Sensitivity Analysis of Voltage Sag Based Fault Location Algorithm

Po-Chen Chen, *Student Member, IEEE*, Vuk Malbasa, *Member, IEEE*, and Mladen Kezunovic, *Fellow, IEEE*
Department of Electrical and Computer Engineering
Texas A&M University
College Station, Texas 77843-3128, United States of America
pchen01@neo.tamu.edu, vmalbasa@tamu.edu, and kezunov@ece.tamu.edu

***Abstract*—In this paper, the global, variance-based, sensitivity analysis is used to quantify the impact of measurement imperfections on voltage sag based fault location. This kind of fault location requires voltage phasor information from meters to be compared to simulated cases in order to locate faults. However, meters are prone to measurement imperfections. It is therefore critical that the impact of measurement imperfections, such as measurement and loading errors, are fully assessed to account for uncertainty in algorithm inputs. Sensitivity analysis was used to attribute responsibility for uncertainty in fault location to uncertainty in the inputs of the fault location algorithm. The results demonstrate that the single most detrimental factor to precise fault location is large fault resistance, both alone and in combination with other factors. Although accurately deduced by the algorithm, other impacts of this fault feature adversely impact accuracy.**

Keywords*—EMTP; fault location; measurement uncertainty; sensitivity analysis; power distribution faults; power system protection; smart grid

I. Introduction

The accuracy of fault location has a direct impact on restoration of service and outage management in distribution systems [1], [2]. The challenges to accurate fault location in distribution systems include large scale power systems models, loading conditions changing over time, the unbalanced nature of the system, heterogeneous lines, the presence of laterals, and load taps.

Fault location methods may be differentiated into the following categories: superimposed components methods [3], [4], intelligent system based methods [5], [6], impedance based methods [7]-[12], frequency component based traveling wave methods [13]-[16], and voltage sag based methods [17]-[23]. A more detailed comparison and analysis of different fault location methods can be found in [7], [16], [20], [24] and [25].

Kezunovic [2] has discussed the implementation of precise fault location using field data measurements. The most distinctive feature of voltage sag based fault location is the potential for identifying unambiguous fault location, where the impedance based methods may suffer from estimates that cannot differentiate the exact feeder. Voltage sag based fault location requires voltage phasor information to be obtained from meters, and 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. Therefore, it is critical that the impact of measurement imperfections [26], such as measurements and loading errors, is fully assessed to account for the uncertainty in algorithm inputs.

In this study, the global, variance-based, sensitivity analysis is used to quantify the impact of measurement imperfections on voltage sag based fault location. The analysis was performed by simulating fault location in a set of scenarios designed to reveal the relationship between inputs and output uncertainty. Inputs were chosen to reflect the realistic operation of a real radial distribution network with underground lines.

This paper is organized as follows. Section II contains the background information. Section III illustrates the voltage sag based fault location method. Section IV describes the theoretical formulation of sensitivity analysis. Section V demonstrates the results and analysis. Section VI contains the conclusions reached in this study.

II. Background

A. Method of Study

The method of study is shown in Fig. 1. First the input factors were generated. Then, a translator [27] was used to create network data in readable form for use in short-circuit analysis software, which simulates faults and the fault location procedure. The generated inputs were then used together with fault location results in the sensitivity analysis software SimLab to compute the results.

B. Network under Study and Meter Placement

An actual underground distribution network was used in this study. Table I shows parameters of the overall system. Since the size of studied system is very

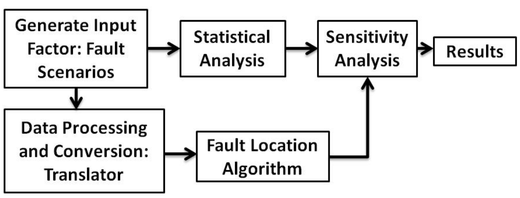

Figure 1. Scope of study.

This paper is based on results from the work supported by the U.S. Department of Energy under Award Number(s) DE-OE0000547 for a project titled "A real-time monitoring, control, and health management system to improve grid reliability and efficiency" completed by ABB, Xcel Energy, and TEES.

Paper submitted to Power Systems Computation Conference, August 18-22, 2014, Wroclaw, Poland, organized by Power Systems Computation Conference and Wroclaw University of Technology.

TABLE I. INFORMATION ABOUT THE OVERALL SYSTEM

Total Number of Components	4352
Number of Line Components	1828
Total length of Line Components (Foot)	655617.6
Total Connected Load (kVA)	33606

large, with detailed modeling, the processing time of designed fault scenarios was excessively long. In practice, a number of candidate fault nodes may be eliminated by a combination of outage mapping techniques [28], such as customer calls, circuit breaker/re-closer status [29], [30], geographical information system (GIS) coordinates [31], [32], smart meter reading [33], [34], and information about maintenance inquires [35], [36], which are applied to narrow down the faulted area. It is also known that the configuration of distribution system varies with time, which will require mentioned data (i.e. GIS data) to constantly be used to update the power system model [28]. This issue is beyond the scope of this study.

In this study, it is assumed that the faulted area has been recognized through outage mapping so that only a part of the system needs to be processed by the fault location algorithm. Note that the preliminary studies, including validation of algorithm, were performed using the full network. The selected part of system is shown in Fig. 2.

The meters from 15 locations are assumed to be available, where the meters are placed at the intersections and the ends of feeders (indicated in Fig. 2). The optimal meter placement has been fully analyzed in [20] with generalized procedures and therefore is not considered in this study.

C. *Sensitivity Analysis Background*

The purpose of sensitivity analysis is to account for the variance in output through the variance of input. In other words, it is used to differentiate how much of the variance in output is caused by different inputs, which are measurement imperfections in this study.

From the literature [17]-[23], for voltage sag based fault location methods, the most significant factor affecting input uncertainty (i.e. input factors) could be one of the following:

- Measurement errors,
- Loading estimation errors,
- Signal transferring (communication) errors,
- Setting errors,
- Absence of information and inaccurate modeling of a system.

In this study it was assumed that the error in fault location could be the result of uncertainties in assumptions about loading, fault resistance and meter aberrations. The interpretation of sensitivity analysis results provides the relative importance of designated input factors. Explanations of comparison indices which were considered are listed in Table II. The comparison between different sensitivity analysis approaches has been summarized in Table III using those comparison indices explained in Table II. Note that Table III serves as a literature survey of how quantifying the performance of fault location techniques may be performed via various sensitivity analysis approaches.

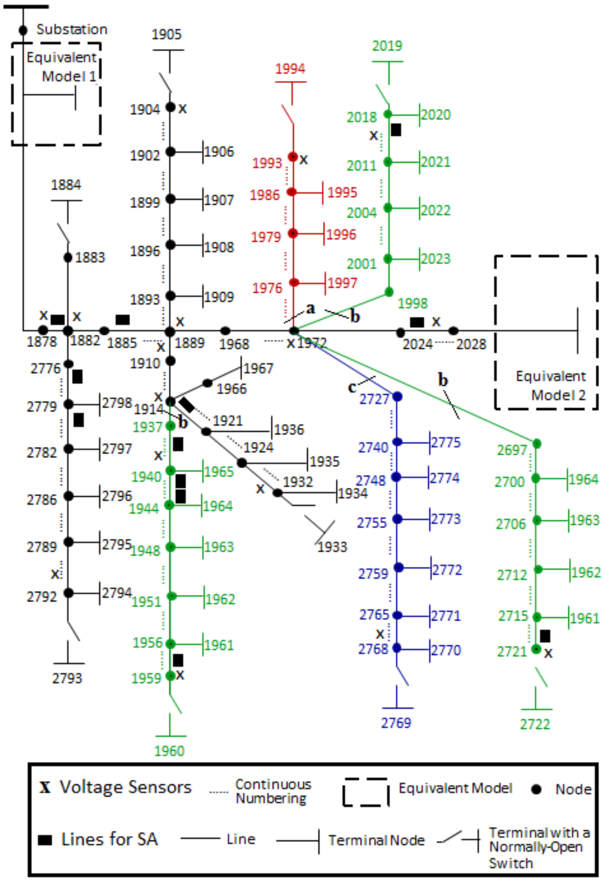

Figure 2. Schematic diagram of the system.

III. VOLTAGE SAG BASED FAULT LOCATION

In this study, the findings from [18]-[20] are applied. The voltage sag based fault location algorithm may be summarized with the following steps.

1. Voltage sag data recorded at the measurement locations, $V_{recorded}$, is sent to the distribution control center for further processing.
2. The fault is simulated at each node, one at a time, using a short-circuit program, and the fault resistance is estimated during this process. Then the calculated voltage sag data at each node, $V_{calculated}$, is obtained.
3. The calculated voltage sag data $V_{calculated}$ of each node is compared with the recorded voltage sag data $V_{recorded}$. The node having the smallest difference, or the best match, is the fault node *M*.
4. The algorithm then searches all lines connected to fault node M (performing Step 2) to pinpoint the fault location.

In some cases where the fault resistance is small or the fault location is close to the root node, the voltages obtained from meters may become similar, which makes it more difficult to recognize the true fault location. In this case, the current phase information at the root node is used. The findings in [18] may be summarized as

$$Error=(\varepsilon_{amplitude(V)})^2+(\varepsilon_{phase\ (I)})^2, \quad (1)$$

$$Flag=\frac{1}{Error+\Delta}, \quad (2)$$

TABLE II. EXPLANATIONS OF COMPARISON INDICES

Comparison Index	Explanation
Direct sensitivity analysis/Fitting	Are the indices are computed directly or is an intermediate model fitted
First order indices	Capability to compute first order indices
Total indices	Capability to compute total effect of indices
Interaction indices	Capability to compute the interaction indices between any two or more factors
Overview/General	The work is a survey of existing methods, providing a comparison of several different approaches, and/or of general applicability for sensitivity analysis

TABLE III. EXPLANATIONS AND REFERECE NUMBERS OF COMPARISON INDICES ('X' INDICATES POSITIVE)

Ref.	Direct sensitivity analysis/Fitting	First order indices	Total indices	Interaction indices	Overview /General
[37]	Dir.	X		X	
[38]	Both	X		X	
[39]	Fit.	X		X	X
[40]	Both	X		X	X
[41]					X
[42]	Dir.	X	X	X	X
[43]	Dir.	X	X		X

where $_{amplitude(V)}$ is the difference between the amplitude of $V_{recorded}$ and $V_{calculated}$, $_{phase(I)}$ is the difference between the phase of calculated and recorded current at the root node, Δ is a small number to prevent the division by zero, and *Flag* is used to identify the faulted node. Realistically, the voltage phase information is not always available; therefore it is not used to compare the difference between the phase of $V_{recorded}$ and $V_{calculated}$ in (1) in this study. Note in Step 4, after locating the maximum value of *Flag* at Node *M*, the algorithm searches for the maximum value of *Flag* on the connected lines to pinpoint the fault.

While obtaining the value of *Flag* at each node, one at a time, the fault resistance was also estimated as described in [19]. The method consists of applying the fault current at the root node, where the difference between the calculated current phasor and the recorded current phasor is expressed as

$$\varepsilon = |I_{calculated}| - |I_{recorded}|, \tag{3}$$

where $|I_{calculated}|$ is the amplitude of calculated current phasor and $|I_{recorded}|$ is the amplitude of recorded current phasor at the root node. In practice, the ε value should be very close to 0 A if the estimated fault resistance is very close to the real one at the true fault location. To enhance the speed of the procedure, a user-given current tolerance $\varepsilon_{user\text{-}given}$ may be provided to stop iterating when ε falls below $\varepsilon_{user\text{-}given}$. The fault resistance process can be summarized as

1. A fault is simulated at a node with fault resistance very close to 0 Ω. If   is smaller than 0 A, then this node could not be the fault node since the greater fault resistance would not be able to produce the same amount of fault current $|I_{recorded}|$.

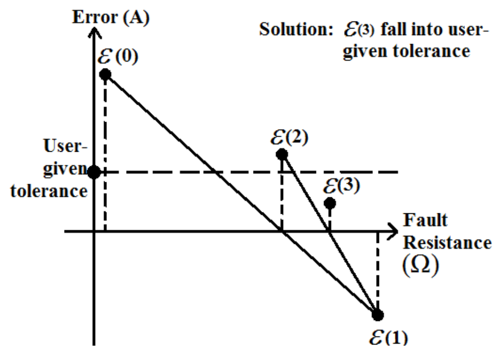

Figure 3. Fault resistance estimation procedure [19].

2. If ε is not smaller than $\varepsilon_{user\text{-}given}$, increase the fault resistance and obtain the new ε. By extrapolating and/or interpolating the obtained ε with estimated fault resistance, a closer estimate of fault resistance is obtained (Fig. 3 [19]).

IV. THEORETICAL FORMULATION OF SENSITIVITY ANALYSIS

Global variance-based sensitivity analysis may be used to understand the impact of measurement imperfections on fault location. The goal of sensitivity analysis is one of distributing responsibility for uncertainty in the output to uncertainty in the inputs of a fault location algorithm. Sensitivity analysis is used to establish the following in relationship to the studied algorithm [37]:

1. Examine the robustness,
2. Obtain the relationship between inputs and outputs,
3. Clarify how the output variance may be reduced by suppressing input variances.

For purposes of analyzing uncertainty in model output using sensitivity analysis, it is assumed the empirically observed uncertainty in fault location is a function $f(x)$ of input factors, which may be represented as $x \in [0,1]^d$. Here, each of the d input factors has been mapped from $\mathbb{R}$ into the interior of a d-dimensional hypercube. Such a mapping can be made without loss of generality since the input factor space is bijectivley mapped to such a hypercube. It is also assumed that the x used to test the fault location algorithm has a diagonal covariance matrix [37]. Then the goal of variance-based sensitivity analysis is to assign to each input a sensitivity index whose magnitude is proportional to the amount of variance in fault location that results from it.

By specifying a univariate probability distribution for each input factor it is possible to create x which has a diagonal covariance matrix. Then sampling from the joint distribution of input factors, a large number of fault location scenarios can be created. By applying the described fault location procedure to each scenario an estimate of $\sigma^2 f(x)$ can be computed. In order to compute the sensitivity indices it is then necessary to decompose the variance $\sigma^2 f(x)$ is such that

$$\sigma^2 f(\mathbf{x}) = \sum_{i=1}^{d} \sigma^2 i + \sum_{i=1}^{d} \sum_{j<i} \sigma^2 ij + \ldots + \sigma^2 1 \ldots d \cdot \tag{4}$$

If the main effect of a factor x_i on the output $f(x)$ is denoted as $\sigma^2 i = \sigma^2 x_i (E[f(x)|x_i])$ then the compound effects of any two factors x_i and x_j may be computed as

$$\sigma^2 ij = \sigma^2 x_i x_j (E[f(x)|x_j, x_i]) - \sigma^2 i - \sigma^2 j \;. \quad (5)$$

The interaction of more than two factors may be similarly described in [42].

V. Results and Analysis

To perform the study, the algorithm interfacing with load flow analysis in the Alternative Transient Program (ATP) [44] was coded in C++. The data was generated in ATP to represent realistic field gathered data about the generated fault scenarios.

A. Validation of Fault Location Method

Prior to the sensitivity analysis, it is necessary that the studied voltage sag based fault location method is validated to ensure the accuracy without measurement imperfections. In pursuit of validation, experiments with no measurement imperfections were performed (no measurement errors and no loading estimation errors). The single-phase-to-ground fault was simulated on every receiving node of all lines.

From the validation results, the accuracy of algorithm is ensured, where there was no bug in the algorithm and the computational error was very small. In cases where the output error was not zero, the algorithm always detected nodes on the same lateral as the true location of fault. In most cases, the detected nodes were downstream of true fault location.

B. Results of Sensitivity Analysis

Simulations of single phase line to ground faults were used in the sensitivity analysis. The considered lines were at differing distance from the root node (near, middle, far) and are shown in Table IV, where in each category, four lines were picked (as indicated in Fig. 2). After preliminary tests, the input factors shown in Table V were determined for sensitivity analysis. The high-impedance faults are not considered in this paper since the number of necessary experiments is already large.

In order to obtain global variance-based sensitivity indices, it is necessary to simulate a large number of fault scenarios under carefully designed conditions. According to the Sobol approach, it is necessary to have 256 sets of the analyzed four input factors in order to compute all levels of interaction on algorithm performance. For more accurate results, that number was doubled, performing 512 experiments on each line (specified in Table IV) while varying the input factor values according to distributions (specified in Table V).

Table VI summarizes the results of this study, where the resulting 6144 experimental assessments of fault location accuracy are summarized. The results are averaged across lines specified in Table IV. The input factor label number in Table VI is specified in Table IV.

In Table VI, the strongest influence on the accuracy of fault location (0.55) comes from fault resistance, with large fault resistance leading to large error in fault location. Fig. 4 illustrates the relationship true fault resistance has with fault location error, where one can see the algorithm tends to overestimate distance from root to fault when fault resistance is high.

Interestingly, the algorithm performs prediction of fault resistance with fair accuracy, as illustrated in Fig. 5, showing the scatter plot of true and predicted fault resistance.

`In Table VI, the second largest influence on error (0.29) comes when all four factors under consideration are at detrimental values for the fault location algorithm. The third most important interaction (0.15) is that of fault resistance, distance from root to fault and loading error taken together. In this case, voltage magnitude error at meters has a very small effect on overall accuracy.

It is also possible to compute total effects of each input factor's influence on error at all levels of interaction as shown in Table VII. Note that while total effects describe a single factor influence on error, it does not discount interactions with other factors and

TABLE IV. 6144 Experimental Assessments On The Considered Lines (512 Experiments for Each Line)

Near Root Node: Line between Nodes	**Middle distance from Root Node: Line between Nodes**	**Far from Root Node: Line between Nodes**
1879 and 1880	1938 and 1939	1958 and 1959
1886 and 1887	1941 and 1942	2016 and 2017
2777 and 2778	1942 and 1943	2025 and 2026
2780 and 2781	1916 and 1917	2720 and 2721

TABLE V. Input Factors and Specified Range for Sensitivity Analysis

Input Factor	**Distribution Function**	**Range**	**Label Number**
Voltage magnitude error at meters	Log-uniform	[-0.02%, 0.02%]	1
Fault resistance	Log-uniform	[1 Ω, 20 Ω]	2
Distance from root to fault location	Uniform	At each line, the fault is assumed to be at 10% to 90% from the receiving end.	3
Loading error	Gaussian μ=0; σ=0.005	[-0.02%, 0.02%]	4

TABLE VI. Summarized Results of sensitivity analysis

Order of Interaction	**Input Factor Label Number**	**Average Sensitivity Index**
1st Order	1	0.0097
	2	0.55
	3	0.071
	4	0.1
2nd Order	1, 2	0.077
	1, 3	0.063
	1, 4	0.056
	2, 3	0.12
	2, 4	0.14
	3, 4	0.076
3rd Order	1, 2, 3	0.021
	1, 2, 4	0.031
	1, 3, 4	0.04
	2, 3, 4	0.15
4th Order	1, 2, 3, 4	0.29

Input Factor Label Number | Total Sensitivity Indices

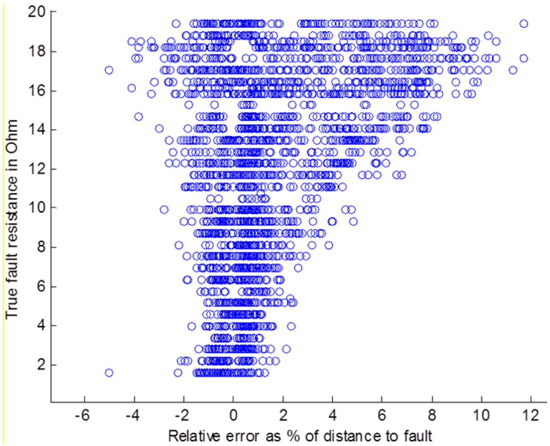

Figure 4. Scatter plot of true fault resistance vs. relative error.

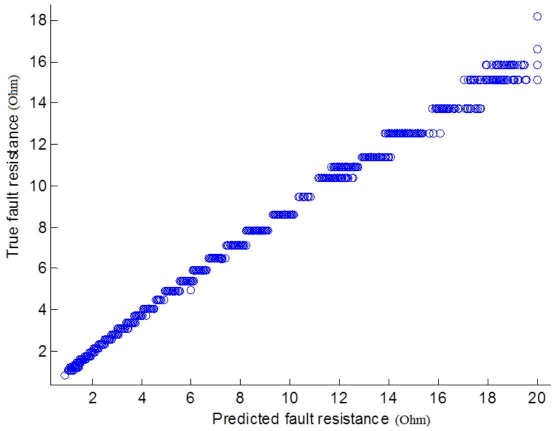

Figure 5. Scatter plot of predicted fault resistance vs.true fault resistance.

therefore some overlapping exists, since fault location error is not purely additive function of input.

In Table VII, the most influential factor (1) for accurate fault location is fault resistance, while distance from root to fault (0.38) and error from loading estimation (0.37) are less influential, andvs. voltage magnitude error at meters (0.2) although important is least detrimental to total algorithm performance.

In Fig. 6, the relationship is illustrated between distance from root to fault in terms of percentage of where the fault is from the receiving end of the line, and the relative error as a percentage of total distance from root to fault. The effect of distance from root to fault is more clearly observed in Fig. 7 showing the scatter plot between total distance from root to fault and relative error. The observations from the results of sensitivity analysis can be summarized as follows.

- The algorithm performs flawlessly under favorable conditions.
- For good performance, the algorithm requires an accurate estimation of load profile.
- On average, under adverse conditions, the algorithm has a tendency towards overestimating fault distance.
- The single most detrimental factor to precise fault location is large fault resistance, both alone and when interacting with other factors. Although accurately deduced by the algorithm, other impacts of this fault characteristic adversely impact accuracy.
- The second most influential factor is total distance from root to fault, which by itself is not very important but in interaction with other factors may result in unfavorable over estimation of distance from root to fault. Faults located closer to the root node have a strong tendency towards overestimation of fault distance while those located further away have smaller error, though this may be an artifact of suboptimal meter placement.
- Loading error, while in and of itself having a small impact on error, may adversely interact with other factors, such as fault resistance, and to a lesser degree distance from root to fault, leading to inaccurate measurements.

TABLE VII. SOBOL INDICES OF TOTAL EFFECTS

Input Factor Label Number	Total Sensitivity Indices
1	0.2
2	1
3	0.38
4	0.37

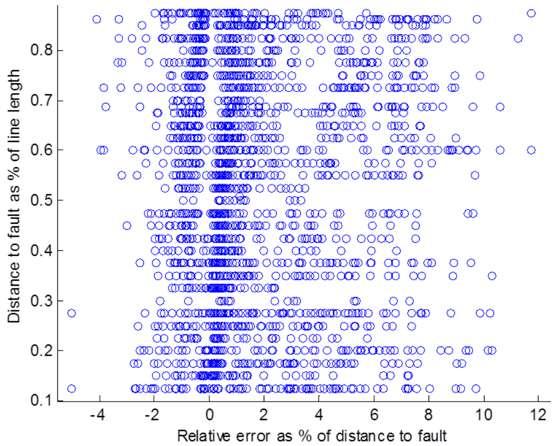

Figure 6. Scatter plot of relative distance from fault to node vs. relative error.

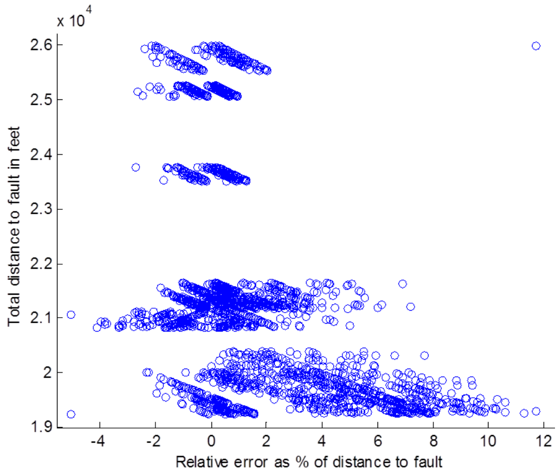

Figure 7. Scatter plot of total distance from root to fault in feet vs. relative error between predicted and actual fault location.

- The voltage magnitude error may be the only factor that could be manipulated, where the voltage measurement error has a very small impact on accuracy compared to other factors considered, both in terms of its direct influence and in terms of interactions with other factors.

C. Results of Uncertainty Analysis

The results of the uncertainty analysis from 6144 experiement assements are summarized in Table VIII, where the fault location algorithm experinces an average relative error of 1.1% of the total distance from root to fault indicating it has a slight tendency towards over estimating the distance from root to fault. This can be confirmed by the error's skewness factor being positive and the 95% confidence intervals being asymmetric around 0. A visual summary can be interpreted as shown in Fig. 8.

In Fig. 9, the relationship between actual total distance from root to fault and predicted total distance from root to fault is shown, along with the linear interpolation fitted with least squares indicating excellent fit across all measurements with a slight bias. In the case of larger distance from root to fault, the algorithm tends to underestimate distance, while in the case of shorter distances to fault the algorithm often overestimates.

During testing, a similar set of tests is performed without any error introduced. The results are illustrated in Fig. 10. When operating under favorable conditions, without noisy measurements, the algorithm shows extremely low error and bias. In Fig. 10, the residuals squared metric between actual and predicted fault location, R^2, is 0.9987, indicating excellent fit.

VI. CONCLUSIONS

This paper makes several contributions:

- The global variance-based method is used to quantify the impact of measurement imperfections on voltage sag based fault location.
- The voltage sag based fault location algorithm performs flawlessly under favorable conditions. For good performance, the algorithm requires an accurate estimation of load profile.
- The single most detrimental factor to precise fault location is large fault resistance, both alone and in combination with other factors. The factor, voltage magnitude error at meters, may be the only one that could be managed, where the voltage measurement error has a very small impact on accuracy compared to other factors considered.
- The fault location algorithm makes an average relative error of 1.1% of the total distance from root to fault, indicating that it has a slight tendency towards over estimating the distance from feeder root to fault. When operating under favorable conditions, without noisy measurements, the algorithm shows extremely low error and bias.

ACKNOWLEDGMENT

The authors gratefully acknowledge Dr. J. Stoupis, Dr. M. Mousavi, Dr. N. Kang, and Dr. X. Feng from the ABB Group for their feedback and valuable advice. The authors would also like to thank Dr. Y. Dong, formerly a graduate student at Texas A&M University and now with Electrocon, for her contributions and suggestions.

TABLE VIII. UNCERTAINTY ANALYSIS RESULTS

Metric	Value
Mean error	252 ft / 1.1%
Mean absolute error	330 ft / 1.6%
Standard deviation of error	437 ft / 2.3%
95% confidence interval	-1.7% to 7.3%
Skew	1.5
Kurtosis	2.2
Distance from root to fault range (in ft)	25983 - 19246

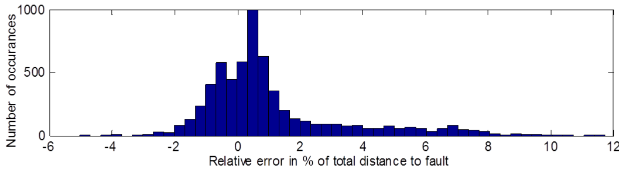

Figure 8. Histogram of relative error values in % of total distance from root to fault.

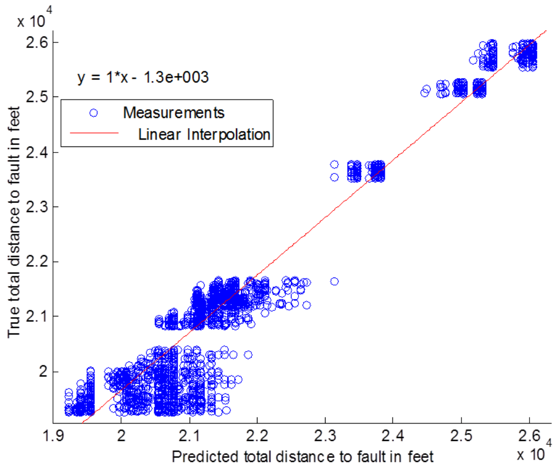

Figure 9. Scatter plot of actual distance from root to fault vs. predicted distance from root to fault, with linear interpolation, when noisy measurements are used.

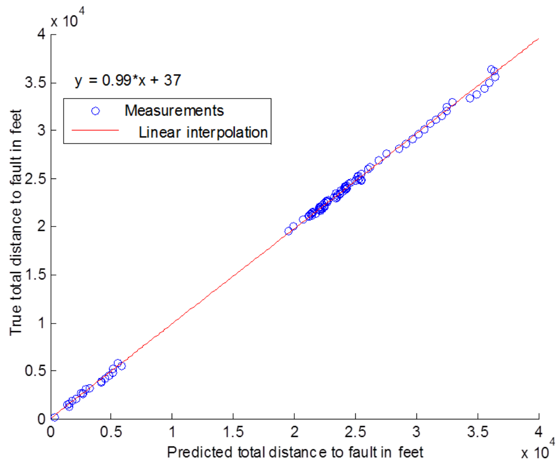

Figure 10. Scatter plot between actual distance from root to fault and predicted distance from root to fault, with linear interpolation, without noisy measurements.

REFERENCES

[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, "Smart fault location for smart grids," *IEEE Trans. on Smart Grid*, vol. 2, No. 1, pp 11-22, Mar. 2011.

[3] R. K. Aggarwal, *et al.*, "New concept in fault location for overhead distribution systems using superimposed components," *IEE Proc. Gen., Trans., Distrib.*, vol. 144, no. 3, pp. 309-316, May 1997.

[4] R. K. Aggarwal, *et al.*, "An interactive approach to fault location on overhead distribution lines with load taps," *6th Int. Conf. Developments in Power Syst. Protection*, pp. 184-187, Mar. 1997.

[5] J. J. Mora, *et al.*, "Fault location in power distribution systems using ANFIS nets and current patterns" *IEEE/PES Trans. Distrib. Conf. and Expo. Latin America*, Venezuela, 2006

[6] J. Mora-Florez, *et al.*, "Fault location in power distribution systems using a learning algorithm for multivariable data analysis," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1715-1721, July. 2007.

[7] J. Mora-Florez, *et al.*, "Comparison of impedance based fault location methods for power distribution systems," *Electric Power Systems Research*, vol. 78, no. 4, pp. 657–666, 2008.

[8] A. A. Girgis, *et al.*, "A fault location technique for rural distribution feeders," *IEEE Trans. Ind. Appl.*, vol. 29, no. 6, pp. 1170–1175, Dec. 1993.

[9] L. Yuan, "Generalized fault-location methods for overhead electric distribution systems," *IEEE Trans. Power Del.*, vol. 26, no. 1, pp. 53–64, Jan. 2011.

[10] S. Das, *et al.*, "Distribution fault-locating algorithms using current only," *IEEE Trans. Power Del.*, vol. 27, no. 3, pp. 1144–1153, Jul. 2012.

[11] R. H. Salim, *et al.*, "Extended fault-location formulation for power distribution systems," *IEEE Trans. Power Del.*, vol. 24, no. 2, pp. 508–516, Apr. 2009.

[12] M. S. Choi, *et al.*, "A direct three-phase circuit analysis-based fault location for line-to-line fault," *IEEE Trans. Power Del.*, vol. 22, no. 4, pp. 2541-547, Oct. 2007.

[13] A. Borghetti, *et al.*, "Integrated use of time-frequency wavelet decompositions for fault location in distribution networks: Theory and experimental validation," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 3139–3146, Oct. 2010.

[14] A. Borghetti, *et al.*, "Continuous-wavelet transform for fault location in distribution power networks: Definition of mother wavelets inferred from fault originated transients," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 380–388, May 2008.

[15] Z. Q. Bo, *et al.*, "Accurate fault location technique for distribution system using fault-generated high-frequency transient voltage signals," *IEE Proc. Gen., Trans. and Distrib.*, vol. 146, no. 1, Jan. 1999.

[16] F. H. Magnago and A. Abur, "Fault location using wavelets," *IEEE Trans. Power Del.*, vol. 13, no. 4, pp. 1475–1480, Oct. 1998.

[17] Z. Galijasevic and A. Abur, "Fault location using voltage measurements," *IEEE Trans. Power Del.*, vol. 17, no. 2, pp. 441–445, Apr. 2001.

[18] R. A. F. Pereira, *et al.*, "Improved fault location on distribution feeders based on matching during-fault voltage sags," *IEEE Trans. Power Del.*, vol. 24, no. 2, pp. 852–862, Apr. 2009.

[19] S. Lotfifard, *et al.*, "Voltage sag data utilization for distribution fault location," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 1239–1246, Apr. 2011.

[20] S. Lotfifard, *et al.*, "A Systematic Approach for Ranking Distribution Systems Fault Location Algorithms and Eliminating False Estimates," *IEEE Trans. Power Del.*, vol. 28, no. 1, pp. 285-293, Jan. 2013.

[21] Y. Dong, *et al.*, "Enhancing Accuracy While Reducing Computation Complexity for Voltage Sag Based Distribution Fault Location," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 1202–1212, Apr. 2013.

[22] P.-C. Chen, *et al.*, "Locating Sub-Cycle Faults in Distribution Network Applying Half-Cycle DFT Method," *IEEE/PES Trans. Distrib. Conf. Expo.* (*T&D*), 2014, in press.

[23] P.-C. Chen, *et al.*, "Sensitivity of Voltage Sag Based Fault Location in Distribution Network to Sub-Cycle Faults", submitted to *46th North American Power Sympo.* (*NAPS*), 2014.

[24] R. H. Diaz and T. M. Lopez, "Fault Location Techniques for Electrical Distribution Networks: A Literature Survey," *Proc. European Power and Energy Syst.*, pp. 311-318. Jun. 2005.

[25] *IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines*, IEEE Std C37.114-2004, Jun. 2005.

[26] P.-C. Chen, *et al.*, "Uncertainty of Measurement Error in Intelligent Electronic Devices", *IEEE/PES General Meeting*, 2014, in press.

[27] F. de León, *et al.*, "Development of Data Translators for Interfacing Power-Flow Programs with EMTP-Type Programs: Challenges and Lessons Learned", *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 1192-1201, Apr. 2013.

[28] P.-C. Chen, *et al.*, "The Use of Big Data for Outage Management in Distribution Systems," *International Conference on Electricity Distribution* (*CIRED*) *Workshop,* 2014, in press.

[29] P. Dehghanian, *et al.*, "Security-Based Circuit Breaker Maintenance Management," *IEEE/PES General Meeting*, Jul. 2013.

[30] Y. Guan, *et al.*, "Assessing Circuit Breaker Life Cycle using Condition-based Data," *IEEE/PES General Meeting*, Jul. 2013.

[31] A. V. Netto, "Visualization System Integrated for Electric Power Distribution Networks," *IEEE Latin Amer. Trans.*, vol. 8, no. 6, pp. 728-733, Dec. 2010.

[32] S.-J. Huang, C.-C. Lin, "Application of ATM-based network for an integrated distribution SCADA-GIS system," *IEEE Trans. Power Syst.*, vol. 17, no. 1, pp. 80-86, Feb. 2002.

[33] H. Tram, "Technical and operation considerations in using smart metering for outage management." *IEEE/PES Trans. Distrib. Conf. Expo. (T&D)*, 2008.

[34] A. Albert and R. Rajagopal, "Smart Meter Driven Segmentation: What Your Consumption Says About You," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4019-4030, Nov. 2013.

[35] P. Dehghanian and M. Kezunovic, "Cost/Benefit Analysis for Circuit Breaker Maintenance Planning and Scheduling", *45th North American Power Symp.* (*NAPS*), Sep. 2013.

[36] P. Dehghanian, *et al.*, "Critical Component Identification in Reliability Centered Asset Management of Distribution Power Systems via Fuzzy AHP", *IEEE Syst. J.*, vol.6, no.4, pp. 593-602, Dec. 2012.

[37] R. Zivanovic and H. B. Ooi, "A Systematic Approach for Testing Transmission Line Fault-Locating Techniques," *Electricity 2007 Conf., The Electric Energy Society of Australia* (*EESA*), Aug. 2007.

[38] R. Zivanovic, "Evaluation of Transmission Line Fault-Locating Techniques Using Variance-Based Sensitivity Measures," *16th Power Syst. Computation Conf.* (*PSCC*), Jul. 2008.

[39] R. Zivanovic, H. B. Ooi, "Sensitivity Analysis of Transmission Line Fault Location," *IEEE Lausanne Power Tech*, pp. 1187-1190, Jul. 2007.

[40] H. B. Ooi, "Global Sensitivity Analysis of Fault Location Algorithms", M.Sc. Thesis, Univ. of Adelaide, Australia, 2008.

[41] I. M. Sobol, "A primer for the Monte Carlo Method," CRC Press Inc., 1994.

[42] A. Saltelli, *et al.*, "Global Sensitivity Analysis: The Primer," John Wiley & Sons, 2008.

[43] A. Saltelli, *et al.*, "Variance-based sensitivity analysis of model output: Design and estimator for the total sensitivity index," *Computer Physics Communications*, 2010.

[44] Alternative Transients Program, ATP-EMTP, 2010. [Online]. Available: http://www.emtp.org