# Sensitivity analysis of fault locators in power distribution systems considering distributed generation

## Analisis de sensibilidad de localizadores de fallas para sistemas de dsitribución considerando generación distribuida

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**ABSTRACT**

This paper presents the methodology to perform the sensitivity analysis for impedance-based fault location methods, considering power distribution systems and the presence of distributed generation. The proposed methodology helps to determine the power distribution system model parameters, which significantly affect the fault locator performance. Having identified such parameters, the next step is to perform improvement strategies and compensations of the fault locators aimed to develop more robust locating tools. As result of the proposed methodology, a set of critical parameters of the power system model is here identified.

**Keywords:** Sensitivity analysis, fault location, power systems, distributed generation.

**RESUMEN**

En este artículo se presenta una metodología para realizar el análisis de sensibilidad para métodos de localización de fallas basados en la estimación de la impedancia, considerando sistemas de distribución de energía eléctrica con presencia de generación distribuida. La metodología propuesta permite determinar los parámetros del modelo del sistema de distribución de energía eléctrica, que afectan significativamente el desempeño del localizador. Luego de determinar estos parámetros, el siguiente paso consiste en desarrollar estrategias de mejoramiento y compensación de los localizadores de fallas para herramientas más robustos. Como resultado de la metodología propuesta, un conjunto de parámetros críticos del sistema de potencia son identificados

**Palabras clave:** Análisis de sensibilidad, localización de fallas, sistemas de potencia, generación distribuida.

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## Introduction

Quality power electrical is an important aspect in power system operation, due the requirements normally associated to the continuity indexes. One of the current applied strategies aimed to maintain the continuity indexes, are associated to fault location [Salim, et al., 2011] [Zhu, et al., 1997]. By an opportune fault location, actions as maintenance, restoration and reconfiguration of the affected power system are significantly improved.

In the case of power distribution systems, the fault location methods are normally classified in impedance-based and knowledge-based methods [Aggarwal, et al., 1997] [Das, 1998] [Mora, et al., 2008]. This research focuses on the impedance-based applied to power distribution systems with distributed generation. These methods are used to determine the distance from the substation to the faulted node using the measurements of voltage and current at the generation sources. As these methods use the power system model parameters, are highly dependent on errors normally presented in real systems due the uncertainty associated to define the values of load, conductor resistance and system capacitance and impedance at the fault time instant.

The validation of fault location methods has been performed using different methodologies. Initially, the methods consist on a simulation of several scenarios that varies the fault location and the fault resistance, however aspects associates to the power system parameters were not considered [Das, 1998]. Several approaches perform the same evaluation of the fault locator as previously presented [Salim, et al., 2011] [Zhu, et al., 1997] [Aggarwal, et al., 1997].

One of the alternatives to consider these parameters is the development of an extensive simulation tool to create a fault database in a power system by considering variations on load size, and values of fault resistance, fault location, conductor resistance, system admittance and capacitance, line arrangement, among others [Mora, et al., 2006].

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By using the extensive data simulation, a methodology to perform a sensitivity analysis for impedance based fault location methods applied to radial and also non-radial power distribution systems, under of hundreds of different operating conditions, is here proposed. The non-radial power systems are those which consider the presence of distributed generation.

The sensitivity analysis determines which of the modelling parameters that most affect the performance of the locator. These have to be deeply analysed to determine the best way to improve the locator. This strategy allows developing more robust fault location methods.

Finally, as contents, this paper is divided into the following sections; section two presents the theoretical aspects; section three presents the proposed sensitivity analysis methodology; section four is devoted to show the obtained results and finally, at the last section the main conclusions of this research are highlighted.

## Theoretical Background

This section is devoted to present the basic aspects of the theoretical foundation, used to develop the sensitivity analysis methodology here proposed. A deep analysis or explanation are out of the scope of this paper, but can be obtained at the provided references.

### A. *Sensitivity analysis*

The sensitivity analysis helps to determine the input parameters that most influence the output variability, by the evaluation of different scenarios that may occur in the daily operation of the power distribution system. This analysis is performed to represent real-life circumstances such as erroneous measurements, lack of information or uncertainty of some modelling parameters.

Sensitivity analysis determines:

a. If a model represent adequately the system under study. If the sensitivity analysis shows a strong dependence on parameters that supposedly are not important, then a revision of the model must be done.

b. The factors that mostly contribute to the output variability and that require additional research. Sensitivity analysis allows to strengthen the model under study, minimizing the impact of erroneous measurements.

c. The model parameters that are insignificant and can be removed of the used model, which reduces the complexity of the model.

d. If a parameter group interacts with others. Often important effects occur when two parameters vary simultaneously, this is important because these effects cannot be seen if the parameters are analyzed individually.

Sensitivity analysis has three main stages: the definition of the sampling technique, the model evaluation, and performing of technical sensitivity. These steps allow identifying the variables that most affect the fault location methods [Saltelli & Chan, 2000].

### B. *Latin Hypercube sampling*

The defined sampling technique is the Latin hypercube. This technique generates a small set of data that completely represents the total data search space, reducing the computational cost. The most important characteristic of this sampling technique is related to the not dependence of the model being analysed [Viana & Venter, 2009].

The input data of the sampling technique consist of a number of variables *s* to be changed and *n* is the number of points to be evaluated. This technique generates an *n* by *s* matrix with values between 0 and 1, where each row represents a point to be evaluated and the columns represent the coordinates of that point [Liefvendahl & Stocki, 2005] [Glover & Kochenberger, 2002].

### C. *Tabu search*

Tabu is a metaheuristic used here to improve the sampling process performed by Latin hypercube. This technique uses the concept of adaptive memory, so the movements are defined as "Tabu movements" to avoid the returning movements into areas that had already been visited, allowing it to escape from local optima [Glover & Kochenberger, 2002].

### D. *Regression analysis*

Regression analysis is a statistical process which is used to determine the input variables that most affect the outputs. Through this analysis, the set of numbers called Beta coefficients are obtained. As high is the Beta coefficient, most important is the associated parameter (input) on the behaviour of the fault locator (output). The Beta coefficients are calculated using (1), where the absolute value of this coefficient indicates the importance of the variable [Saltelli & Chan, 2000].

$$\beta_j = \frac{b_j \, Sx_j}{Sy} \tag{1}$$

To calculate the variables in (1), the Equations (2), (3) and (4) are required. Where, *x* is the uncertainty matrix obtained from Latin hypercube, *y* is the vector of results and *n* is the number of evaluated points.

$$b_j = (x^T x)^{-1} x^T y \tag{2}$$

$$Sx_j = \sqrt{\sum_{k=1}^{n} \frac{\left(x_{kj} - \bar{x}_j\right)^2}{n-1}} \tag{3}$$

$$Sy = \sqrt{\sum_{k=1}^{n} \frac{(y_k - \bar{y})^2}{n-1}} \tag{4}$$

## Methodology

The general scheme of the proposed methodology used in sensitivity analysis of impedance-based fault locator for power distribution systems considering distributed generation, is shown in Figure 1.

Sensitivity analysis is performed by a cooperative strategy between ATP and MATLAB. ATP is used as modelling and simulation software and MATLAB is used as software for handling the information.

*A. Sampling using Latin Hypercube*

The first step of the proposed methodology consists in sampling the total space using Latin hypercube. This technique has as input data, the variables *n* and *s*. In the specific case of the sensitivity analysis, *n* represents the number of operating states in which the power system is analysed and *s* represents the considered power system modelling parameters. The parameters considered in this paper are the magnitude and unbalance of the voltage at the generation sources, the magnitude of the load, the power factor, the line length and the system frequency. Each parameter is varied within a certain range to represent changes or different operational states of a real distribution system.

Latin hypercube generates an uncertainty matrix, *n* by *s*, where each row indicates an operating state of system and each column indicates the percentage change of each parameter.

To complement this sampling technique is used a Tabu, as previously described, to maximize the distance between samples and then ensure the uniform distribution of the sampled space.

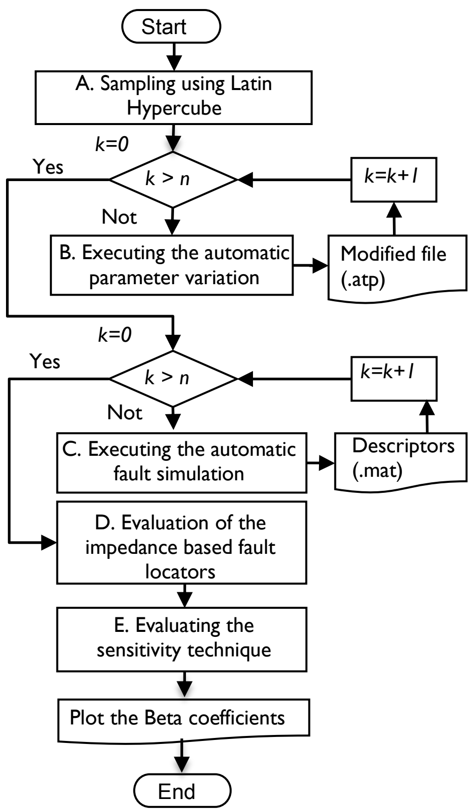


Fig. 1. Sensitivity analysis methodology. "Own compilation".

*B. Executing the automatic parameter variation*

Having defined the operating conditions, the automatic parameter variation is performed, by using the base ATP card that describes the nominal power system and the uncertainty matrix [Viana & Venter, 2009]. As result of this step, *n* modified ATP cards are obtained and each card represents a case that may occur in the daily operation of the distribution power system.

*C. Executing the automatic fault simulation*

The modified cards are the input to the automatic fault simulation tool. Each card or power system operating condition is simulated considering faults at different fault location and also different fault resistances, to obtain the values of voltage and current, during the pre-fault and fault steady states at the generation sources [Mora, et al., 2006].

*D. Evaluation of the impedance based fault locators*

Subsequently, the fault database of measurements of voltage and current is used to perform an extensive evaluation of the impedance based fault location method, which considers the presence of distributed generation. After evaluating the method, the error of locator is obtained by comparing the real distance of the fault and the distance obtained by the impedance based fault locator [Mora, et al., 2008].

*E. Evaluating the sensitivity technique*

Finally, the proposed methodology generates the Beta coefficients through the regression analysis technique. This statistical process uses the uncertainty matrix and the errors obtained by the impedance based fault locator, to calculate Beta coefficients. Each coefficient indicates the importance of the modelling parameters on the fault locator. The coefficients are presented using graphs for an easy analysis.

## Test power systems and result analysis

The methodology above presented is applied to a modification of the IEEE 34-node system with distributed generation, which is obtained from the "Distribution System Analysis Subcommittee" of the "Institute of Electrical and Electronics Engineers" [IEEE distribution system]. The power system was simulated in ATP and as is shown in Figure 2 and contains a distributed source at the end of the analysed feeder. The sensitivity analysis tool is validated using one extension to consider three phase faults of the impedance-based method presented in [Orozco, et al., 2012]. Faults were located at the longest radial feeder, which is indicated in figure 2 by the dashed lines. The tests were performed considering fault resistances of 0 Ω to 40 Ω [Dagenhart, 2000].

Sensitivity analysis is performed for 200 operating conditions and varying the six parameters in the range shown in Table 1. Considering the operator experience and national normative, the range variation was defined.

Table 1: Uncertainty ranges of the parameters. "Own compilation".

| **Modelling parameters** | **Variation range** | |
|---|---|---|
| | **Minimum** | **Maximum** |
| Voltage source magnitude | 0.95 p.u | 1.10 p.u |
| Voltage source unbalance | -3.4 ° | 3.4° |
| Magnitude system load | 10% | 150% |
| Power factor | -0.02 | 0.02 |
| Line length | 95% | 105% |
| Frequency | 59.8 Hz | 60.2 Hz |

Additionally, the sensitivity analysis tool, whose simplified interface is presented in figure 3, has spaces to include the working folder, the ATP card of the analysed power system and the number of operating states to be analysed, among others. In addition, the parameters to be modified and their respective ranges are also defined.

The results of the sensitivity analysis are shown on a graph, where the vertical axis represents the value of the Beta coefficients and the horizontal axis represents the nodes where faults are analysed.

A total of 32000 single-phase faults and three-phase faults were used to perform the sensitivity analysis.

*A. Single-phase faults*

In figure 4, the results of the average Beta coefficients for single faults are presented. The result shows how the magnitude of the load is one of the parameters that most affects the fault locator. As a consequence, a good estimation strategy of the load magnitude has to be developed as a first strategy aimed to improve the fault locator performance.

An additional parameter analysed is the line length. This parameter has a major influence in the most distant nodes from the main power substation, because the modelled admittance and impedance parameters are not accurate, therefore the resulting error is accumulated along the radial. The real systems sometimes have additional measures to the main power substation. These measures can be used to decrease the error.

The frequency is the other parameter that has a significant influence. This parameter is varied to represent measurement errors that appear in the databases of the utilities. In this case, the results show a random behaviour.

Finally, the figure shows that the unbalance of the phases of the generation sources and the load power factor are the parameters that have the lowest affect in the fault locator performance.

*B. Three-phase faults*

An additional result is presented in figure 5, in the case of three phase faults at the same distribution feeder.

As it is presented, the results are similar to those obtained in the case of single-phase faults. The load is the most influential parameter of the performance of the analysed fault location method. As in the previous case, variations in the power frequency and the line length are also parameters which affect the fault locator.

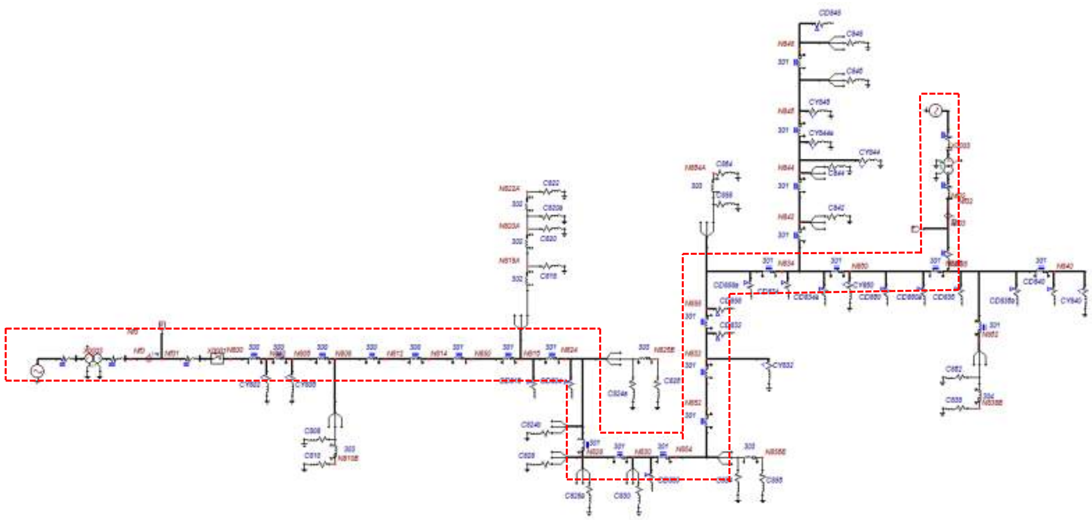

Fig. 2. IEEE 34-node power distribution system. “Own compilation”.

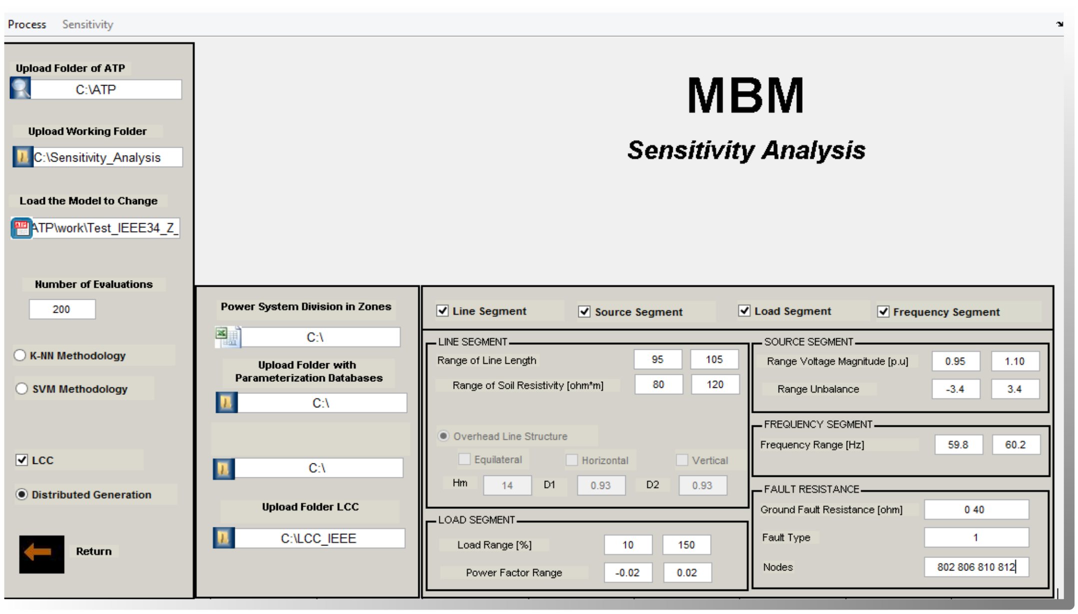


Fig. 3. Main working interface of the sensitivity analysis tool. “Own compilation”.

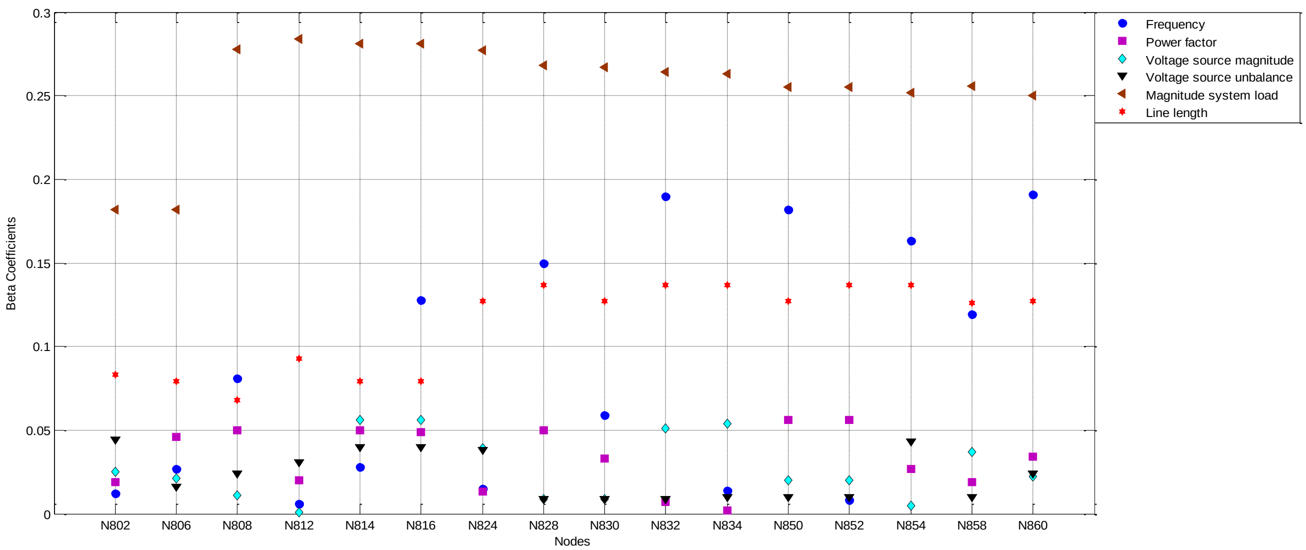


Fig. 4. Results of the sensitivity analysis for single phase fault (A-g). "Own compilation".

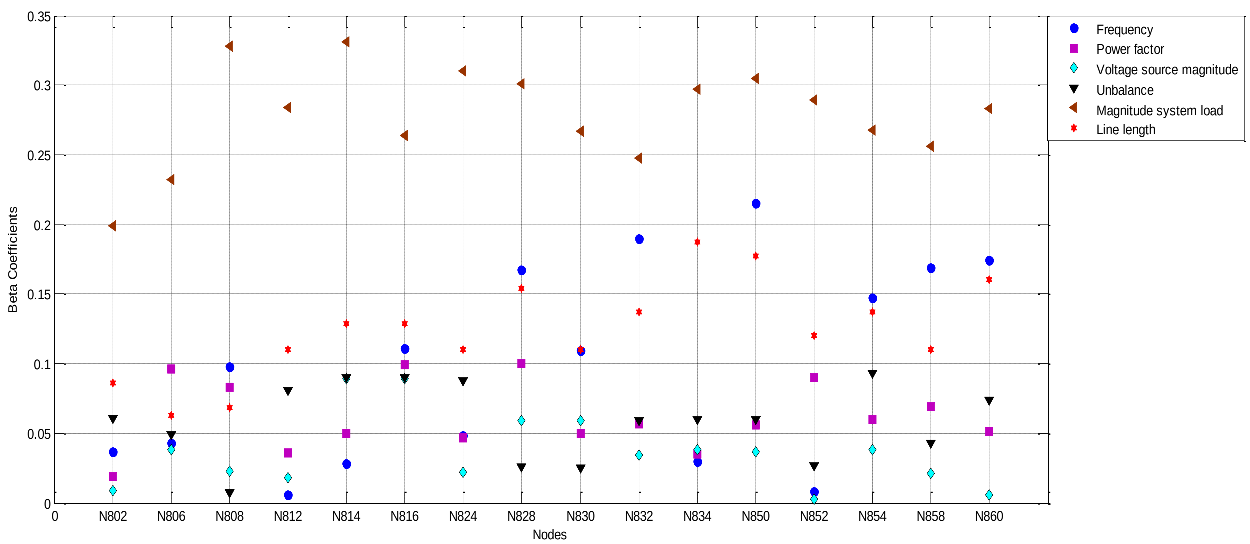


Fig. 5. Results of the sensitivity analysis for three phase faults (A-B-C-g). "Own compilation".

## Conclusions

The sensitivity analysis methodology helps to identify such modelling parameters of the power distribution system, which have a significant effect on the fault locator performance. According to the obtained results for a single-phase and three phase faults, considering fault resistances form 0 and 40 Ω, the most influential parameter is the load size. Parameters as the line length and frequency also influence the fault locator performance. Then, the next step in the improving process aimed to obtain a really robust fault locator, is to develop strategies for the adequate estimation of the load size at any time, and also adequately verify the line length along the analysed feeder.

As it was demonstrated, the proposed sensitivity analysis methodology is really helpful in the fault locator improving process, by the identification of those influential parameters.

Finally, robust fault locators allow fast restoration of the power system, ensuring high levels of the power supply continuity indexes.

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