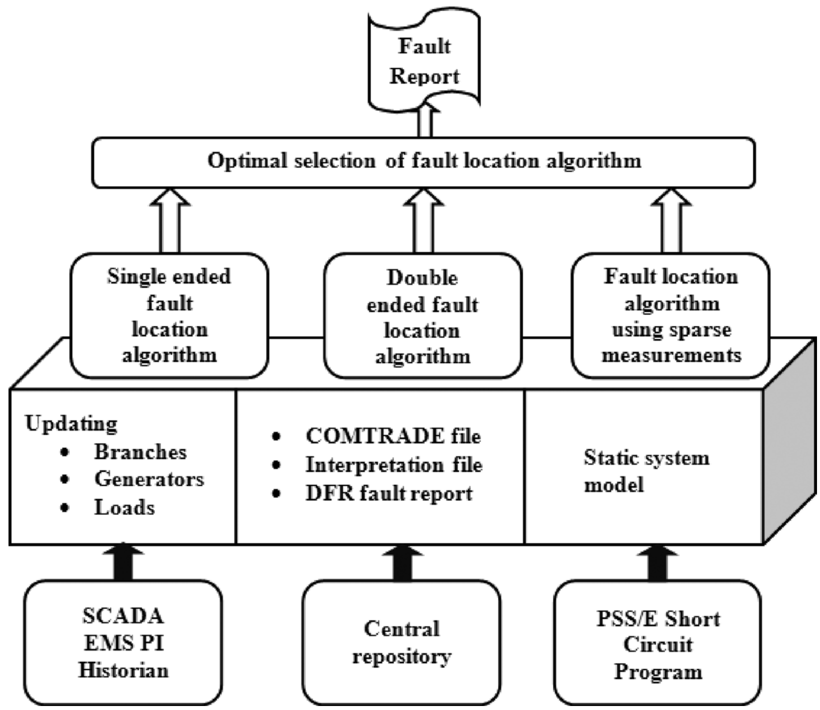

Fig. 9. Architecture of optimized fault location algorithm.

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. 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 postfault phasors are synchronized using the same reference.

Alternatively, phasors captured by PMUs may be used directly.

Tuning the Power System Model With Real-Time Power System Conditions: The saved case model from PSS/E software may not reflect prevailing operating condition 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 consists of updating power grid topology (switching status) and then updating generation and load data near the substations of interest. The topology update is performed using information of the prefault breaker status and the prefault current magnitudes of the monitored branches derived from the DFR data. 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 is achieved using PI Historian data. The updated model is saved in a new saved case data (*.sav) which is used for further simulation.

After gathering all the data and updating system information, the optimal fault location algorithm estimates location of fault using the following architecture (Fig. 9).

The software is implemented using Java programming language. To interact between PSS/E activities and Java programming language, IPLAN [52] 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.

Implementation of OFLA is evaluated for the following issues: using varying number of DFR files, specifying the search region, using preprocessed fault location estimation, using different quantities for the match between measured and simulated data, evaluating differences in the accuracy when different input data are available and different assumption are satisfied etc. These different options may produce different results. Test activities are conducted on the data collected from a real life electric power system [53]. Again, further details are given in the publically available PSerc report dedicated to Optimized Fault Location [54], [23].

V. Distribution System Solution That Utilizes Data From Smart Grid IEDs

Implementing the smart grid is a gradual process. All of the technologies for the smart grid may not yet be available in all networks. The key is to take full advantage of the existing level of automation and have a plan for each step as the networks are evolving to final vision of the smart grid.

A method has been proposed in [39] for fault location in distribution systems. It requires voltage sag data gathered from few power quality or revenue meters with transient recording capabilities installed at strategic points along the feeder. The proposed method is based on the fact that when a fault occurs on the feeder captured voltage sags are different based on how far the meters are installed from the fault location. Having the voltage sag waveforms, it is possible to locate the faulty node or the faulty area of the feeder by matching the waveform patterns. Prefault and during-fault voltage and current phasors at root node (substation), as well as knowledge about faulted phase(s) and fault type are utilized. Prefault measurements are used for estimating load variations and updating load models. During-fault data is used for finding the location of the fault. Moreover, voltage sags at some selected nodes along the feeder are gathered.

Fault at each node (one at a time) in the modeled network is applied and voltage sags are calculated using a load flow program. The fault location is determined by comparing how well each calculated case matches up to what was actually observed at the meters in the network. The case that shows the highest similarity is considered the location of the fault.

To quantify the similarity, the voltage mismatch, for each faulted phase, is given by

$$\delta_k^{i,j} = V_{k,\mathrm{med}}^i - V_{k,\mathrm{sim}}^{i,j} \tag{1}$$

where:

$V_{k,\mathrm{med}}^i$ magnitude of the during-fault voltage sag, on phase k, measured at node I;

$V_{k,\mathrm{sim}}^{i,j}$ magnitude of the during-fault voltage sag, on phase k, at node i calculated for a fault at node j.

Equation (1) provides three voltage mismatches for three-phase faults, two voltage mismatches for line-to-line faults, and one voltage mismatch for single-line-to-ground fault. Only the mismatches for the faulted phases are calculated in order to reduce the amount of information handled by the algorithm for asymmetric faults and to ensure that the faulted node is selected based on voltage sags, i.e., the experimented voltage swells on healthy phases for asymmetric faults will not play a role in the final results.

The fault location index, η, is defined by

$$\eta_j = \frac{1.0}{\max[\max(\delta_k^{i,j}) - \min(\delta_k^{i,j})] + \Delta}. \tag{2}$$

$\mathrm{i} = 1, \ldots, \mathrm{mp}, \mathrm{j} = 1, \ldots, \mathrm{mp}$
where:

k phase a, b or c;

mp quantity of voltage measurement nodes used for fault location purposes;

mn number of analyzed nodes;

Δ a small number in order to avoid division by zero.

In (2), the term $\max[\max(\delta_k^{i,j}) - \min(\delta_k^{i,j})]$ ensures that for each analyzed node, among the differences calculated for the phases, the biggest one is chosen. Choosing the biggest difference assures that the likely faulted node presents the smallest difference among the biggest differences selected. Thus, the fault location index calculated for the faulted node, by means of (2), will be the one having biggest value among all analyzed nodes.

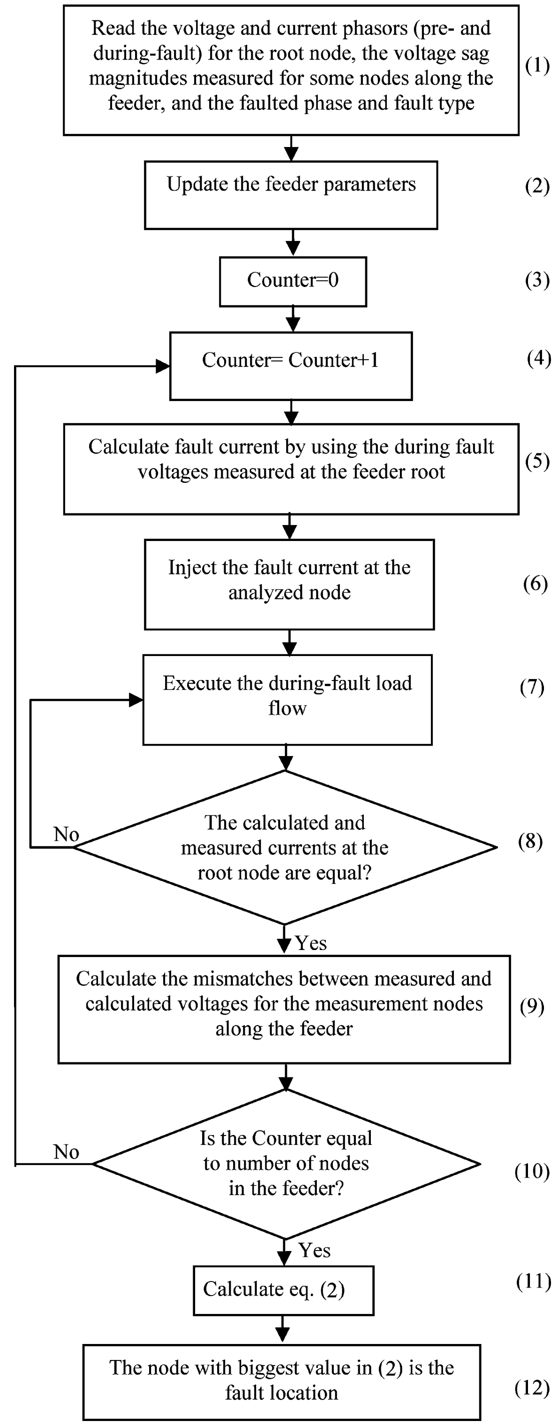

Fig. 10. Flow chart of the distribution fault location method based on voltage sag data.

Fig. 10 shows the flowchart of the algorithm. At first the measured voltage and current phasors, and information about the type of fault and faulted phases are provided to the method. In the next step, the load models are updated as explained in [39].

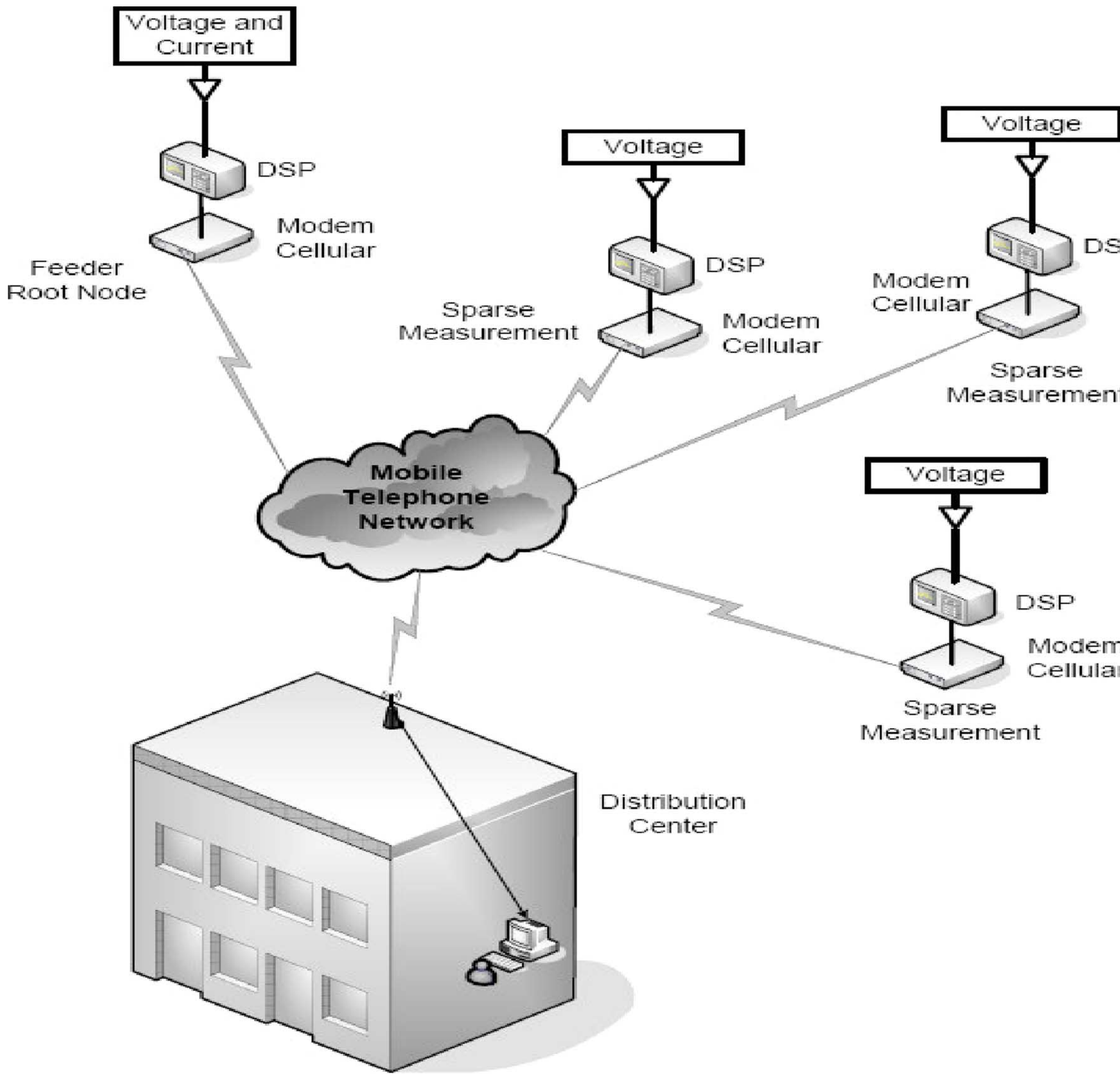

Fig. 11. Basic architecture of the fault location method [39].

The variable "Counter" is defined to check whether the process is performed for each node of the network.

In steps (5) and (6) fault current is calculated and injected to the network at assumed fault location nodes as explained in [39]. In steps (7) and (8) the calculated fault current is tuned until the calculated current at root node (substation) becomes equal to the measured one. Step (9) calculates mismatch between calculated and measured voltage values for the measurement nodes along the feeder which will be used in step (11). Step (10) checks that all nodes are analyzed one at a time. In step (11) the index value in equation (2) is calculated for each node, and finally the fault location is estimated at step (12).

Since the algorithm requires the voltage and current phasors recorded at the feeder root node, these quantities need to be recorded in a time-synchronized fashion. Additionally, the algorithm requires the voltage sag magnitudes recorded at sparse measurement nodes, but these recorded quantities neither need to be synchronized among themselves nor with the quantities recorded at the feeder root node, which may be synchronized using GPS means. However, it is required that quantities delivered to the algorithm be recorded for the same fault event. For this purpose, a mobile telephone network can be used to provide the time stamp for the sampled voltage sag magnitudes and to transmit the recorded quantities, since they will be transmitted to a central point for the algorithm processing when a fault occurs. Fig. 11 illustrates in a simplified way the data recording architecture for a fault locator using the proposed algorithm. The simulation results presented in [39] show the merits of the proposed method. This fault location method is a good example that shows how by developing suitable methods it is possible to take advantage of smart grid technologies at each level of progress toward the final vision of a smart grid.

VI. Conclusion

The paper discusses the existing approaches and future trends in fault location methods for both transmission and distribution systems. The smart grid technologies and sources of data that could be utilized to improve fault location methods by matching the field measurements to the simulated values obtained using power system models are presented. Two automated fault location methods, one for transmission and one for distribution systems were selected to show how the smart grid technologies could help reach more accurate fault location results. The examples illustrate how suitable fault location method could be selected based on type of field data and availability of information about the network .This in turn allows achieving better accuracy by taking advantage of availability of field data and communications to transfer such data to desired locations in a timely manner.

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