Extended formulation for elimination of multiple estimation for fault location in power distribution systems considering the load current

Formulación extendida para la eliminación de la estimación múltiple para localización de fallas en sistemas de distribución de energía considerando la corriente de carga

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ABSTRACT

In this paper, an extension in the methodology for elimination of multiple estimation for fault location in power distribution systems considering the load current is presented. This paper presents a modification to increase the robustness of the methodology used to eliminate the multiple estimation problem, of fault location methods based on the impedance estimation for two-phase and three-phase faults. The approach here proposed uses the power distribution system parameters and the available measurements at the main power substation. Tests were performed on two power distribution systems simulated in ATP, analyzing the effect of fault resistance and load variations. The obtained results show that it is possible determine a unique fault location, eliminating the multiple estimation problem. This method also helps to improve the power continuity indexes in power distribution systems by the determination of the faulted node.

Keywords: Fault location, multiple estimation, radial power distribution systems, service continuity indexes, load current.

RESUMEN

En este artículo, se presenta una extensión de la metodología para la eliminación de la estimación múltiple para localización de fallas en sistemas de distribución de energía, teniendo en cuenta la corriente de carga. Este artículo presenta una modificación para aumentar la robustez de la metodología utilizada para eliminar el problema de la múltiple estimación de los métodos de localización de fallas basados en la estimación de impedancia para fallas bifásicas y trifásicas. El enfoque aquí propuesto utiliza los parámetros del sistema de distribución de energía y las medidas disponibles en la subestación principal. Las pruebas se realizaron en dos sistemas de distribución de energía simulados en ATP, analizando el efecto de la resistencia de falla y las variaciones de carga. Los resultados obtenidos muestran que es posible determinar una única ubicación de la falla, eliminando el problema de la múltiple estimación. Este método también ayuda a mejorar los índices de continuidad de la energía en los sistemas de distribución de energía por la determinación del nodo bajo falla.

Palabras clave: Localización de fallas, múltiple estimación, sistema de distribución de energía radial, índices de continuidad del servicio, corriente de carga.

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Introduction

Service continuity in transmission and distribution systems is considered as an important aspect, especially when electricity markets are included in a competitive environment. The most common indexes of service continuity are the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) and faults cause supply interruptions that are responsible for low rates of these service continuity [Short,2007] [Crozier & Wisdom,1999].

In distribution systems, the presence of tapped loads, laterals, not homogeneous conductors, unbalances and large load fluctuations make that fault location as an unsolved problem. Additionally, the presence of several laterals at the power distribution system, difficulties the location of a single faulted node [Das, et al., 2000].

One of the problems in impedance based methods is the multiple estimation of the faulted node. An alternative to solve this problem is using the methodology proposed in [Morales, et al., 2009], which is based on the determination of differences between the laterals, such as the topology, tapped loads and impedance lines, to locate the fault distance, eliminating the multiple estimation

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problem. In [Ramírez, et al., 2014] a method in which the load current is included in the circuital analysis for single-phase faults, in the method of elimination of multiple estimation proposed in [Morales, et al., 2009], obtaining better results. Though in distribution systems, single-phase faults are the most common, the number of two and three phase faults that occurred is also considerable [Choi, et al., 2004].

According to the previously exposed, in this paper an extension of the methodology proposed in [Ramírez, et al., 2014] for analysis to two and three-phase faults in the methodology of elimination of multiple estimation considering the load current is proposed.

This paper is presented in five sections. In section II, the theoretical aspects are given. Next, in section III the extension approach is detailed described. In section IV the tests and the result analysis are presented. Finally, section V is aimed to conclude and summarize the main contributions of this research.

Theoretical aspects

Some impedance based methods eliminates the multiple estimation of the fault location, using only network parameters and voltage and current measurements at the distribution substation [Morales, et al., 2009]. The method here proposed for eliminating the multiple estimation problem is based on the classical reactance approach described in [Sachdev, et al., 1999], but considering the load current at the faulted phases, which increases its robustness.

The approach proposed in [Morales, et al., 2009] to eliminate the multiple estimation assumes that the fault has zero impedance and therefore no current flows downstream the faulted node. The estimation of the load current in the here proposed methodology is performed by an iterative process, by using an additional fault location method [Salim, et al., 2009].

Estimation of multiple faulted node.

The multiple estimation problem of the faulted node is explained by considering the power distribution system of Fig.1, where four different places with the same value of electrical reactance to locate the fault F1 are obtained (*Xd1=Xd2=Xd3=Xd4*).

By identifying only one faulted node, the approach provides accurate information to the maintenance team, in order to find and restore the fault as soon as possible [Aggarwal, et al., 1997].Considering that it is not common to find identical laterals in power distribution systems, the here proposed methodology is based on the determination of differences between the laterals, such as the topology, tapped loads and impedance lines, to locate the fault distance, eliminating the problem of multiple estimation, using a MBM as the method based on the estimation of reactance [Das, et al., 2000] [Sachdev, et al., 1999].

Estimation of the load current

The load current and the current through the fault are included in this proposal, as a contribution to the methodology initially proposed at [Salim, et al., 2009]. The current through the fault is estimated by an iterative process, which considers three variables, the voltage at the faulted node, the fault resistance and the fault distance from the initial node of the analyzed section.

Initially, it is assumed that the load current and the pre-fault current are the same. Then, the current flowing through the fault is calculated. With this approximate value of *IFn*, the circuit parameters and the available measurements, the distance to the

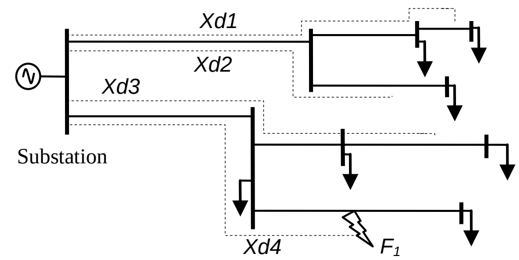

Figure 1. Multiple estimation problem of impedance based fault location methods. "Own compilation".

fault is estimated as presented in [Salim, et al., 2011]. Subsequently, using the estimated fault distance and the Fig. 2, the load current is recalculated. An iterative process is performed to improve the estimation of the *IFn*, until the error in the fault distance from one iteration respect to the previous one, become lower than a defined tolerance [Salim, et al., 2011].

Elimination of multiple estimation method

In [Morales, et al., 2009] is presented a methodology to eliminate multiple estimation of the faulted node, also considering the mutual effect at the line impedance. Additionally, a more robust approach is also proposed, by considering the effect of the load current [Ramírez, et al., 2014].

Using the proposed approach, it is possible to estimate an error for each lateral. Having estimated multiple distances, the lateral with the lowest error corresponds to faulted lateral, because the behavior of the three-phase measurements is unique for each lateral. This is possible due to differences in line impedance, parameters and loads on each lateral [Morales, et al., 2009], [Ramírez, et al., 2014].

The implemented algorithm considers an iterative procedure, which is performed section by section, on each lateral of the power distribution system under analysis. In general, this allows the estimation of a set of distances, where the error is obtained as is presented in (1).

$$Error_i = \frac{1}{n}\frac{\sum_{j=1}^{n}\left|m - m_j\right|}{m} \tag{1}$$

The proposed method considers that at the lateral which has the lowest error (weighted differences of the distances), is where the fault is found. Thus, the faulted lateral is selected.

The line impedance from node *N* to *N+1*, and the load impedance accumulated from the end of the line, are given by (2) and (3) respectively.

$$Z_{line} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \tag{2}$$

$$Z_{Load} = \begin{bmatrix} Z_{La} & Z_{Lab} & Z_{Lac} \\ Z_{Lba} & Z_{Lb} & Z_{Lbc} \\ Z_{Lca} & Z_{Lcb} & Z_{Lc} \end{bmatrix} \tag{3}$$

Z_{Load} is calculated as the ratio between the pre-fault voltage and pre-fault current in the main power substation, assuming that load is Y-connected.

Proposed Extension

Two-phase to ground fault

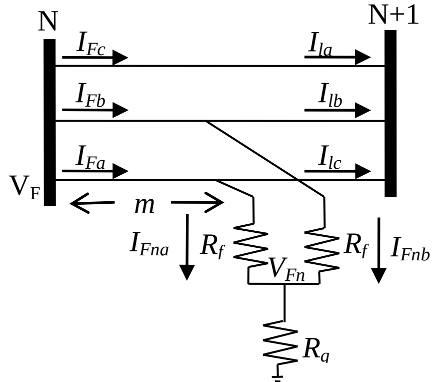

Figure 2. Three phase equivalent for a two-phase to ground fault (ab-g). "Own compilation".

In the case of two-phase to ground faults, from the analysis of the circuit shown in Figure 2, the equation (4) is obtained. For the line section between the nodes N and N+1, as shown in the test system proposed in Fig. 2, it is possible to obtain an equation of the voltage drop caused by the fault, as is shown in (4) [Morales, et al., 2009].

$$\begin{bmatrix} V_{Fa}-V_{Fn} \\ V_{Fb}-V_{Fn} \\ V_{Fc} \end{bmatrix} = \begin{bmatrix} mZ_{aa} & mZ_{ab} & mZ_{ac} \\ mZ_{ba} & mZ_{bb} & mZ_{bc} \\ mZ_{ca} & mZ_{cb} & Z_{cc}+Z_{Lc} \end{bmatrix} \begin{bmatrix} I_{Fa} \\ I_{Fb} \\ I_{Fc} \end{bmatrix} + \begin{bmatrix} R_f & 0 & 0 \\ 0 & R_f & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{Fn_a} \\ I_{Fn_b} \\ I_{Fn_c} \end{bmatrix} \tag{4}$$

$$m = \frac{imag\left(\frac{V_{F_a}-V_{F_b}}{I_{Fn_a}-I_{Fn_b}}\right)}{imag\left(\frac{DI_{F_a}+EI_{F_b}+FI_{F_c}}{I_{Fn_a}-I_{Fn_b}}\right)} \tag{5}$$

$$m1 = \frac{imag\left(\frac{V_{F_a}-V_{F_b}-V_{F_c}+(Z_{cc}+Z_{Lc})I_{F_c}}{I_{Fn_a}-I_{Fn_b}}\right)}{imag\left(\frac{(D-Z_{ca})I_{F_a}+(E-Z_{cb})I_{F_b}+FI_{F_c}}{I_{Fn_a}-I_{Fn_b}}\right)} \tag{6}$$

Where D, E and F are given by (7).

$$\begin{aligned} D &= Z_{aa}-Z_{ba} \\ E &= Z_{ab}-Z_{bb} \\ F &= Z_{ac}-Z_{bc} \end{aligned} \tag{7}$$

Furthermore, it is possible to obtain other linearly independent equation of the complex equation presented in (4). The possible additional solution, consider only the imaginary component of the fault reactance, because this is relatively constant under variations of Rf. These equations are presented in (6).

According to the information presented above, the most appropriate equation to estimate the fault distance is presented in (5). Equation 6 is additional estimation of the distance obtained in (5), taking into account all the parameters of the analyzed lateral.

Using the proposed equations, the faulted lateral can be determined, since the behavior of three-phase measurements for each lateral is only due to differences at line impedance parameters or load on each lateral. Therefore, it is possible to obtain a fault distance using the phase measurements during fault steady state, as presented in (5). Further, by using the additional distance, the error presented in 1 can be estimated. Variable n represents the number of possible additional distances (in case of two-phase fault, this number is 1)[Morales, et al., 2009].

Using (1) the error is estimated to determine the faulted node using information of the faulted phase. The fault is in the lateral with the lowest error, calculated using the estimations of (5), (6) and (7).

The multiple estimation error on the unfaulted laterals is greater than the error calculated on the faulted lateral. This is due to electromagnetic coupling occurring on the faulted lateral, at the time of occurrence of the fault.

Finally, the sweep to the distribution system takes into account all the power system parameters, including the shunt admittance of the line and load couplings.

Two-phase fault

When considering the equivalent circuit under two-phase fault, the resulting equations are the same as those presented in the case of two-phase to ground fault (these are not influenced by *Rg*). As a result, (5) and (6) are also used for the case of two-phase faults [Morales, et al., 2009].

Importantly, the estimate of the fault current varied for a two-phase or two-phase to ground fault as proposed in the method described in [Morales, et al., 2009]. It is therefore important to identify the fault type to adequately estimate the load current in the section analyzed.

Three-phase to ground fault

In the case of three-phase faults, from the analysis of the circuit shown in Figure 3, the equation (8) is obtained.

$$\begin{bmatrix} V_{Fa}-V_{Fn} \\ V_{Fb}-V_{Fn} \\ V_{Fc}-V_{Fn} \end{bmatrix} = \begin{bmatrix} mZ_{aa} & mZ_{ab} & mZ_{ac} \\ mZ_{ba} & mZ_{bb} & mZ_{bc} \\ mZ_{ca} & mZ_{cb} & mZ_{cc} \end{bmatrix} \begin{bmatrix} I_{Fa} \\ I_{Fb} \\ I_{Fc} \end{bmatrix} + \begin{bmatrix} R_f & 0 & 0 \\ 0 & R_f & 0 \\ 0 & 0 & R_f \end{bmatrix} \begin{bmatrix} I_{Fn_a} \\ I_{Fn_b} \\ I_{Fn_c} \end{bmatrix} \tag{8}$$

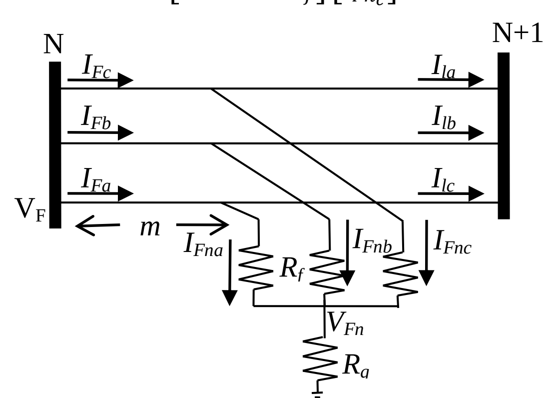

Figure 3. Three phase equivalent for a three-phase to ground fault (abc-g). "Own compilation".

From (8), three linearly independent equations for calculating m are obtained, which take into account the load current before the fault, as shown in (9), (10) and (11).

$$m1 = \frac{imag\left(\frac{V_{F_a}-V_{F_b}}{I_{Fn_a}-I_{Fn_b}}\right)}{imag\left(\frac{DI_{F_a}+EI_{F_b}+FI_{F_c}}{I_{Fn_a}-I_{Fn_b}}\right)} \tag{9}$$

$$m2 = \frac{imag\left(\frac{V_{F_b}-V_{F_c}}{I_{Fn_b}-I_{Fn_c}}\right)}{imag\left(\frac{GI_{F_a}+HI_{F_b}+JI_{F_c}}{I_{Fn_b}-I_{Fn_c}}\right)} \tag{10}$$

$$m3 = \frac{imag\left(\frac{V_{F_c}-V_{F_a}}{I_{Fn_c}-I_{Fn_a}}\right)}{imag\left(\frac{KI_{F_a}+LI_{F_b}+MI_{F_c}}{I_{Fn_c}-I_{Fn_a}}\right)} \tag{11}$$

Where G, H, J, K, L y M are given by (12)

$$\begin{aligned} G &= Z_{ba} - Z_{ca} \\ H &= Z_{bb} - Z_{cb} \\ J &= Z_{bc} - Z_{cc} \\ K &= Z_{ca} - Z_{aa} \\ L &= Z_{cb} - Z_{ab} \\ M &= Z_{cc} - Z_{ac} \end{aligned} \tag{12}$$

Because the methodology uses information from the phases not failed to calculate multiple estimates of the distance to the fault, and in this case all phases are in failure, *m* is obtained as the average of the three estimates, as shown in (13).

$$m = \frac{1}{3}(m1 + m2 + m3) \tag{13}$$

To determine the lateral under fault as proposed previously, the error is calculated using (1); In this case *n=3*.

Three-phase fault

When considering the equivalent circuit under three-phase fault, the resulting equations are the same as those presented in the case of three-phase to ground fault (these are not influenced by *Rg*). As a result, (14), (15) and (16) are also used for the case of three-phase faults [Morales, et al., 2009].

Testing and analysis

All of the proposed power systems used in tests were modeled and simulated in ATP. Two additional tools as Atpxchange and SimulacionRF were also used [Mora, et al., 2006], [Bedoya, et al., 2012]. The proposed method was implemented in Matlab.

Test power systems

The first system selected for the validation of the proposal is presented in Fig. 4, and was implemented using section lines and loads from the IEEE 34 nodes, 24.9 kV system [IEEE]. This is used to consider the elimination of the multiple estimation problem in a power system with similar laterals.

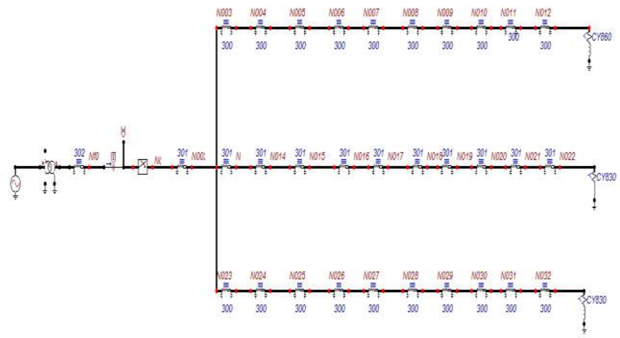

Figure 4. Power system with similar laterals. “Own compilation”.

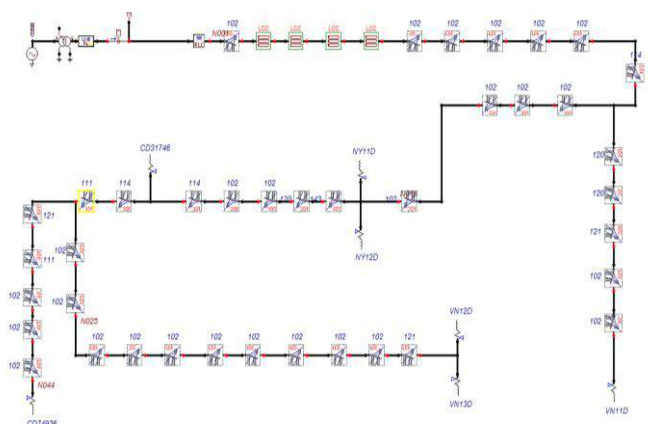

Figure 5. Real power distribution system. “Own compilation”.

The power distribution system of Fig. 4 has the same line parameters in the laterals 1 and 3, and the same impedance load in the lateral 2 and 3.Sections of line of the laterals 1 and 3 correspond to the configuration 300 of the IEEE 34 nodes system. Additionally, the load in the lateral 1 is the same as the node 860. The impedance of each section of the lateral 2 corresponds to the configuration 301 and the lateral load at the end of 2 is the same as the load on the node 830 [Morales, et al., 2009].

The second proposed test system is shown in Fig. 5, and corresponds to a real power distribution system located at Cundinamarca, Colombia. It has unbalanced loads, laterals and different line configurations, considering underground and overhead lines.

Test proposed scenarios

Two-phase, two-phase to ground, three-phase and three-phase to ground faults on a fault resistance range from 0Ω to 40Ω were simulated in all nodes for both power distribution systems [Dagenhart, 2000]. Considering the size of the power system, the analyzed faults (ab, ab-g, abc and abc-g), the fault resistances (0, 20 and 40 ohms) and the load scenarios (rated load, 1.5 rated load and 0.6 rated load), the number of analyzed faults are 324 in the case of the power system in figure 3, while 516 in the case of the power system of figure 4.

Tables I and II show the comparative behavior of the proposed approach for two-phase and three-phase faults, considering 3 different fault resistances and for different load variations.

Efficiency is calculated as the ratio of the faults adequate located and the total fault number of considered faults, under the same condition, as is given by (9). It should be noted that it is considered as a correctly localized fault, the one located at the corresponding lateral an also near to the faulted node (In a range of two nodes from the faulted one).

$$Efficiency = 100\frac{number\ of\ faults\ adecuate\ located}{total\ number\ of\ faults} \quad (14)$$

Result analysis at the power system with similar laterals: For the power system on Fig. 4, 27 faults were simulated, using three different fault resistances and also considering load variations respect to the nominal value. The results are presented in table II.

In the case of the results reported in table I, in case of a 0Ω fault resistance, fault type ab, and the system operating at nominal load, the obtained efficiency with and without consider the approach here proposed, is the same. It indicates that 14 faults (51.8519%) are identified at the corresponding lateral and at the right distance. The average reported in the last row of each table correspond to the efficiencies the performance of the methodology with and without the proposal, for each load variation stage.

The efficiency in localization of the methodology with and without the proposed, unsurprisingly, presents a very similar behavior to solid faults, regardless of variation in the load. When the fault impedance increases, is where the proposed approach makes its contribution, because as it considers the effect of the load current.

Despite the similarity in the laterals at the power system, it is noticed that in most cases the proposal improves the efficiency of the method.

Result analysis at the real power system: For the power system on Fig. 5, 43 faults were simulated, using three different fault resistances and also considering load variations respect to the nominal value. The results are presented in table II.

Although this is a real power system, which is heavily loaded and is not balanced, it shows that the proposed approach helps to obtain good results.

It can be clearly seen that in most of the cases, the efficiency of the proposed methodology is similar to the obtained in the original methodology. An acceptable overall efficiency of the strategy here proposed is observed, then the approach improves the location and elimination of multiple estimation when the fault resistance is different of zero.

TABLE I. TESTS PERFORMED IN THE CIRCUIT OF FIGURE 4. "Own compilation".

		Efficiency with original method			Efficiency with the proposed method		
Rf	**Fault type**	**Zload**	**Zload 150%**	**Zload 60%**	**Zload**	**Zload 150%**	**Zload 60%**
0	ab	51,8519	51,8519	37,037	51,8519	51,8519	37,037
	ab-g	85,1852	51,8519	81,4815	85,1852	51,8519	81,4815
	abc	55,5556	48,1481	48,1481	55,5556	48,1481	48,1481
	abc-g	55,5556	48,1481	48,1481	55,5556	48,1481	48,1481
20	ab	55,5556	51,8519	33,3333	62,963	22,2222	33,3333
	ab-g	81,4815	55,5556	29,6296	66,6667	22,2222	44,4444
	abc	44,4444	3,7037	40,7407	77,7778	70,3704	48,1481
	abc-g	44,4444	3,7037	40,7407	77,7778	70,3704	48,1481
40	ab	55,5556	3,7037	33,3333	55,5556	18,5185	33,3333
	ab-g	55,5556	3,7037	29,6296	55,5556	18,5185	48,1481
	abc	40,7407	18,5185	33,3333	48,1481	48,1481	48,1481
	abc-g	40,7407	18,5185	33,3333	48,1481	48,1481	48,1481
Average Efficiency		**55,5555**	**29,9383**	**40,7407**	**61,7284**	**43,2099**	**47,2222**

TABLE II. TESTS PERFORMED IN THE CIRCUIT OF FIGURE 5. "Own compilation".

		Efficiency with original method			Efficiency with the proposed method		
Rf	**Fault type**	**Zload**	**Zload 150%**	**Zload 60%**	**Zload**	**Zload 150%**	**Zload 60%**
0	ab	90,6977	88,3721	83,7209	90,6977	88,3721	83,7209
	ab-g	93,0233	90,6977	86,0465	93,0233	90,6977	86,0465
	abc	100	100	93,0233	100	100	93,0233
	abc-g	100	100	93,0233	100	100	93,0233
20	ab	65,1163	30,2326	44,186	81,3953	76,7442	65,1163
	ab-g	65,1163	34,8837	44,186	88,3721	83,7209	81,3953
	abc	4,6512	4,6512	4,6512	100	88,3721	67,4419
	abc-g	4,6512	4,6512	4,6512	100	88,3721	67,4419
40	ab	27,907	0	6,9767	81,3953	62,7907	72,093
	ab-g	27,907	0	6,9767	88,3721	79,0698	65,1163
	abc	4,6512	4,6512	4,6512	100	65,1163	65,1163
	abc-g	4,6512	4,6512	4,6512	100	65,1163	65,1163
Average Efficiency		**49,0310**	**38,5659**	**39,7287**	**93,6047**	**82,3644**	**75,3876**

Conclusions and future works

The methodology was successfully implemented including the load current for the two and three-phase faults, improving the efficiency in the case fault resistance values different of zero, as it was demonstrated by the obtained results in the tables I and II.

This method helps to determine the faulted lateral, even in case of similar line and load characteristics at the power distribution system. By the determination of the faulted lateral, the multiple estimation problems could be avoided, speeding up the restoration process.

As future work, considering the automation of power distribution systems is proposed as a further work the use of additional information to those obtained at the substation. According to the expected, by using information such as additional measurements and recloser and fusible operating, performance of this methodology is improved.

Finally, this approach contributes to improve the continuity indexes in real power distribution systems.

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References

A. Bedoya, J. Mora and, S. Perez, “Estrategia de reducción para la aplicación generalizada de localizadores de fallas en sistemas de distribución de energía eléctrica”. Revista EIA, ISSN 1794-1237 Número 17, p. 21-37. Julio 2012.

C. Crozier and W. Wisdom, “A power quality and reliability indexbased on customer interruption costs,” IEEE Power Eng. Rev., vol. 19,no. 4, pp. 59–61, Apr. 1999.

G. Morales, J. Mora and H. Vargas. “Elimination of Multiple Estimation for Fault Location in Radial Power Systems by Using Fun mental Single-End Measurements”. IEEE Transactions on power delivery, Vol. 24, No. 3, 2009.

IEEE. Distribution System Analysis Subcommittee. Radial Test Feeders. Available: http://www.ewh.ieee.org/soc/pes/sacom/testfeeders.html.

J. Dagenhart, “The 40-Ω ground-fault phenomenon”. Industry Applications, IEEE Transactions on, vol.36, no.1, pp.30-32, Feb 2000.

J. Mora, J. Melendez and J. Bedoya, “Extensive Events Database Development using ATP and Matlab to Fault Location in Power distribution Systems,” IEEE PES Transmission and Distribution Conference and Exposition: Latin America, Caracas, 2006.

J. Ramírez-Ramírez, J. Arrieta-Giraldo, and J. Mora-Florez, “Elimination of multiple estimation for single phase fault location in power distribution systems considering the load current,” IEEE PES Transmission & Distribution Conference and Exposition, Medellin, Colombia, 2014.

M. Choi, S. Lee, D. Leeand, B. Jin “A new fault location algorithm using direct circuit analysis for distribution systems”. 2004, pp. 35-41. IEEE Transactions on Power Systems.

M. Sachdev, R. Das, and T. Sidhu, “Distribution line shunt fault locations from digital relay measurements,” Can. J. Elect. Comput. Eng., vol. 24, no. 1, pp. 41–47, Jan. 1999.

R. Aggarwal, Y. Aslan and A. Johns “An interactive approach to fault location on overhead distribution lines with load taps”.IEEE Developments in Power System Protection Conference Publication No. 434. 1997, pp184-187.

R. Das, M. Sachdev, and T. Sidhu, “A fault locator for radial subtransmission and distribution lines,” in Proc. Power Engineering Society Summer Meeting, 2000, vol. 1, pp. 443–448.

R. Salim, K. Salim, A. Bretas, “Further improvements on impedance-based fault location for power distribution systems”. Generation, Transmission & Distribution, IET (Volume: 5, Issue: 4). 2011 pp. 467-678.

R. Salim, M. Resener, A.D. Filomena, K.R. Caino de Oliveira and A. S. Bretas: ‘Extended fault-location formulation for power distribution systems’, IEEE Trans. Power Deliv., 2009, 24, (2), pp. 508–516.

T. A. Short, Electric Power Distribution Handbook, 1st ed. London U.K.: Taylor & Francis, Apr. 2007.