On-Line Fault Location of Transmission System based on Synchrophasor Measurements

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Abstract

Transmission line fault location is an indispensable task for reliable performance of power systems. Accurate determination of fault location could lead to rapid returning of a line to the circuit. Miscellaneous methods have been propounded in the past for the transmission line fault location depending on the accessible measurement sets. Inaccurate and uncertain line parameters are among factors that reduce the precision of transmission line fault location algorithms. In this paper, a novel method is devised for the on-line transmission line fault location based on the synchronized data of phasor measurement units (PMUs). The proposed method estimates the line parameters using pre-fault voltage and current phasors provided by PMUs; thereafter, these parameters are used in the fault location algorithm. Estimation process is done with the non-linear weighted least square (NWLS) method which is a powerful method in the non-linear estimation problems. In order to demonstrate the application and effectiveness of the proposed method, a set of case studies are conducted.

Keyword: Fault Location, Transmission Line Parameter Estimation, Phasor Measurement Unit (PMU), Non-Linear Weighted Least Square (NWLS)

1. Introduction

Transmission lines are one of the most crucial components in electric power systems, which deliver the generating unit output powers to the consumption centers. At the event of any fault in the transmission system, the protection schemes isolate the faulted line by opening the line breakers at its both ends. The out of service status of faulted lines will lead to considerable losses in either or both production and consumption sections. As a result, transmission line fault location should be specified through a rapid and accurate method. Timely and precise determination of fault location will hasten the restoration of power delivery, reduce the outage time and ameliorate the system reliability [1-3].

Various algorithms for the transmission line fault location have been presented in the past literature. In [4], a new protection scheme is presented for both transposed and untransposed parallel transmission lines. The method is based on the distributed line model and uses the synchronized phasor measurement units (PMUs) data located at both ends of the line. Based on the reactance method of fault distance estimation and by use of data associated with one terminal of the line, reference [5] has proposed a new technique for calculation of the transmission line fault location. A concept of fault location observability and a new fault location scheme by using of the synchronized voltage and current phasors were presented in [6]. In [7, 8], differential equations of transmission lines based on synchronized sampling has been used for the fault location objective. Neural network technique has been employed in [9, 10] for the transmission line fault location.

This paper proposes a new method for estimation of a transmission line fault location using synchronized voltage and current phasors obtained by located PMUs at both sides of the line. The proposed method is based on the equivalent π model of the line during the fault time. Initially, distributed line parameters are estimated using prefault voltage and current phasors of both sides of the line. Thereafter, these parameters are used for estimation of the fault location using the equivalent π model of the line. Estimation process is done by the non-linear weighted least square (NWLS) algorithm. The proposed method is examined using Electromagnetic Transients Program (EMTP), and results demonstrate the accuracy of the proposed method.

2. Proposed Methodology for Transmission Line Fault Location

The overall description of the method is presented in Section 2.1. The required steps for the proposed transmission line fault location are described in Sections 2.2 and 2.3, respectively. Section 2.4 explains the NWLS method for the estimation process.

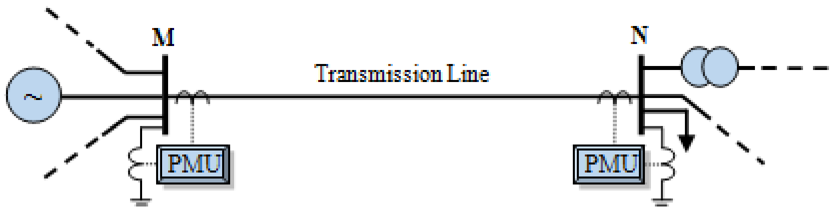

Fig. 1. A typical transmission line.

2.1 Overall Description of the Method

A fully transposed transmission line between two buses, is considered in this paper for the study. Fig. 1 depicts this transmission line with measurement devices. The data, which could be used for fault location process may include: Prefault voltage and current data, fault time voltage and current data, Thevenin equivalent source voltages and impedances, and the synchronized angle between two ends of line. Normally, there are only positive sequence components for a balanced three-phase transmission line. However, in unsymmetrical faults, the negative and/or zero sequence components may appear as well. There may be positive-, negative- and zero-sequence components in the network during the fault depending on the fault type [3]. In this paper, the prefault voltage and current phasors are employed for the estimation of transmission line parameters in the positive sequence space. Thereafter, these parameters are used for the transmission line fault location based on the equivalent π model of the line during the fault time.

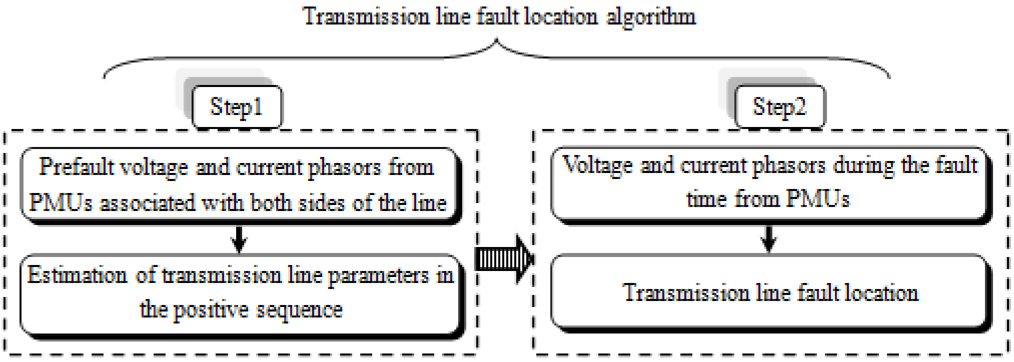

Fig. 2. The overall framework.

The overall framework of the proposed transmission line fault location algorithm is illustrated in Fig. 2.

2.2 Transmission Line Parameter Estimation Algorithm

One of the factors that reduce the precision of transmission line fault location algorithms is the inaccuracy and uncertainty in line parameters. Different factors such as climate changes, system operation conditions, load fluctuations, aging, manufacturing deviations, and so on, change transmission line parameters. As a result, accurate estimation of these parameters will improve the accuracy of transmission line fault location algorithms along with other suits of power system analyses. With the emergence of PMU technology, accurate and on-line estimation of transmission line parameters has been became a feasible solution. Along different proposed methods for on-line estimation of transmission line parameters, methods based on the Kirchhoff's voltage and current laws are more popular. As indicated in Section 2.1, prefault voltage and current phasors are adopted here for on-line estimation of line parameters.

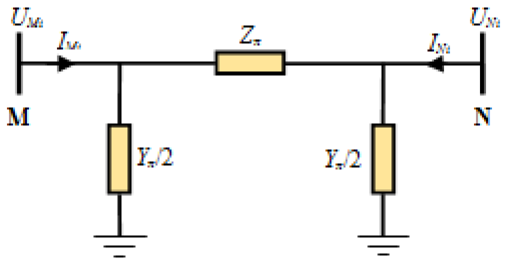

Fig. 3. Equivalent π model of a transmission line.

The equivalent π model for a long transmission line is illustrated in Fig. 3. In this figure, we have the following notations. U_{Mi}, U_{Ni} are the i^{th} positive sequence voltage phasors associated with terminals M and N, respectively; I_{Mi}, I_{Ni} are the i^{th} positive sequence current phasors associated with terminals M and N, respectively; $i = 1, 2, \ldots, N$ is the measurement set index; N is the total number of the measurement sets; Z_π is the π model impedance; Y_π is the π model admittance.

Utilizing Kirchhoff's voltage and current laws for the model shown in Fig. 3, we have

$$U_{Mi} - Z_\pi \left(I_{Mi} - U_{Mi} Y_\pi / 2\right) - U_{Ni} = 0 \quad (1)$$

$$I_{Mi} - U_{Mi} Y_\pi / 2 - U_{Ni} Y_\pi / 2 + I_{Ni} = 0 \quad (2)$$

Owing to the fact that the real part of Y_π is negligible, the real and imaginary parts of Z_π, along the imaginary part of Y_π are three unknown parameters. Based on the NWLS method which will be explained in Section 2.4, we need three or more equations for estimation of the designated unknown parameters. Either of (1) or (2), which is complex and could be rewritten as two real equations, could be used for the estimation process. Here, line equation (1) is adopted for the estimation of three unknown parameters. The unknown variable vector and the measurement vector are defined as follows, respectively

$$\mathbf{Y} = \left[y_1, y_2, y_3 \right]^T \quad (3)$$

$$\mathbf{X} = \left[x_{1i}, x_{2i}, x_{3i}, x_{4i}, x_{5i}, x_{6i} \right] \quad (4)$$

where, y_1, y_2 are the real and imaginary parts of Z_π; y_3 is the imaginary part of Y_π; x_{1i}, x_{2i} are the real and imaginary parts of U_{Mi}; x_{3i}, x_{4i} are the real and imaginary parts of I_{Mi}; x_{5i}, x_{6i} are the real and imaginary parts of U_{Ni}; x_{7i}, x_{8i} are the real and imaginary parts of I_{Ni}; and T is vector or matrix transpose operator.

Employing **Y** and **X**, equation (1) is rewritten as

$$f_i(X,Y)=(x_{1i}+jx_{2i})-[(y_1+jy_2)((x_{3i}+jx_{4i})-(x_{1i}+jx_{2i})(jy_3/2))]-(x_{5i}+jx_{6i})=0 \tag{5}$$

Equations (5) is complex and could be rewritten as two real equations, which are

$$F_i^1(X,Y)=real(f_i(X,Y)) \tag{6}$$

$$F_i^2(X,Y)=imag(f_i(X,Y)) \tag{7}$$

We need two or more measurement sets for estimation of the unknown variable vector based on the NWLS method and using (6) and (7). In this paper, we use three sets of prefault voltage and current phasors for the estimation of line parameters. Since the fault location algorithm needs distributed line parameters, these parameters are to be calculated after the estimation of π model parameters. Distributed line parameters could be calculated as bellow

$$Z_\pi = Z_c \sinh(\gamma l) \tag{8}$$

$$Y_\pi = \frac{2}{Z_c}\tanh(\gamma l/2) \tag{9}$$

$$\gamma = \frac{2}{l}\sinh^{-1}\sqrt{Z_\pi Y_\pi/4} \tag{10}$$

$$Z_c = \left(\sqrt{Z_\pi/Y_\pi}\right)/\cosh\left(\sinh^{-1}\sqrt{Z_\pi Y_\pi/4}\right) \tag{11}$$

$$z = Z_c\gamma \tag{12}$$

$$y = \gamma/Z_c \tag{13}$$

where, Z_c is the characteristic impedance of line; γ is the propagation constant of the line; l is the total length of the line in mile or km; and z and y are the series impedance and shunt admittance of the line per mile or km, respectively.

2.3 Fault Location Algorithm

When a fault occurs in a given transmission line, we can consider two series equivalent π models with distributed parameters equal to those of the line. Fig. 4 depicts the positive sequence equivalent π model of a transmission line during the fault time.

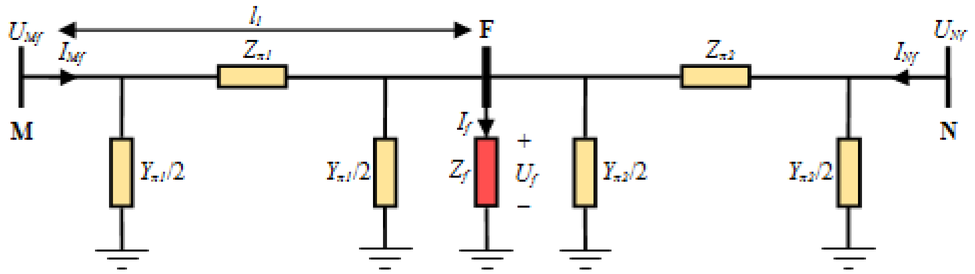

Fig. 4. Equivalent π model of a transmission line during the fault time.

Despite different equivalent π model parameters for line sections M-F and F-N, the distributed parameters for these two sections are equal. The equivalent π model parameters for line sections M-F and F-M, are calculated as follows

$$Z_{\pi 1} = Z_c \sinh(\gamma l_1) \tag{14}$$

$$Y_{\pi 1} = \frac{2}{Z_c} \tanh(\gamma l_1 / 2) \tag{15}$$

$$Z_{\pi 2} = Z_c \sinh(\gamma (l - l_1)) \tag{16}$$

$$Y_{\pi 2} = \frac{2}{Z_c} \tanh(\gamma (l - l_1)/2) \tag{17}$$

where, l_1 is the length of section M-F (in mile or km) and l is the total length of the line MN. Referring to Fig. 4, the Kirchhoff's voltage law allows us to eliminate the fault point voltage in the equations, thus

$$U_{Mf} - Z_{\pi 1}\left(I_{Mf} - U_{Mf} Y_{\pi 1}/2\right) - U_{Nf} + Z_{\pi 2}\left(I_{Nf} - U_{Nf} Y_{\pi 2}/2\right) = 0 \tag{18}$$

where, U_{Mf} and U_{Nf} are positive sequence voltage phasors associated with terminals M and N during the fault time; I_{Mf} and I_{Nf} are positive sequence current phasors associated with terminals M and N during the fault time.

Substitution of $Z_{\pi 1}$, $Y_{\pi 1}$, $Z_{\pi 2}$ and $Y_{\pi 2}$ from (14)-(17) in (18) yields

$$U_{Mf} - Z_c \sinh(\gamma l_1)\left(I_{Mf} - \frac{U_{Mf}}{Z_c} \tanh(\gamma l_1/2) \right) - U_{Nf} + Z_c \sinh(\gamma (l - l_1)) \cdot \left(I_{Nf} - \frac{U_{Nf}}{Z_c} \tanh(\gamma (l - l_1)/2) \right) = 0 \tag{19}$$

The voltage and current phasors associated with both ends of the line during the fault time are available from located PMUs. Considering that distributed parameters will be estimated using pre fault data, l_1 is the only unknown parameter in (19). Equation (19) is a complex equation and can be reordered into two real equations, by which the only unknown parameter, namely l_1, can be theoretically solved by either of these equations.

2.4 None-Linear Weighted Least Square (NWLS) Method

If the measurements are a non-linear function of the parameters, we may have

$$0 = \mathbf{f}(\mathbf{X}, \mathbf{Y}) + \boldsymbol{\varepsilon} \tag{20}$$

where, $\boldsymbol{\varepsilon}$ is the unbiased measurement error vector with normal distribution and mean values of zero. Then, the task is to find $\hat{\mathbf{Y}}$ while minimizing

$$J = [-\mathbf{f}(\mathbf{X}, \mathbf{Y})]^T \mathbf{W}^{-1} [-\mathbf{f}(\mathbf{X}, \mathbf{Y})] \tag{21}$$

where, $\mathbf{W}$ is called the covariance matrix of measurement errors. Equation (21) must be minimized recursively as follows

$$\mathbf{Y}_{j+1} = \mathbf{Y}_j + \Delta \mathbf{Y} \tag{22}$$

$$\Delta \mathbf{Y} = \left[\mathbf{H}^T \mathbf{W}^{-1} \mathbf{H}\right]^{-1} \left[\mathbf{H}^T \mathbf{W}^{-1} \left(-\mathbf{f}(\mathbf{X}, \mathbf{Y}_j)\right)\right] \tag{23}$$

$$\mathbf{H} = \frac{\partial \mathbf{f}(\mathbf{X}, \mathbf{Y}_j)}{\partial \mathbf{Y}_j} \tag{24}$$

where, $\mathbf{Y}_j$ and $\mathbf{Y}_{j+1}$ are variable vectors after and before j^{th} iteration, respectively; $\mathbf{H}$ is a matrix of first partial derivatives of the elements of $\mathbf{f}$ with respect to the components of $\mathbf{Y}$. When $\Delta\mathbf{Y}$ is smaller than a specified tolerance, the iterative process would be terminated.

3. Simulation Results

In this section, a number of case studies are conducted to demonstrate performance of the proposed method for the transmission line fault location. In order to simulate the fault conditions, the EMTP program is adopted. A typical 500 kV, 60 Hz and 150 km transmission line is simulated in EMTP program. Fig. 4 illustrates the simulated circuit in the EMTP program.

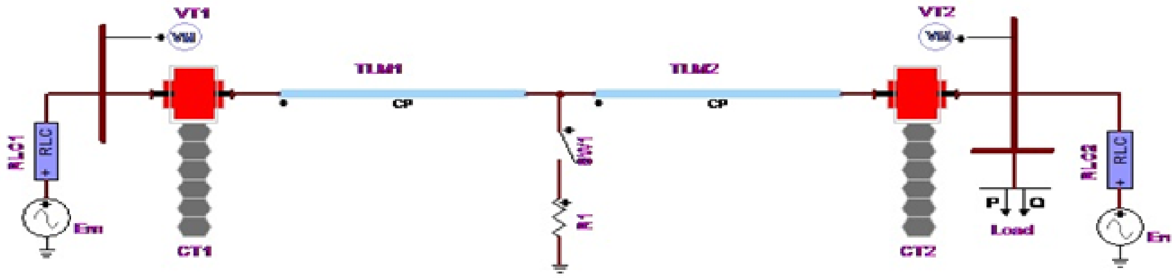

Fig. 5. The simulated circuit in the EMTP program.

As previously mentioned, in the first step, we need three sets of prefault voltage and current phasors in order to estimate transmission line parameters. These voltage and current sets could be obtained by changing the power flows in the line. Owing to this fact that the measurement devices may have some errors, the obtained voltage and current phasors are disturbed with Gaussian noises with specified variances. The estimation process is done in MATLB programing environment. Table I shows the actual and estimated π model parameters, which are estimated based on the explained method in Section 2.2 and using prefault voltage and current phasors associated with both sides of the line. It can be deduced from Table I that the estimated values using ideal measurement sets are exactly equal to actual values. Whereas, for the case containing noisy measurement sets, estimated line parameters have a good accuracy.

TABLE I Estimated π Model Parameters Using Pre Fault Voltage and Current Phasors

Quantity	Actual Value	Estimated Value	
		Without Measurements Errors	With Measurements Errors
R_π (Ω)	2.46	2.46	2.41
X_π (Ω)	30.23	30.23	30.15
B_π (℧)	0.00000265	0.00000265	0.00000264

After estimation of the π model parameters, distributed parameters are calculated and are demonstrated in Table II. The distributed parameters of the line r, l and c, are also given in this table.

TABLE II Estimated Distributed Parameters

Quantity	Actual Value	Estimated Value	
		Without Measurements Errors	With Measurements Errors
R (Ω/km)	0.01637	0.01637	0.01606
X (Ω/km)	0.2015	0.2015	0.2010
B (℧/km)	0.01767e-6	0.01767e-6	0.01760e-6

In order to testify the performance of the proposed methodology, various fault conditions (in location and fault resistance) are taken into consideration. Owing to the point that the proposed method is based on the positives sequence measurements and parameters, other types of faults particularly those with asymmetrical nature should be accounted for too. Table III outlines actual and estimated fault location with the same fault resistance. It can be seen that very precise estimates have been attained by the proposed method even when the measurement sets have some errors.

4. Conclusion

In this paper, a new and accurate method has been devised for the transmission line fault location using synchronized voltage and current phasors obtained by located PMUs at both sides of the line. The proposed method estimates transmission line parameters and uses these values as input parameters for fault location algorithm. As a result, the inaccuracy caused by uncertain and imprecise line parameters in the fault location algorithm is averted. Owing to the use of distributed parameter line model in the fault location algorithm, the proposed method could fully consider the effect of shunt capacitance of long transmission lines. Simulation results demonstrate the correctness and applicability of the new method.

Table III Estimated of Different Fault Locations

Quantity	Actual Value	Estimated Value	
		Without Measurements Errors	With Measurements Errors
Location of fault number 1 (km)	20	20	19.95
Location of fault number 2 (km)	40	40	39.93
Location of fault number 3 (km)	60	60	59.84
Location of fault number 4 (km)	80	80	79.81
Location of fault number 5 (km)	100	100	99.76
Location of fault number 6 (km)	120	120	119.7
Location of fault number 7 (km)	140	140	139.65

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