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FAULT LOCATION IN DISTRIBUTION NETWORK BASED ON PHASOR MEASUREMENT UNITS (PMU)

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Abstract: ***Nowadays, phasor measurement units have many applications in the power network. Fault location using the network's impedance matrix and phasor measurement units (PMU) is a subject that has been recently brought to the location light. In this research, we review the effect of the increased number of PMUs on the precision of the fault location. The method presented in this study uses the impedance transferring between these units and the fault location based on the fault distance. In the suggested method, the uncertainty on the network's parameters has been considered and using the least-squares of faults, we can obtain the most optimal response. The advantage of this method is that it is not affected by the fault type and resistance of the short connection. In the end, the suggested method is implemented on the 14 bus distribution network and its performance has been evaluated.***

Keywords: Fault location, Phasor measurement units, Fault observability, Network's impedance matrix

1. INTRODUCTION

Electric energy transmission lines are imposed on all kinds of faults including short connection faults. Precise locating of the fault increases the network recovery pace, reduces the outage period and consequently increases the network reliability and customer satisfaction [1].

Phasor measurement units were first introduced in 1980. These units are synchronized using Global Positioning System (GPS) and measure the voltage phasor of the bus they're installed in and the current phasor of all the branches connected to that bus with high accuracy [2].

Fault location methods are generally divided into three categories:

- Impedance methods
- Traveling waves methods
- Smart methods

It seems that using voltage and main harmonic current of the transmission line terminal along with line parameters is the easiest way to detect faults. This method is simple and affordable to implement. Depends on which signals we use for locating, the impedance method is divided into groups of one terminal, two terminals, and several terminals. The one-terminal method [3-5] uses voltage and current of one side of the line and doesn't need communication tools and is usually placed in micro-processing relays. Effect of fault resistance on these methods and the need to know the Thevenin's equivalent circuit at the end of the line are the main problems of these methods.

With the advancement of communication equipment and to improve the location accuracy of the estimated fault, several terminals methods have been presented which use meters synchronized or non-synchronized in two terminals [6-12] or three terminals [13-14] or several terminals [15-16].

The two-terminal method benefits from signals of two sides of the transmission line and as a result consume more information and therefore has a better performance and accuracy compared to the one-terminal method. Depending on whether the signals from both sides are synchronized or not, methods to find the fault location are different from each other [1].

Three-terminal and several-terminal methods have been achieved from developing and expanding two-terminal algorithms. These algorithms first use several meters to detect the faulty area and section and then use two-terminal methods to find the exact fault location [17-20]. In this article, the effect of the increased number of PMUs on precision of fault location has been investigated. Fault locating is done using a network's impedance matrix. In the suggested method and because the uncertainty of the network's parameters has been considered, the equations are solved, and the most optimal response is gained through the least-squares of fault. In the end, the mentioned method will be implemented on a network and we can observe that it has high accuracy.

2. FAULT LOCATING METHOD

We assume that information of positive, negative and zero sequence information is available and thus we can obtain the network's impedance matrix. It is important to point out that the capacitance of the distribution network lines has been excluded.

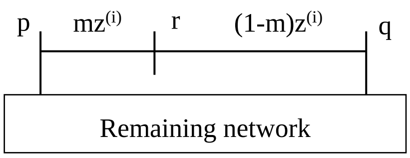

Figure 1. Fault location in the network.

According to Figure 1, we assume that the fault has occurred in point r of the p-1 line. Point r is in the per-unit distance m of the bus p. point r is considered as the bus number n+1. Network's impedance matrix before the fault is named $Z_o^{(i)}$ i can be zero, one or two and it shows the zero, positive and negative sequence. If the capacitance is neglected, then the network's impedance matrix is developed as the following [21]:

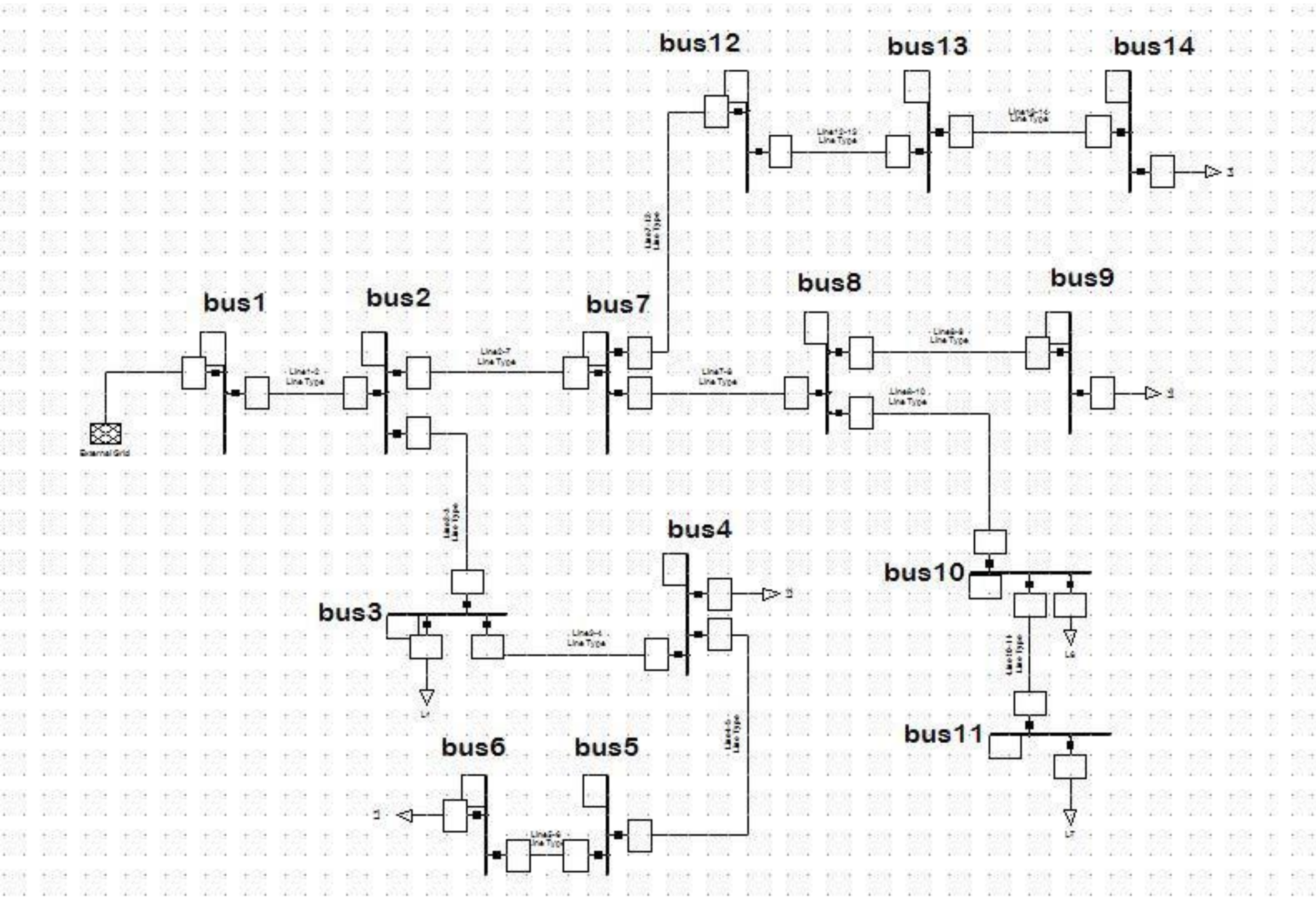

Figure 2. Single linear diagram of the sample network [23].

$$Z_{kl}^{(i)} = Z_{0,kl}^{(i)}, k, l = 1,2, \dots, n \quad (1)$$

$$Z_{rk}^{(i)} = B_k^{(i)} + C_k^{(i)} m \quad (2)$$

$$Z_{rr}^{(i)} = A_0^{(i)} + A_1^{(i)} m + A_2^{(i)} m^2 \quad (3)$$

$$B_k^{(i)} = Z_{0,pk}^{(i)} \quad (4)$$

$$C_k^{(i)} = Z_{0,kp}^{(i)} - Z_{0,kq}^{(i)} \quad (5)$$

It is obvious that the matrix Z_0 has n number of rows and columns and the matrix Z has n+1 rows and columns. $C_k^{(i)}$, $B_k^{(i)}$, $A_0^{(i)}$, $A_1^{(i)}$ and $A_2^{(i)}$ are constants that are obtained from network parameters. Based on the above equations, it is clear that when the fault location is considered as a new bus, impedance between the fault point and other buses ($Z_{rk}^{(i)}$) is expressed as a function of the unknown variable of fault location (m) in the form the equation (2).

$$E_k^{(1)} = E_k^{(1)0} - Z_{kr}^{(1)} I_f^{(1)} \quad (6)$$

$$E_k^{(2)} = -Z_{kr}^{(2)} I_f^{(2)} \quad (7)$$

$$E_k^{(0)} = -Z_{kr}^{(0)} I_f^{(0)} \quad (8)$$

In equations (6-8), $E_k^{(1)0}$ is the pre-fault voltage of positive sequence in bus k, $E_k^{(1)}$, $E_k^{(2)}$ and $E_k^{(0)}$ are respectively the voltage of positive, negative and zero sequences of the bus k during the fault. Also, $I_f^{(1)}$, $I_f^{(2)}$ and are the components of the fault current sequence $I_f^{(0)}$. It should be noted that all the voltage and current components in the above equations are of Phase A. equations (6-8) show that voltage components in each bus can be obtained depending on the corresponding transitional impedance and the fault current component.

If the voltage of the positive sequence is used, equation (9) is achieved:

$$\Delta E_k^{(1)} = Z_{kr}^{(1)} I_f^{(1)} \quad (9)$$

By placing equation (2) inside equation (9) and simplifying it, equation (10) will be the result:

$$\Delta E_k^{(1)} = Z_{0,kp}^{(i)} x I_f^{(1)} + Z_{0,kq}^{(i)} (1-x) I_f^{(1)} \quad (10)$$

Therefore, if n is the number of meters in the network, equations can be written this way:

Table 1. Chance of observability (percentage) in a way that locating error for different uncertainties in different parts of the network is less than 5 percent (PMU installation in Buses 1, 6, 9, 11, 14)

line	Fault local (pu)	Fault type						Ref [23]
		LLL			LG			
		R_f (ohm)			R_f (ohm)			
		0	25	50	0	25	50	
1-2	0.2	100	100	100	100	100	100	100
	0.5	100	100	100	100	100	100	
	0.8	99.5	99.5	99.5	99.5	99.5	99.5	
2-3	0.2	100	100	100	100	100	100	100
	0.5	100	100	100	100	100	100	
	0.8	93.5	93.5	93.5	93.5	93.5	93.5	
3-4	0.2	58.5	58.5	58.5	58.5	58.5	58.5	100
	0.5	51.5	51.5	51.5	51.5	51.5	51.5	
	0.8	50.5	50.5	50.5	50.5	50.5	50.5	
4-5	0.2	100	100	100	100	100	100	100
	0.5	100	100	100	100	100	100	
	0.8	100	100	100	100	100	100	
7-8	0.2	100	100	100	100	100	100	0
	0.5	100	100	100	100	100	100	
	0.8	100	100	100	100	100	100	
10-11	0.2	100	100	100	100	100	100	0
	0.5	100	100	100	100	100	100	
	0.8	99	99	99	99	99	99	
12-13	0.2	59.5	59.5	59.5	59.5	59.5	59.5	0
	0.5	54.5	54.5	54.5	54.5	54.5	54.5	
	0.8	49	49	49	49	49	49	
13-14	0.2	99.5	99.5	99.5	99.5	99.5	99.5	0
	0.5	99	99	99	99	99	99	
	0.8	99	99	99	99	99	99	

$$\begin{bmatrix} \Delta E_1^{(1)} \\ \vdots \\ \Delta E_n^{(1)} \end{bmatrix} = \begin{bmatrix} Z_{0,1p}^{(i)} x I_f^{(1)} + Z_{0,1q}^{(i)}(1-x) I_f^{(1)} \\ \vdots \\ Z_{0,np}^{(i)} x I_f^{(1)} + Z_{0,nq}^{(i)}(1-x) I_f^{(1)} \end{bmatrix} \quad (11)$$

The matrix left of the equation (11) is considered as M (Measurement Matrix) and $X = \left[x, I_f^{(1)}\right]$ is considered as the matrix of unknown variables. Then, equation (11) can be re-written this way:

$$M - F(x) = 0 \quad (12)$$

If there is no uncertainty in the network, equation (12) takes hold. But because of uncertainty in the network, such as changes of reactance and lines resistance due to temperature changes or errors of metering units, voltage changes that are obtained by measurement units have errors and thus, the number of meters should increase in order to enhance the fault location accuracy. In this condition and with the number of meters exceeding the unknowns, we use the least fault squares to detect the fault location. Considering what has been stated, equation (12) is rewritten this way:

$$M = F(X) + e \quad (13)$$

Table 2. Chance of observability (percentage) in a way that locating error for different uncertainties in different parts of the network is less than 5 percent (PMU installation in Buses 1, 3, 6, 9, 11, 12, 14)

line	Fault local (pu)	Fault type						Ref [23]
		LLL			LG			
		R_f (ohm)			R_f (ohm)			
		0	25	50	0	25	50	
1-2	0.2	100	100	100	100	100	100	100
	0.5	100	100	100	100	100	100	
	0.8	100	100	100	100	100	100	
2-3	0.2	100	100	100	100	100	100	100
	0.5	100	100	100	100	100	100	
	0.8	95.5	95.5	95.5	95.5	95.5	95.5	
3-4	0.2	86.5	86.5	86.5	86.5	86.5	86.5	100
	0.5	80	80	80	80	80	80	
	0.8	81.5	81.5	81.5	81.5	81.5	81.5	
4-5	0.2	100	100	100	100	100	100	100
	0.5	100	100	100	100	100	100	
	0.8	100	100	100	100	100	100	
7-8	0.2	100	100	100	100	100	100	0
	0.5	100	100	100	100	100	100	
	0.8	100	100	100	100	100	100	
10-11	0.2	99	99	99	99	99	99	0
	0.5	98.5	98.5	98.5	98.5	98.5	98.5	
	0.8	99.5	99.5	99.5	99.5	99.5	99.5	
12-13	0.2	86.5	86.5	86.5	86.5	86.5	86.5	0
	0.5	84	84	84	84	84	84	
	0.8	87.5	87.5	87.5	87.5	87.5	87.5	
13-14	0.2	100	100	100	100	100	100	0
	0.5	100	100	100	100	100	100	
	0.8	100	100	100	100	100	100	

In which e represent the fault. Least fault squares (LS) method is expressed as minimizing the following objective function:

$$\min f = [M - F(X)]^T [M - F(X)] \quad (14)$$

3. SIMULATION

In this article, in order to check the accuracy and efficiency of the suggested method, a 14 bus distribution network (its information is available in reference [23]) has been used. The single-linear model simulated on Digsilent software has been shown in Figure 2.

One of the causes of uncertainty in the power system is changes of lines resistance and reactance due to temperature changes. In this section, the uncertainty of reactance and resistance of positive, negative and zero sequences of the lines has been taken into consideration and results of fault location by the said algorithm are shown in this article. It is necessary to point out that in order to model uncertainty, normal distribution with the standard deviation of 5% and an average of zero has been used.

In this stage, the said fault location algorithm is implemented for short connection faults of three phases (LLL), two phases (LL), single-phase to the ground (LG) and two phases to the ground (LLG) with fault resistances of 0, 25 and 50 ohm in all the lines (three points of each line) and for all the uncertainties (to a thousand times) and we calculate the probability of fault location error is less than 5 percent. It should be mentioned that the locating error is calculated by the following equation (15):

$$error(\%) = \frac{d_{est} - d_{exact}}{L} \times 100 \qquad (15)$$

Table 3. Location error average (percentage) for all types of short connection faults in different parts of the network (PMU installation in buses 1, 6, 9, 11 and 14)

line	Fault local (pu)	Fault type						Ref [23]
		R_f (ohm)			R_f (ohm)			
		0	25	50	0	25	50	
1-2		LLL			LG			100
	0.2	0.21	0.21	0.21	0.21	0.21	0.21	
	0.5	0.54	0.54	0.54	0.54	0.54	0.54	
	0.8	0.87	0.87	0.87	0.87	0.87	0.87	
2-3		LG			LL			100
	0.2	1.11	1.11	1.11	1.11	1.11	1.11	
	0.5	2.74	2.74	2.74	2.74	2.74	2.74	
	0.8	4.34	4.34	4.34	4.34	4.34	4.34	
3-4		LLG			LLL			100
	0.2	0.76	0.76	0.76	0.76	0.76	0.76	
	0.5	2.03	2.03	2.03	2.03	2.03	2.03	
	0.8	3.29	3.29	3.29	3.29	3.29	3.29	
4-5		LG			LL			100
	0.2	0.29	0.29	0.29	0.29	0.29	0.29	
	0.5	0.15	0.15	0.15	0.15	0.15	0.15	
	0.8	0.53	0.53	0.53	0.53	0.53	0.53	
7-8		LLL			LL			0
	0.2	0.25	0.25	0.25	0.25	0.25	0.25	
	0.5	0.11	0.11	0.11	0.11	0.11	0.11	
	0.8	0.28	0.28	0.28	0.28	0.28	0.28	
10-11		LG			LLG			0
	0.2	1.16	1.16	1.16	1.16	1.16	1.16	
	0.5	3.96	3.96	3.96	3.96	3.96	3.96	
	0.8	1.95	1.95	1.95	1.95	1.95	1.95	
12-13		LLL			LG			0
	0.2	3.97	3.97	3.97	3.97	3.97	3.97	
	0.5	3.10	3.10	3.10	3.10	3.10	3.10	
	0.8	2.44	2.44	2.44	2.44	2.44	2.44	
13-14		LL			LLG			0
	0.2	0.28	0.28	0.28	0.28	0.28	0.28	
	0.5	0.39	0.39	0.39	0.39	0.39	0.39	
	0.8	0.81	0.81	0.81	0.81	0.81	0.81	

d_{est}, d_{exact} and L are estimation error, exact fault location, and line's length, respectively and they can be expressed by different units or as per-units. Also, fault observability chance is defined as the following:
The ratio of the locating attempts counts with fault location estimation error less than 5% to all the locating attempts.

In the first stage, it has been assumed that PMUs have been installed in buses 1, 6, 9, 11 and 14. Values in Table 1 and Table 2 show the fault observability at different points. For example, numbers 100 and 99.5 show that if we consider different uncertainties for N times (thousand times in this simulation) and then run the fault locating algorithm, the location error will be less than 5 percent for 1000 and 995 of the uncertainties. According to Table 1, the least observability chance is for lines 3-4 and 12-13 which are respectively 50.5 and 49%. If we increase the PMUs and install them in buses 3 and 12, then according to Table 2, the least observability chance in lines 3-4 and 12-13 will rise to 80 and 84 percent. According to the mentioned topics, PMU installation in buses 1, 3, 6, 9, 11, 12 and 14 can make the network more visible with a minimum probability of 80 percent.

Table 4. Location error average (percentage) for all types of short connection faults in different parts of the network (PMU installation in buses 1, 3, 6, 9, 11, 12 and 14)

line	Fault local (pu)	Fault type						Ref [23]
		R_f (ohm)			R_f (ohm)			
		0	25	50	0	25	50	
1-2		LLL			LG			100
	0.2	0.05	0.05	0.05	0.05	0.05	0.05	
	0.5	0.27	0.27	0.27	0.27	0.27	0.27	
	0.8	0.01	0.01	0.01	0.01	0.01	0.01	
2-3		LG			LL			100
	0.2	0.90	0.90	0.90	0.90	0.90	0.90	
	0.5	1.28	1.28	1.28	1.28	1.28	1.28	
	0.8	1.77	1.77	1.77	1.77	1.77	1.77	
3-4		LLG			LLL			100
	0.2	0.04	0.04	0.04	0.04	0.04	0.04	
	0.5	0.64	0.64	0.64	0.64	0.64	0.64	
	0.8	0.85	0.85	0.85	0.85	0.85	0.85	
4-5		LG			LL			100
	0.2	0.03	0.03	0.03	0.03	0.03	0.03	
	0.5	0.14	0.14	0.14	0.14	0.14	0.14	
	0.8	0.32	0.32	0.32	0.32	0.32	0.32	
7-8		LLL			LL			0
	0.2	0.02	0.02	0.02	0.02	0.02	0.02	
	0.5	0.10	0.10	0.10	0.10	0.10	0.10	
	0.8	0.34	0.34	0.34	0.34	0.34	0.34	
10-11		LG			LLG			0
	0.2	0.58	0.58	0.58	0.58	0.58	0.58	
	0.5	0.70	0.70	0.70	0.70	0.70	0.70	
	0.8	0.45	0.45	0.45	0.45	0.45	0.45	
12-13		LLL			LG			0
	0.2	1.23	1.23	1.23	1.23	1.23	1.23	
	0.5	0.99	0.99	0.99	0.99	0.99	0.99	
	0.8	0.71	0.71	0.71	0.71	0.71	0.71	
13-14		LL			LLG			0
	0.2	0.22	0.22	0.22	0.22	0.22	0.22	
	0.5	0.20	0.20	0.20	0.20	0.20	0.20	
	0.8	0.23	0.23	0.23	0.23	0.23	0.23	

In the next simulation step, fault location results for all types of short connection faults were investigated and location error average has been shown in Table 3 and Table 4. Based on Table 4, it is concluded that increased PMUs lead to lower location error average. It should be noted that the results of only two short connection faults for 8 out of 13 lines have been presented in Table 3 and Table 4. Based on these tables, we can observe that fault type and resistance of short connection do not have any influence on the accuracy of this algorithm.

As you can see in Table 1, Table 2, Table 3, and Table 4, the results of the proposed method are compared with the reference [23]. In the reference [23], the idea of installing PMU is presented at the beginning and end of the network main line, but in the proposed scheme the performance of the algorithm for different faults, resistance of different faults has been investigated and it has been able to detect the faulted section in addition to detecting the fault distance. This was not included in the reference [23] and could only detect faults in the network main line.

4. CONCLUSION

In this article, the effect of an increased number of PMUs on fault location accuracy was investigated and it was observed that an increase of measurement units enhances the fault location accuracy. In the suggested method, the least fault squares were used to detect the fault location. Advantages of the suggested fault location algorithm are mentioned below:

- The algorithm is applicable to all networks.
- Type and resistance of short connection fault has no impact on the algorithm accuracy.
- In order to find the fault location, there is no need to know its type.
- The most important advantage is the ability to find the fault location with high accuracy with uncertainty in network parameters.

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