Fault resistance sensitivity of sparse measurement based transmission line fault location

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***Abstract*—Traditional transmission line fault location methods require measurements from at least one end of the faulted line. Measurements from all the ends of the faulted line are desirable but not always available. Sparse measurement based fault location scheme using phasor measurements from different substations located in the vicinity where the fault has occurred can be applied if the measurements are not available from any of the line ends. Fault resistance is one of the major sources of uncertainty in transmission line fault location estimation. This paper presents a correction scheme to reduce impact of fault resistance on sparse measurement method.**

I. Introduction

Transmission lines exposed to different weather, as well as human and animal contact are subject to several types of faults which are caused by random and unpredictable events. Protective relays placed at both (all) ends of the line sense the fault immediately and isolate the faulted line by opening the associated circuit breakers. To restore service after a fault, an accurate location of the fault is needed to help the maintenance crew find and repair the faulted line section as soon as possible. Fault may occur between transmission line phases or have a ground return path. When a phase-to-phase fault occurs, the fault current flows through arc resistance and if the fault is a ground fault the current path includes earth resistance (consists of tower resistance, tower footing resistance and ground return path) also. Fault resistance is the combined resistance which appears in the fault current path. This is an uncertain parameter as both the arc resistance and earth resistance depend on many parameters that are sometimes very hard to predict.

Distance relay algorithm selectivity may suffer from the combined effect of fault resistance and load current which is known as *reactance effect* [1]. Such algorithms assume that the fault current is in phase with measured current. Presence of remote infeed complicates the situation. Takagi et al. [2-3] decomposed the faulted network to pre-fault and pure-fault network and take some assumptions to eliminate fault resistance part from the circuit equation. Another one-end method using quadratic formula to eliminate fault resistance is introduced in [4] yielding much more accurate result. Using one-end data to estimate fault resistance by modeling the arc is discussed in [5-6]. [7] is based on equalizing voltage of fault point from both ends of the line based on measurements from both ends and thus eliminates the impact of fault resistance . A settings free fault location method using synchronized samples from both ends of the line is completely independent of fault resistance, which is not used to develop the algorithm [8].

Typically digital fault recorders (DFRs) or digital protective relays (DPRs) are placed in substations and they record current, voltage and status signals on occurrence of an event like fault. Due to the lack of measurement transformers in certain transmission line configurations such as tapped lines availability of measurements from at least one end of the line becomes a problem. If the measurements from other ends are not available, some unconventional fault location techniques based on system-wide sparse measurements may have to be used [9-10]. In this case, fault location is estimated by using measurements recorded from IEDs installed in the substations close to the faulted line (but not from the ends of the line) and also using SCADA measurements from all the substations near the fault.

Performance of the system-wide sparse measurement based fault location algorithms depend on fault resistance. The analysis of the impact of the fault resistance on the sensitivity of fault location output is crucial for estimating an accuracy of the output. In [11-12] sensitivity of one-end fault location methods is analyzed to determine most contributing uncertainty factors and interaction of uncertainty factors.

This paper explains how accuracy of system wide sparse measurement based fault location can be impacted by fault resistance. An intuitive scheme to choose proper fault resistance range is also proposed.

The next section is focused on describing sparse measurement based fault location method and the correction scheme proposed to reduce sensitivity to fault resistance. Software implementation and case study are discussed in the subsequent sections followed by the conclusion.

II. SPARSE MEASUREMENT METHOD WITH FAULT RESISTANCE SENSITIVITY ANALYSIS

A. *Sparse measurement based fault location method*

The basic idea of transmission line fault location is to estimate the distance of the fault point from any one end of the line.

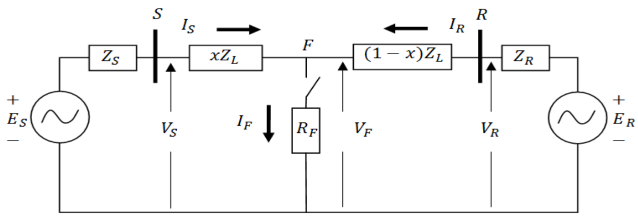

Figure 1. Faulted circuit model

In Fig.1 a fault with resistance R_F has occurred on point F between two ends (S and R) of a line section S-R. Considering a homogeneous line, the distance can be expressed as a function of the impedance measured from one end$\left(xZ_L\right)$. The above circuit can be solved accurately if voltage and current measurements from both ends are available.

Installing recording devices (DFRs in our case) on the ends of all the transmission lines is not economical. Although protective relays exist on every transmission line, most of them may still be electromechanical and they do not have capability to record measurements. As a result, in some cases it may happen that there are no recordings at all available at line ends close to a fault. System-wide sparse measurement based fault location method can be applied in such instances [9-10].

In sparse measurement based fault location method, phasor measurements from different substations located in the region where the fault has occurred are used. The measurements are 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 DFRs connected to Global Positioning System (GPS) receivers [13].

Besides the sparse measurements, the technique also uses short circuit program, which is initialized and tuned with SCADA PI Historian [14], power system model data and measurements associated with the time of the fault occurrence.

The method uses waveform matching technique between the current and voltage phasors calculated from the waveforms recorded in a substation (nearby the faulted line) and phasors simulated using short circuit simulation of possible fault locations. A commercial short circuit program tool PSS/E^{TM} 27 is used for short circuit calculation [15]. The calculated and simulated phasors are compared while the location of the fault is changed in the short circuit program. This process is repeated automatically until the difference between measured and simulated values reaches global optimum (minimum), 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.

In this 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 between the recorded and the simulated waveforms can be formulated as [9]:

$$f_c\left(x, R_F\right) = \sum_{k=1}^{N_V} r_{kV}\left|V_{ks} - V_{kr}\right| + \sum_{k=1}^{N_I} r_{kI}\left|I_{ks} - I_{kr}\right| \tag{1}$$

Where,

$f_c\left(x, R_F\right)$: The cost function using 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 calculated from measurements during-fault voltages respectively

I_{ks}, I_{kr} : Simulated and calculated from measurements during-fault currents respectively

N_V, N_I : Total number of voltage and current phasors to be matched respectively

k : The index of voltage or current phasors

Ideally when the simulated phasors and phasor calculated from the recorded waveforms match completely, the cost function should become zero. In practical solution, the cost function is not zero and should be minimized using some mathematical optimization method. To obtain good phasor matching the fault search range should be extensive. All possible faulty 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) [16]. The flowchart of this method is shown in Fig. 2.

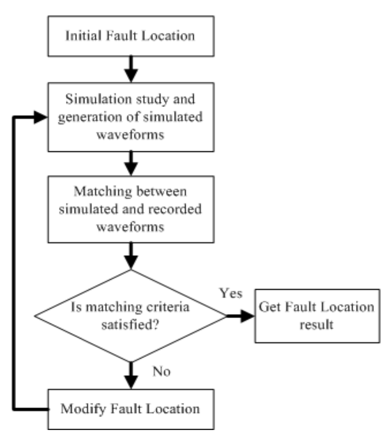

Figure 2. Flowchart of sparse measurement algorithm

B. Fault resistance compensation correction scheme

Since fault resistance is the most uncertain parameter, a correction scheme to compensate the effect of fault resistance can be proposed.

The correction scheme (shown in Fig. 3) compensate the effect of fault resistance by using an optimization scheme over the sparse measurement method which selects the fault location and fault resistance pair that cause the output to be least sensitive to fault resistance variation.

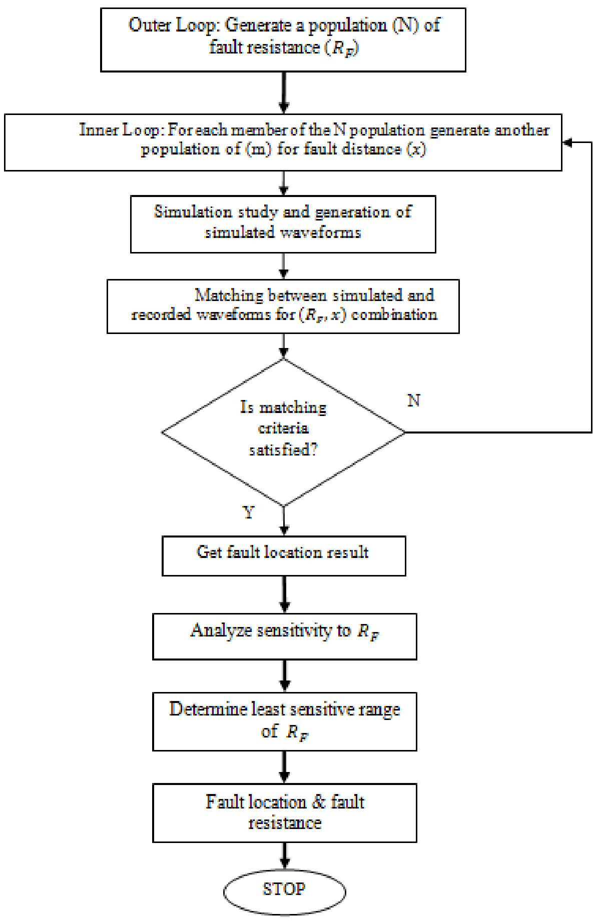

Figure 3. Flowchart of corrected sparse measurement algorithm

The proposed corrected sparse measurement algorithm can be explained in the following step by step method:

Step 1: Initialization: Generate a population of fault resistance values R_F (1 to N)

Step 2: Sparse measurement based fault location: For each R_F, perform original sparse measurement algorithm and get fault location x (1 to N). Therefore a pair of (x, R_F) is obtained for N number of cases.

Step 3: Estimation of unknown function g by non-parametric method:

We have N pairs of observations (x_i, R_{F_i}) for $i = 1:N$ which are used to estimate the unknown regression function $g(R_F)$ where fault location is expressed as a function of fault resistance:

$$x = g(R_F) + \varepsilon \tag{2}$$

ε is assumed to be zero mean error

Therefore; expected value of x given R_F is:

$$E(x/R_F) = g(R_F) \tag{3}$$

We can approximate the true function g by $\hat{g}$ using traditional non-parametric regression method [17].

Step 3: Calculate sensitivity to R_F :

The variance based global sensitivity analysis method (ANOVA decomposition) is used [18]. The method is summarized below:

If we consider a deterministic model $Z = f(y)$

Where

y is a vector of input variables $y = (y_1, y_2, ..., y_k)$

Z is the model output

We can decompose $Z = f(y)$ into main effects and interactions

$$f(y) = f_0 + \sum_{i=1}^{k} f_i(y_i) + \sum_{i}\sum_{j>i} f_{ij}(y_i, y_j) + \\ ... + f_{1,2,...,k}(y_1, y_2, ..., y_k) \tag{4}$$

If each term is chosen with zero mean

$$\int_0^1 f_i(y_i)dy_i = 0, \forall y_i, i = 1,2,...,k$$

$$\int_0^1\int_0^1 f_{ij}(y_i, y_j)dy_i dy_j = 0, \forall y_i, y_j, i < j$$

$$\int_\Omega f_{1,2,...,k}(y_1, y_2, ..., y_k)dy_1 dy_2 ... dy_k = 0$$

Therefore

$$\int_\Omega f(y)dy = f_0 \tag{5}$$

So we can write

$$Z - E(Z) = f_0 + \sum_{i=1}^{k} f_i(y_i) + \sum_{i}\sum_{j>i} f_{ij}(y_i, y_j) + \\ ... + f_{1,2,...,k}(y_1, y_2, ..., y_k) \tag{6}$$

As terms orthogonal, we can square and integrate (6) over Ω and decompose the variance of $f(y)$ into terms of increasing dimensionality

$$\sigma_Z^2 = \sum_{i=1}^{k} \sigma^2_{E(Z/y_i)} + \sum_i \sum_j \sigma^2_{E(Z/y_i,y_j)} + \ldots + \sum_i \sum_j \sum_k \sigma^2_{E(Z/y_i,y_j,y_k)} \tag{7}$$

Now we can define sensitivity indices as:

$S_i = \dfrac{\sigma^2_{E(Z/y_i)}}{\sigma_Z^2}$: First order index. Corresponds to main effect of y_i

$S_{ij} = \dfrac{\sigma^2_{E(Z/y_i,y_j)}}{\sigma_Z^2}$: Second order index. It measures the effect of pure interaction between any pair of factors on the output

And so on.

So the (7) becomes

$$1 = \sum_{i=1}^{k} S_i + \sum_i \sum_j S_{ij} + \ldots + S_{1,2,\ldots,k} \tag{8}$$

Therefore in our case, Sensitivity of x with respect to R_F (first order index) is given by:

$$S_{R_F} = \frac{\sigma^2_{E(x/R_F)}}{\sigma_x^2} \tag{9}$$

Now $\sigma^2_{E(x/R_F)}$ and σ_x^2 are unknown parameters which can be estimated from the pair of observations generated.

Now σ_x^2 is estimated by its unbiased estimator

$$S_x^2 = \frac{1}{(N-1)} \sum_i \left(x_i - \bar{x}\right)^2 \tag{10}$$

which is also known as sample variance of x

And $\sigma^2_{E(x/R_F)}$ is equal to $\sigma^2_{g(R_F)}$ which can be estimated by its unbiased estimator

$$S^2_{E(x/R_F)} = \frac{1}{(N-1)} \sum_i \left(g_i - \bar{g}\right)^2 \tag{11}$$

Where $g_i = g\left(R_{F_i}\right)$

Here we don't know the true g but we can obtain its estimate $\hat{g}$ by the traditional non-parametric regression method.

Hence we can estimate $\sigma^2_{E(x/R_F)}$ by

$$S^2_{E(x/R_F)} = \frac{1}{(N-1)} \sum_i \left(\hat{g}_i - \bar{\hat{g}}\right)^2 \tag{12}$$

Where $\hat{g}_i = \hat{g}\left(R_{F_i}\right)$

Now we can segment the range of R_F in some sub-ranges and also determine the sensitivity in those individual sub-ranges.

Step 4: Determine optimal pair of (x, R_F) :

From the different sensitivity indices in different sub-ranges of R_F, we can choose the sub-range of R_F that corresponds to least sensitivity. Now the optimal pair of (x, R_F) should be the pair that corresponds to minimum of mismatch computed in (1).

III. Implementation

The architecture of the fault location scheme is shown in Fig. 4.

Several commercial packages are used to implement this solution. The static power system is modeled using PSS/E^{TM} 27. To tune the power grid with pre-fault data, SCADA PI-Historian data is used.

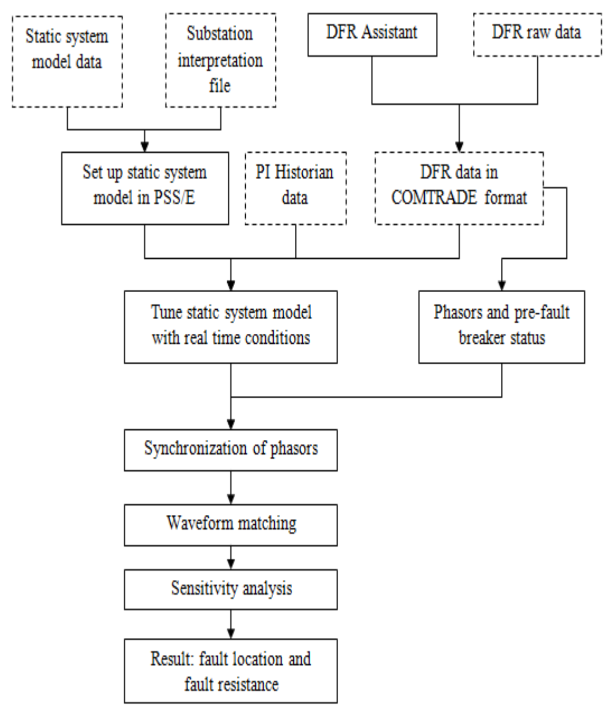

Figure 4. Solution architecture

The detailed data requirements for the implementation are:

- Static system model data: These include power flow system specification data for the establishment of a static system model (in *.raw format). Power system model data can also be used in saved case format (*.sav) which is used to extract *.raw data.
- Event data: These include event data captured by recording devices (DFRs here) after occurrence of a fault. The raw DFR data is converted to COMTRADE format [19] using DFR Assistant software [20] which can generate an analysis report (containing the type of fault and a possible faulted line) in addition to generating the COMTRADE files. The COMTRADE files contain:
    - Configuration files(*.cfg): information for interpreting the allocation of measured data to the equipment (input channels) for a specific substation
    - Data files (*.dat): analog and digital sample values for all input channels (described in configuration file) in substation
- SCADA PI Historian data: This data reflects real time changes in power system including the latest load, branch and generator data to tune the static system model with the actual pre and post fault conditions.

The nomenclature of power system components in all three types of data is different. Correlation between all three types of data is required. Substation interpretation files are prepared to correlate the nomenclature used in DFR files and the one used in PSS/E file and PI Historian data. The interpretation files should be modified as frequently as needed to reflect the DFR configuration or system model changes.

Implementation of fault location software is a four step procedure:

A. System initialization

This is a onetime procedure used to set up the system. Power system static model data (in *.raw format) is used to extract all the components and construct topology which will be used later.

B. Pre-process event data

The event data captured by DFRs should be pre-processed to obtain required information to be integrated with power system model data.

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.

For a typical fault case, several DFRs may be triggered and the phasors calculated from the recorded waveforms may lack time 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.

C. Tuning with real time data

The static system model may not reflect the operating conditions of the system when an event is recorded. A tuning with real-time power systems is required. The tuning procedure is done in two steps:

- Tuning topology: 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.
- Tuning generation and load data: The SCADA PI Historian data 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 load and generation.

The updated model is saved in a new saved case data (*.sav) which is used for further simulation.

D. Estimating fault location and evaluating sensitivity to R_F

The fault location solution using GA is performed in the following steps. The outer loop optimization requires iterations with different R_F in a pre-determined range. The initial population for the inner loop optimization is chosen randomly for this one dimensional (i.e. with one variable x) optimization problem. Fault location variable can be chosen from a range of zero to the length of the possible faulted line. Short circuit studies are carried out using PSS/E and the mismatch value from (1) is evaluated for each of the possible fault locations. Now 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, and updating the fault location and resistance, the GA based search engine guides the search process for a globally optimal solution for a given value of R_F . Now the variance based sensitivity analysis method is used to determine sensitivity of fault location with respect to the fault resistance in the partitioned sub-ranges of R_F. The sub-range corresponding to least sensitivity is chosen and the minimum mismatch in that range corresponds to the optimal pair of (x, R_F) for that fault.

IV. CASE STUDY

An actual utility case study is presented here. In the faulted network shown in Fig. 5, a DFR installed on bus 1 is triggered upon the occurrence of the fault and DFR report indicates the fault is on the line section 1-5 while actually the fault was reported to be 3 miles from bus 8. With our algorithm, the fault is recognized as being either in line section 6-5 or in line section 7-9.

Our software yields much more accurate fault location estimation than what is feasible using other techniques.

Fault resistance range is chosen as 0 per unit to 0.8 per unit and. Fault resistance is changed within its range by increasing its value by 0.008 per unit in each iteration.

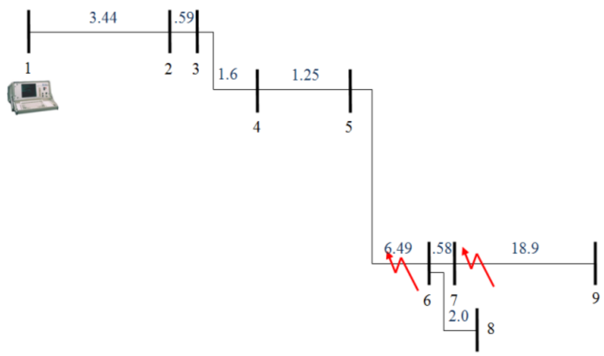

Figure 5. Faulty network

Fault resistance vs. fault location is plotted in Fig.6. Sensitivity analysis with respect to fault resistance is performed for several iteration runs and the sensitivity indices corresponding to different sub-ranges of R_F are presented in Table 1.

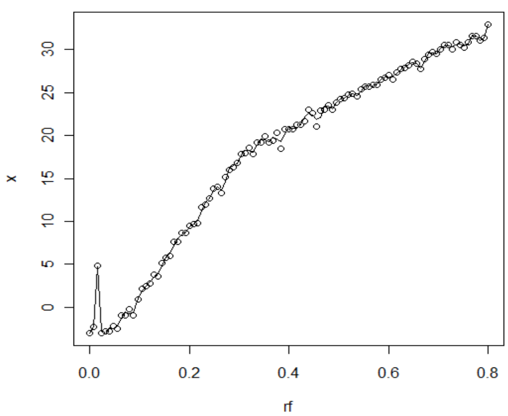

Figure 6. R_F vs. x plot

This reflects that for fault resistance in the range of 0-0.1 per unit, the sparse measurement based fault location method yields accurate result but after that the algorithm becomes sensitive to the choice of fault resistance.

TABLE I. SENSITIVITY TO R_F FOR DIFFERENT R_F RANGES

Sensitivity to R_F (S_{R_F})	**Range of R_F (per unit)**							
	0-0.1	***0.1-0.2***	***0.2-0.3***	***0.3-0.4***	***0.4-0.5***	***0.5-0.6***	***0.6-0.7***	***0.7-0.8***
Run 1	0.04	0.98	0.99	0.65	0.71	0.95	0.99	0.99
Run 2	0.02	0.88	0.97	0.94	0.85	0.99	0.84	0.69

V. CONCLUSION

An efficient scheme for reducing the impact of fault resistance on the sparse measurement fault location algorithm for transmission line is proposed. The following are the scheme properties:

- It can estimate fault location and fault resistance value even if the measurement from the ends of the faulty line are unavailable.
- A correction scheme to reduce the impact of fault resistance which is an unpredictable parameter in fault location estimation procedure is proposed.
- To achieve better accuracy, this method takes advantage of waveform data recorded by IEDs and archived data measured by SCADA RTUs.
- The fault resistance compensation process is automated to allow practical use in actual power network application.

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