Sensitivity of Voltage Sag Based Fault Location in Distribution Network to Sub-Cycle Faults

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***Abstract*—Single-phase-to-ground sub-cycle faults in the distribution network can be located using voltage sag. This paper illustrates how a sensitivity study of measurement imperfections can be used to quantify the impact of sub-cycle faults on voltage sag based fault location. Our results suggest that there is a complex relationship between factors influencing error in fault location because the design of the study covered a wide range of conditions. The more complicated, higher order interactions have a stronger influence on error than any particular input factor alone.**

***Index Terms*—Fault location, power distribution faults, power system faults, power system protection, smart grids.**

I. Introduction

Electrical faults in power system must be detected, located, and cleared within a short period of time to prevent from the possible consequential damages to people, property, and environment. Fault detection in power distribution systems is performed with the help of data coming from sensors and remote terminal units [1]. Fault location plays a critical role in facilitating the quick repair by the maintenance personnel and restoration of faulted area [2], [3] and finally the fault clearing process which is accomplished with the reliable circuit breakers being called to operate via a protection device [4], [5].

Fault location is crucial to restoration and outage management of power systems. The accuracy of fault location therefore directly impacts the reliability of utility services. A wide variety of research efforts on fault location methods in distribution systems has been carried out [6]-[23]. The techniques include superimposed components methods [6], [7], intelligent system methods [8], [9], impedance based methods [10]-[14], traveling wave methods [14]-[16], and voltage sag based methods [18]-[21]. Detailed comparison and analysis of different fault location methods may be found in [22] and [23].

Relatively common sub-cycle faults, whose observable signal change is shorter than one cycle [24]-[26], are not easily handled using conventional fault location methods. The IEEE Standard C37.114™ Section 6.10 [27] expresses that traveling-wave approaches may be the only solutions for short-duration faults. Impedance-based approaches require that fundamental voltage and current quantities are properly measured over at least 0.5 of a cycle and most likely over several cycles. In cases when fault clears faster than two cycles, impedance-based approaches may not be able to discover the existence of sub-cycle faults.

Our literature review reveals that there are various phasor estimation methods based on samples from short time-windows proposed, including improved DFT method [28], recursive wavelet [29], and adaptive signal processing [30], [31]. It appears, however, that these methods have not been used to improve voltage sag based fault location to cope with sub-cycle faults in distribution networks. In [32], authors show that the sub-cycle faults (greater than 0.5 cycle) can be located accurately with the proposed method when no measurement imperfections [33] (e.g. magnitude and phase errors) are excluded.

In this paper, a sensitivity study is presented to quantify the effect of measurement imperfections on sub-cycle voltage sag based fault location method proposed in [32]. Extensive sets of test cases have been used. Our results suggest that there is a complex relationship between factors influencing error in fault location where different input factors have different effects under each order of interaction.

In Section II, background for implementation of a fault location algorithm for sub-cycle faults is described and voltage sag based fault location is introduced. In Section III, sensitivity analysis for voltage sag fault location is formulated. Results are presented and discussed in Section IV, and conclusions are provided in Section V.

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II. Implementation of Fault Location Algorithm

A. Background

The method of calculating the duration of a sub-cycle-fault has been discussed in [25], where half-cycle Discrete Fourier Transform (DFT) is applied for sub-cycle faults between 0.5 and 1 cycle. In this paper, it is assumed that the fault type is a single-phase-ground [24]. The method described in [25] to identify the fault starting time and the faulty phase has been used in [32], where the algorithm identifies the fault starting time and fault type using the current waveform at the root node.

For sub-cycle faults shorter than 0.5 cycle, detection of fault inception is still possible using the current measured at the substation. Our preliminary research reveals that if a 0.5 cycle window is maintained, where the window "slides" across data, at one point in time the fault waveform will be fully contained within the window and phasors may be correctly extracted. However, following issues arise:

1. Voltage sag would be observable only within 0.5 cycle delay since the half-cycle DFT is applied,

2. The extracted voltage sag would not be completely correct since the sliding window includes waveform data from before the fault.

Further research is necessary to find phasor extraction approaches for events causing fault waveforms to be shorter than 0.5 cycles.

B. Fault Location Algorithm for Sub-Cycle Faults

The work in [18]-[21] demonstrates that utilizing voltage sag may be used to accurately locate faults. As demonstrated in [32], since the voltage sag data during sub-cycle fault period can be obtained by using the half-cycle DFT method, the same method could be applied to obtain the fault location. The overall flow chart of proposed method is shown in Fig. 1, [32]. The process of voltage sag based FL algorithm is summarized as shown in Fig. 2, where the findings in [20] are applied so that

$$Error = \varepsilon^2_{amplitude\ (V)} + \varepsilon^2_{phase\ (V)} + \varepsilon^2_{phase\ (I)}, \qquad (1)$$

and

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

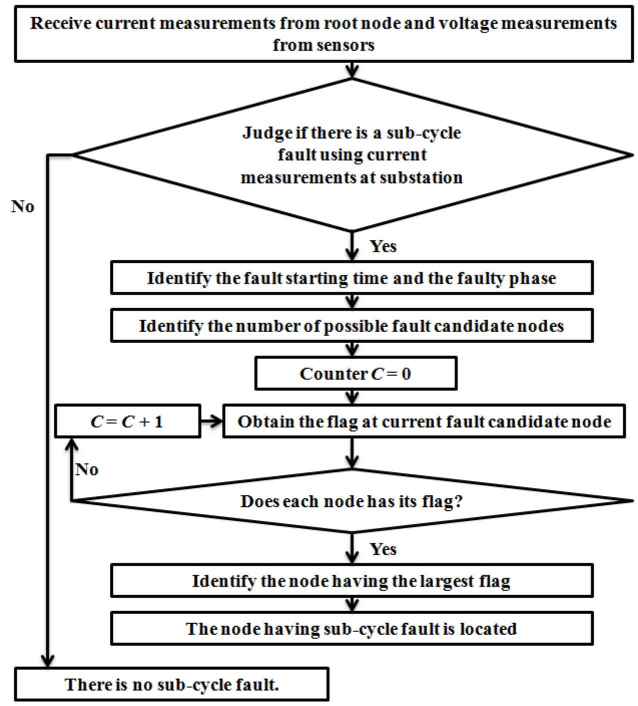

Figure 1. The process of proposed sub-cycle fault location [31].

where $\varepsilon_{amplitude(V)}$ is the difference between the amplitude of calculated and recorded voltage, $\varepsilon_{phase(V)}$ is the difference between the phase of calculated and recorded voltage, $\varepsilon_{phase(I)}$ 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 fault node.

C. Assuptions

1) Optimal meter placement [21]: The goal of the optimization of number of meter is to reduce the cost but still cover the fault detection of full network. In this paper, meters have been placed on all nodes for testing purposes. A generalized procedure may be found in [21].

2) Overall characteristic of current-limiting fuses (CLF) [34]: While not all characteristics of CLF are taken into account, from the literature [18]-[21] the fault may be accurately located based on voltage sags. Therefore, if it is assumed that the maximum voltage sag is recorded during the CLF operation, the fault may be accurately located [34].

III. Theoretical Formulation of Sensitivity Analysis

Global variance-based sensitivity analysis may be used to analyze variance of output in connection to variance of inputs to a model. In other words, it differentiates the uncertainties of output which could be caused by a certain set of input uncertainties. Detailed literature and formulation have been given in [18].

Using sensitivity analysis in conjunction with uncertainty analysis reveals the dependence of the discrepancy between true and estimated fault location while simulating different operating scenarios. In our study, the advantages for such an approach are listed below [35]:

1. Testing the robustness of the algorithm,

2. Obtaining the relationship between inputs and outputs of algorithm, and

3. Understanding how the output uncertainties may be reduced by suppressing input uncertainties.

The sensitivity of a model $f(x)$ is analyzed, which is the distance from the root node to the fault location, to input factors which may be represented as $x \in [0,1]^d$, where each of the d input factors has been mapped from $\mathbb{R}$ into the interior of a d-dimensional hypercube, without loss of generality since the input factor space may be bijectively mapped to such a hypercube, but incurring the condition that the inputs x are independently distributed [35].

Then the goal of variance-based sensitivity analysis is to distribute responsibility for uncertainty in the output $f(x)$ among the model inputs x. The importance, or sensitivity index, of an input factor $x_i \in \{x_1, x_2, \ldots, x_i, \ldots, x_d\}$, is then related to the amount of variance in output which can be attributed to it.

In order to perform variance-based sensitivity analysis it is necessary to perform the fault location procedure on a large number of scenarios defined by input factor value combinations, sampled from the joint distribution of input factors, and then perform a decomposition of the exhibited variance. The decomposition of variance $\sigma^2 f(x)$ is such that

$$\sigma^2 f(x) = \sum_{i=1}^{d} \sigma^2 i + \sum_{i=1}^{d} \sum_{j<i} \sigma^2 ij + \ldots + \sigma^2 1 \ldots d \quad (3)$$

Here if the main effect of a factor x_i is denoted on the output $f(x)$ as $\sigma^2 i = \sigma^2 x_i(E[f(x)\,|x_i])$ then the compound effects of two factors x_i and x_j can be described as

$$\sigma^2 ij = \sigma^2 x_i x_j(E[f(x)\,|x_j, x_i]) - \sigma^2 i - \sigma^2 j \,. \quad (4)$$

The combined effects of more than two input factors interacting can be similarly described as demonstrated in [36]. More details can be found in [18].

IV. Results and Analysis

Alternative Transient Program (ATP-EMTP) [37] is chosen as the platform for obtaining the phasor information of sub-cycle faults in time-domain simulations. The sampling frequency is set to be 32 samples per cycle. A 25 kV radial distribution network known as the Saskpower network was used in this study, and is shown in Fig. 3. Details of network components can be found in [10] and [23]. The validation of studied fault location is detailed in [32], where the results reveal that the single-phase-to-ground sub-cycle fault can be located when no measurement imperfections are present.

To indicate the effects of different measurement imperfections on the algorithm, the sensitivity and uncertainty analysis will be demonstrated in this section. The labeling numbers of each factor considered are shown in Table I. The given node names can be found in Fig. 3. There were 1000 cases simulated at each phase of every node, so there were 15000 cases in total run in time-domain.

A. Resutls of Sensitivity Analysis

Tables II and III present the results of sensitivity analysis, where the label numbers representing different Sobol indexes are indicated in Table I. Table II shows the results of first to fourth order interactions, and Table III shows the results of fifth and sixth order interactions. The concluded remarks of Tables II and III are illustrated below.

- Overall, the results indicate that input factors have a complex relationship with the accuracy of the algorithm, as there is no single factor showing large effect on accuracy when cases are averaged.

- Of the first order factors, the Voltage Phase Error was most related to error with average un-normalized Sobol index of 0.113.

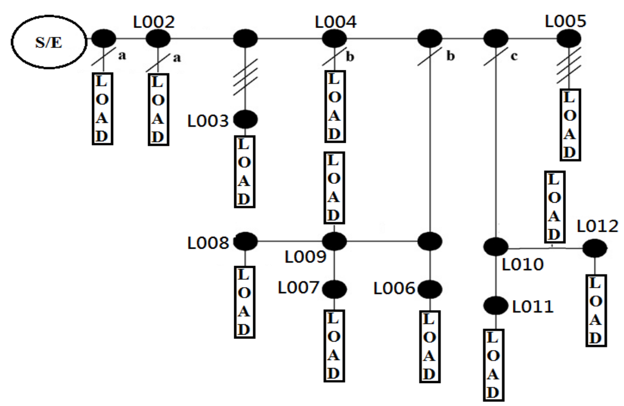

Figure 3. Saskpower network, Canada [10], [23].

TABLE I. Labeling Number of Sobol Index

Sobol Index	Label Number
Voltage Magnitude Error at Meters	1
Voltage Phase Error at Meters	2
Current Phase Error at the Root Node	3
Availability of Voltage Phase Information at Meters	4
Fault Start Time	5
Length of Fault Cycle [0.5, 1]	6

TABLE II. RESULTS OF SENSITIVITY ANALYSIS: FIRST TO FOURTH ORDER INTERACTIONS

N^{th} Order Interaction	Sobol Index Label Number	Experiments on Each Node									Average
		L002A	**L003A**	**L003B**	**L004B**	**L005A**	**L005B**	**L005C**	**L006B**	**L008B**	
1^{st} Order	**1**	0.0000	0.0000	0.0055	0.0000	0.0000	0.0000	0.0187	0.0000	0.0000	0.0027
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0170	0.0000	0.0000	**0.1130**
	3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0187	0.0000	0.0644	0.0092
	4	0.0000	0.0000	0.1823	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0203
	5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	6	0.0000	0.0000	0.0123	0.0000	0.0000	0.0000	0.0187	0.0000	0.0644	0.0106
2^{nd} Order	**1, 2**	0.0341	0.0000	0.2249	0.0500	0.0000	0.1197	0.0000	0.0331	0.1365	0.0665
	1, 3	0.0000	1.6679	0.0090	0.0694	0.0000	0.1235	0.0000	0.0000	0.0077	0.2086
	1, 4	1.1063	0.0000	0.0000	0.0500	0.0000	0.1209	0.0000	0.0000	0.1925	0.1633
	1, 5	0.0000	0.0000	0.0266	0.0500	0.0000	0.1209	0.0187	0.0000	0.0000	0.0240
	1, 6	0.0341	0.0000	0.0000	0.0500	0.0000	0.3372	0.0000	0.0000	0.0000	0.0468
	2, 3	0.0000	1.3803	0.0926	0.0194	0.0000	0.3309	0.0000	0.0331	0.0084	0.2072
	2, 4	0.1150	0.0000	0.0000	0.0000	0.0000	0.1094	0.0000	0.0000	0.2028	0.0475
	2, 5	0.0341	0.0000	0.0728	0.0000	0.0000	0.1094	0.0000	0.0331	0.0264	0.0307
	2, 6	0.0671	0.0000	0.0000	0.0000	0.0000	0.1094	0.0000	0.0331	0.0644	0.0304
	3, 4	0.0259	0.0000	0.0000	0.0000	0.0000	0.1120	0.0000	0.0000	0.0644	0.0225
	3, 5	0.0000	1.6679	0.1115	0.0194	0.0000	0.1004	0.0187	0.0000	0.0000	0.2131
	3, 6	1.0513	1.6679	0.0407	0.0194	0.0000	0.0951	0.0000	0.0000	0.0000	**0.3194**
	4, 5	0.0259	0.0000	0.0000	0.0000	0.0000	0.1094	0.0375	0.0000	0.0728	0.0273
	4, 6	0.1078	0.0000	0.0000	0.0000	0.0000	0.1082	0.0000	0.0000	0.0741	0.0322
	5, 6	0.0341	0.0000	0.0000	0.0000	0.0000	0.1329	0.0187	0.0000	0.0000	0.0206
3^{rd} Order	**1, 2, 3**	0.0308	0.0000	0.0000	0.0000	0.0368	0.0000	1.0358	0.0000	0.0000	0.1226
	1, 2, 4	0.0000	1.7638	0.0000	0.0104	1.1283	0.0000	1.0708	0.0381	0.0000	0.4457
	1, 2, 5	0.0121	0.0000	0.8728	0.0000	0.2503	0.0000	0.9959	0.0000	0.0000	0.2368
	1, 2, 6	0.0000	1.4762	0.0000	0.0000	3.5101	0.0000	1.0521	0.0000	0.0000	**0.6709**
	1, 3, 4	0.0000	0.0000	0.1236	0.0000	0.2749	0.0000	0.0024	0.1043	0.0000	0.0561
	1, 3, 5	0.0627	0.0000	0.0000	0.0000	0.2135	0.0000	0.0000	0.0811	0.0000	0.0397
	1, 3, 6	0.0000	0.0000	0.0963	0.0000	0.0614	0.0000	0.0375	0.0381	0.0000	0.0259
	1, 4, 5	0.0000	0.2876	0.3286	0.0000	0.4884	0.0000	0.0000	0.0662	0.0000	0.1301
	1, 4, 6	0.0000	0.4984	0.1580	0.0000	0.2062	0.0000	0.0187	0.0331	0.0000	0.1016
	1, 5, 6	0.0000	0.0000	0.0533	0.0000	0.1522	0.0000	0.0000	0.0381	0.0258	0.0299
	2, 3, 4	0.0000	0.0575	0.0862	0.0715	0.1448	0.0000	1.0170	0.0050	0.6896	0.2302
	2, 3, 5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9796	0.0431	0.0000	0.1136
	2, 3, 6	0.0000	4.0370	0.0000	0.0000	0.0000	0.0000	1.0170	0.0000	0.0000	0.5616
	2, 4, 5	0.0000	0.2492	0.1049	0.0708	0.7042	0.0000	0.9796	0.0000	0.0000	0.2343
	2, 4, 6	0.0000	2.7415	0.1927	0.0604	0.4367	0.0000	1.0170	0.0000	0.0000	0.4942
	2, 5, 6	0.0000	2.4922	0.2308	0.0396	0.0368	0.0000	0.9796	0.0000	0.0000	0.4199
	3, 4, 5	0.0000	1.7254	0.0595	0.0000	0.0000	0.0000	0.0000	0.0431	0.0000	0.2031
	3, 4, 6	0.0000	1.9363	0.1693	0.0000	0.0614	0.0000	0.0000	0.0000	0.0000	0.2408
	3, 5, 6	0.0000	0.0000	0.0000	0.4201	0.0614	0.0000	0.0000	0.0811	0.0000	0.0625
	4, 5, 6	0.0000	0.4984	0.2700	0.0604	0.0000	0.0000	0.0000	0.0050	0.0000	0.0926
4^{th} Order	**1, 2, 3, 4**	1.0276	5.0875	0.0438	0.0562	0.0000	0.3334	0.0000	0.0000	0.0000	0.7276
	1, 2, 3, 5	0.0000	2.1088	0.0000	0.1076	0.1472	0.2319	0.0187	0.0000	0.1449	0.3066
	1, 2, 3, 6	0.7883	0.0000	0.1711	0.0971	0.0000	0.4338	0.0000	0.0000	0.1913	0.1868
	1, 2, 4, 5	1.1987	0.0000	0.0000	0.0000	0.0000	0.0734	0.0000	0.0331	0.1893	0.1661
	1, 2, 4, 6	1.1816	0.0000	0.0592	0.0000	0.0000	0.3373	0.0000	0.0662	0.3909	0.2261
	1, 2, 5, 6	0.0523	3.7455	0.0000	0.0208	0.0000	0.3106	0.0000	0.0994	0.2093	0.4931
	1, 3, 4, 5	1.0078	0.0000	0.0000	0.1193	0.0000	0.0643	0.0350	0.0000	0.0000	0.1363
	1, 3, 4, 6	2.0602	1.8405	0.9418	0.1193	0.0000	0.3229	0.0000	0.0000	0.1545	0.6044
	1, 3, 5, 6	0.9418	5.7553	0.0000	0.0000	0.0000	0.2901	0.0000	0.0000	0.1108	**0.7887**
	1, 4, 5, 6	1.1041	0.0000	0.0000	0.0000	0.0000	0.3595	0.0725	0.0000	0.1848	0.1912
	2, 3, 4, 5	0.1903	0.0000	0.1699	0.0000	0.0000	0.3193	0.0000	0.0000	0.0000	0.0755
	2, 3, 4, 6	0.8438	0.0000	0.0000	0.0000	0.0000	0.2100	0.0000	0.0662	0.0000	0.1245
	2, 3, 5, 6	0.9351	0.0000	0.0000	0.0000	0.6111	0.2273	0.0000	0.0000	0.0908	0.2071
	2, 4, 5, 6	0.2580	0.0000	0.0000	0.0000	0.0000	0.1316	0.0000	0.0563	1.4840	0.2144
	3, 4, 5, 6	1.0551	0.0000	0.0000	0.0000	0.2135	0.1099	0.0912	0.0182	0.1468	0.1816

TABLE III. RESULTS OF SENSITIVITY ANALYSIS: FIFTH AND SIXTH ORDER INTERACTIONS

N^th Order Interaction	Sobol Index Label Number	Experiments on Each Node									Average
		L002A	**L003A**	**L003B**	**L004B**	**L005A**	**L005B**	**L005C**	**L006B**	**L008B**	
5th Order	**1, 2, 3, 4, 5**	0.0000	0.0000	0.8071	0.0000	1.2803	0.0000	0.0000	0.1192	0.7089	0.3240
	1, 2, 3, 4, 6	0.0000	0.0000	0.0000	0.0000	4.7413	0.0000	1.0732	0.0199	0.5273	0.7069
	1, 2, 3, 5, 6	0.0000	0.0000	0.9450	0.3993	3.1076	0.0000	0.0000	0.0629	0.0000	0.5016
	1, 2, 4, 5, 6	0.0000	0.7788	1.5792	0.1554	5.1167	0.0000	0.9796	0.0000	0.0000	0.9566
	1, 3, 4, 5, 6	0.0000	3.2935	0.0000	0.3202	0.1448	0.0000	0.0000	0.1242	0.0000	0.4314
	2, 3, 4, 5, 6	0.0000	15.0524	0.1926	0.4562	0.3090	0.0000	0.9608	0.0000	0.2607	**1.9146**
6th Order	**1, 2, 3, 4, 5, 6**	2.9556	0.0000	0.8983	0.6042	0.0000	1.4579	0.9976	0.9271	1.0047	**0.9828**

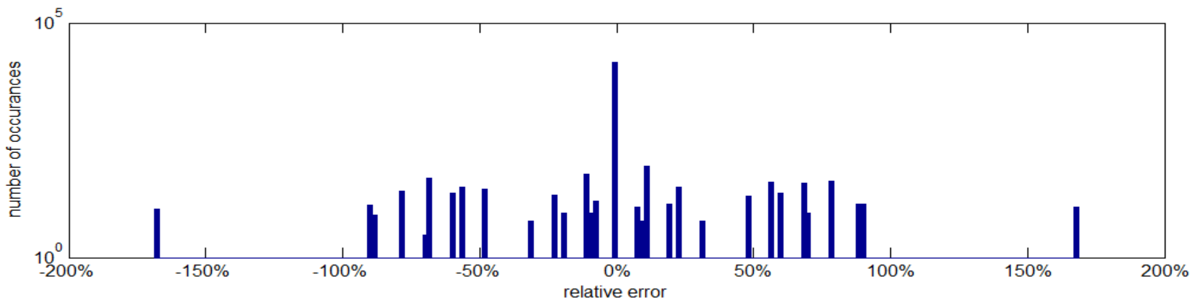

Figure 4. Histogram of errors.

- Of the second order interactions, the combination of Current Phase Error at Root Node and Length of Fault Cycle has the strongest second order effect with an average un-normalized Sobol index of 0.3194.
- Of the third order interactions, the combination of Voltage Magnitude Error at Meters, Voltage Phase Error at Meters, and Length of Fault Cycle have the strongest influence on error with average un-normalized Sobol index of 0.6709.
- Of the fourth order interactions, the combination of Voltage Magnitude Error at Meters, Current Phase Error at the Root Node, Availability of Voltage Phase Information at Meters and Length of Fault Cycle had the strongest influence with average un-normalized Sobol index of 0.7887.
- Of the fifth order interactions, the combination of Voltage Phase Error at Meters, Current Phase error at Root Node, Availability of Voltage Phase Information at Meters, Fault Start Time and Length of Fault Cycle had the strongest influence on error with un-normalized Sobol index of 1.9146.
- Taken together the interaction of all the input factors had an un-normalized average Sobol index of 0.9828.
- The more complicated, higher order interactions have a stronger influence on error than any particular input factor alone.
- The results from sensitivity analysis also suggest that the measurement errors have negative impact on the accuracy of studied fault location method. From the preliminary experiments, when the errors were very large, the algorithm was not able to locate the fault anywhere in the system.

Table IV presents the results of uncertainty analysis. The results show that the mean error is extremely small, showing the unbiasedness of the error. The mean absolute error is much larger due to many extreme values. Large Kurtosis and standard deviation of error reveal a distribution of error with a heavy tail, and many extreme values, even though the 95% confidence interval indicates no errors.

The distribution is better described in Fig. 4, which represents a log-histogram of the resulting error in absolute terms. The histogram reveals that 95.7% of the cases have zero error, represented with the peak at 0% error, and many extreme values on both sides.

V. CONCLUSIONS

This paper has demonstrated the quantification of impact of measurement imperfections on voltage sag based fault location for sub-cycle faults:

- Global variance-based sensitivity analysis has been applied to analyze the variances of output which are related to the variances of inputs under a probabilistic frame.
- A large number of cases has been applied to obtain the results for sensitivity and uncertainty analysis. Results of sensitivity analysis show the negative impact of measurement imperfections to studied voltage sag based fault location algorithm. Results of uncertainty analysis suggest that the mean error is extremely small, showing the unbiasedness of the error. The mean absolute error is much larger due to many extreme values.
- Because the design of the study covered a wide range of conditions, the results suggest that there is a complex relationship between factors influencing error in fault location. The more complicated, higher order interactions

have a stronger influence on error than any particular input factor alone.

- The measurement errors a have negative impact on the accuracy of the studied fault location method. When the errors are very large the algorithm may not be able to locate the fault anywhere in the network.

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